Cranfield University

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Modelling and Analysis of Engineering Changes in Complex Systems

School of Engineering

A dissertation submitted for the Degree of Doctor of Philosophy

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2007

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Academic Year 2006 to 2007

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

(NB. This section can be removed if the award of the degree is based solely on examination of the thesis)

ABSTRACT

Complex products are comprised of a large number of tightly integrated components, assemblies and systems resulting in extensive logical and physical interdependences between the constituent parts. Thus a change to one item of a system is highly likely to lead to a change to another item, which in turn can propagate further. The aim of this research therefore is to investigate dependency models that can be used to identify the impact and trace the propagation of changes in different information domains, such as requirements, physical product architecture or organisation.

Initially, the state-of-the-art on causes of engineering changes together with change management and change impact analysis methods was explored. This showed that the latter have limited capabilities to model dependencies and focus on only one or two specific domains.

A meta-model was developed that enables the effective elicitation of dependencies between items in multiple domains. Subsequently, novel algorithm was developed to trace these dependency models while considering the appropriate level of detail, limit redundant information and control the propagation between different domains. Finally, an additional algorithm was developed to identify possible impact sets in order to support the discrimination of alternative concepts.

A prototype software was developed in collaboration with the partners in the European project VIVACE in order to evaluate the developed methodology. A large case study based on a Masters' course group design project of a supersonic business jet was then used to discuss with industry the capabilities of the methodology. The evaluation studies and discussions indicated that the proposed methodology can be useful, especially with regard to establishing the potential extent of the impact of changes within a complex single domain or across multiple domains. It was further observed that there is a limit to the level of design detail that can practically be modelled and additional tacit knowledge is needed for a proper interpretation of the change impact.

Keywords:

Qualitative Dependencies, Design Structure Matrix, Domain Mapping Matrix, Propagation Paths, Knowledge Management, Aircraft Architecture

ACKNOWLEDGEMENTS

I would like to thank everyone that helped and supported me during my PhD studies. First and most of all, my gratitude goes to my supervisor, Prof. Marin D Guenov, for his advice and guidance. Additionally, I would like to thank Dr Helen Lockett for helping me, particularly with the E-5 Neutrino case study and revising this thesis. I am also grateful to Dr Dunbing Tang, Dr Sergio Campobasso, Dr Craig Lawson and the other Cranfield staff that helped me throughout my stay at the University.

Also, I would to thank the people from the Change Impact Analysis Task in the VIVACE project. I enjoyed working together with them and their advice, feedback and support in organising the external review sessions have been invaluable. I would like to thank in particular Peter Coleman from Airbus UK, André Rutka from Airbus SAS, Tobias Schmidt-Schäffer and Arnaud Rivière from EADS Innovation Works.

Furthermore, I would like to thank the other PhD students in the research group, for their help and friendship, Libish, Jeremy, Mattia, Marco and in particular Paolo for driving me to the University most days.

Finally, I would like to give special thanks to my family for putting up with my absence and to Ingrid for her love and support.

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CHAPTER I:

Introduction

This chapter introduces the research presented in this thesis by first laying out the importance of design changes or engineering changes (ECs) to complex product development in industry and consequently their relevance as a research topic. Secondly, particular issues related to product changes faced in the aerospace industry are discussed. Thereafter, the motivation for the research is described and the contribution of the research to industry discussed. Subsequently, the research aim, objectives and research questions were formulated. An overview of the thesis structure and summary concludes this introductory chapter.

1 Importance of design changes

Changes to the design of a product occur continuously from concept, through definition and development, to manufacture, and then into service (Figure I-1). These are often more the rule than the exception during product development. There can be different reasons for introducing changes. Changes can emerge when product weaknesses or deficiencies are identified (Eckert et al., 2004). These deficiencies can appear over the whole of the product life cycle. But even with the best design practice, it is impossible to prevent these product changes. Design is a human activity and design outcomes can never be completely predicted. Influences outside the control of a designer can always affect a product design. As result, a design can always be improved and "*the nirvana of a perfect design is constantly out of reach*" (Inness, 1994).

On the other hand, changes can be initiated by a designer. A reason can be to create a new product by modifying or changing an existing one. These modifications can address customers' needs by making products faster, cheaper or increasing their functionality. Also changes can be initiated to bring products in line with new regulations or industry standards. Modifying existing products can furthermore enable a rapid introduction of new products necessary in the current highly competitive markets (Inness, 1994). Also creating product variety to extend its potential market is an important driver for design modifications (Fricke & Schulz, 2005). Sometimes, new product development by means of modifying tested and validated products is even preferred to radical new designs from a safety and reliability point of view (Eckert et al., 2006).

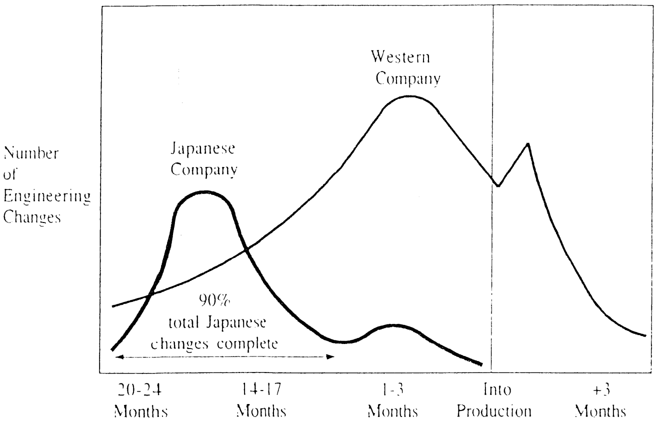


Figure I-1: Number of ECs over product life cycle (Nichols, 1990)

Furthermore, the consequences of ECs during the product development and afterwards are not always expected and wanted. Particularly for complex products where no single person has the full understanding of all the design aspects in detail (Eckert et al., 2004), it becomes difficult to predict the complete detailed impact of a change. Simons (2000) gives an example of a helicopter redesign case at GKN Westland where the unexpected propagation of a change to the wheels led to a 3-4 month delay and an additional cost of £50,000. Terwiesch and Loch (1999) report that ECs can consume one-third to one-half of engineering capacity and represent 20% to 50% of tool costs. Nichols (1990) concludes that changes can have major impacts on the product's time to market, pricing and quality. The effectiveness and efficiency with which a company can predict or control changes could have a significant impact on its competitiveness. Therefore, companies initiate a formal or informal EC process when a request for a change is made. This process strives to find the best solution to implement the change in the product design. A generic EC process is depicted in Figure I-2 and comprises of three stages, namely EC Proposal, EC investigation and EC embodiment. (Rivière et al., 2002b).

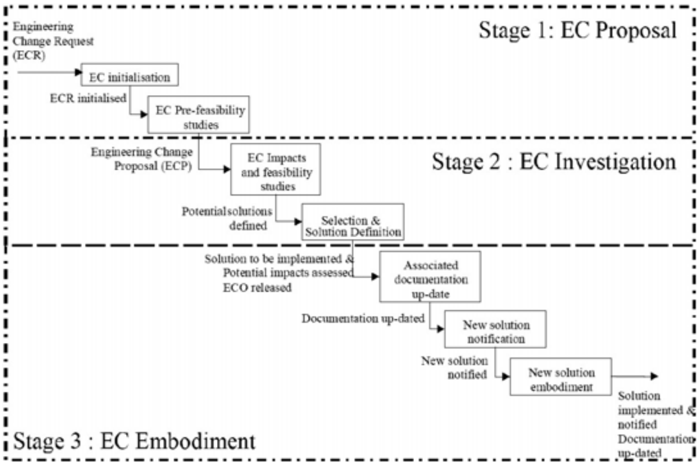


Figure I-2: A Generic EC Process (Rivière et al., 2002a)

Current practices for dealing with ECs often use formal configuration management procedures and rely heavily on human communication, the knowledge and experience of individuals in a specific system area, as well as common sense. In order to improve the capacity to manage time, cost, resources and quality, many industrial studies (Fricke et al., 2000; Huang & Mak, 1999; Hsu, 1999; Pikosz & Malmqvist, 1998; Earl et al., 2005) have been carried out and strategies to cope with changes have been suggested. Much research in the past focussed on the development of methods to better manage changes (Fricke et al., 2000; Huang et al., 2000). Others tried to minimise the impact of ECs by suggesting strategies to design more robust products which can resist or absorb changes better (Schulz et al., 2000; Martin & Ishii, 2002).

Another approach focuses on methods to predict the extent of impact of a change using connectivity models of the product and its related knowledge (Guenov, 1996). This research takes into account that complex products or systems are comprised of a large number of tightly integrated components, assemblies and systems resulting in extensive logical and physical interdependences between the constituent parts. Thus a change to one item of a system is highly likely to result in a change to another item, which in turn can propagate further (Eckert et al., 2004). It is widely acknowledged (Jarratt et al., 2002b; Rivière et al., 2003) that the analysis of change propagation is necessary for predicting and simulating the impact of change. Proposed methods include probabilistic analysis (Clarkson et al., 2001) of the connectivity model and visualisation of change propagation paths (Eckert et al., 2006).

2 Changes in the aerospace industry

In the aerospace industry, companies are continually aiming for more reliable, higher performing products which fulfil better the individual customer's needs through product variety at an ever lower cost. Furthermore, the aerospace industry as other manufacturing industries faces globalisation and fragmentation resulting in an increasingly mobile workforce. Additionally, its product and its associated processes are complex and require design experts from many different disciplines and increasingly, located in different companies. As a result, the conjecture is that relevant knowledge that can be formalised needs to be elicited, stored and, when appropriate, retrieved in subsequent design projects (Clarkson & Hamilton, 2000). This should help to enable a global and consistent shared view of the product information across a distributed design environment that has been envisioned (Coleman et al., 2005; Rutka et al., 2006). An argument in support is that aerospace products are developed in the context of a highly regulated and safety conscious industry. As a result, designs are generally conservative since new products based primarily on older certified designs are generally more likely to meet with regulatory approval (Clarkson & Hamilton, 2000). Consequently, the availability of product information of existing aircraft will support the development of new aircraft. If aerospace companies are to improve the efficiency and effectiveness of their design processes, a more integrated and shared EC impact analysis approach within organisations and across their supply chains appears to be needed to support the decision-making in the EC processes (Rivière et al., 2002b).

3 Motivation

The research presented in this thesis is the author's contribution to Cranfield University's work performed for the 'Change Impact Analysis' (CIA) task in the project VIVACE which stands for 'Value Improvement through a Virtual Aeronautical Collaborative Enterprise'. This project is partly funded by the sixth framework programme of the European Commission. It brings Airbus and other European aerospace companies together with research institutes to enable "*an Aeronautical Collaborative Design Environment and associated Processes, Models and Methods […] providing to the aeronautics supply chain in an extended enterprise, virtual products with all requested functionality and components in each phase of the product engineering life cycle*" (VIVACE, 2005). The CIA task specifically aimed to develop new methods or improve existing methods "*to support decision-making in engineering change processes and concept alternative discrimination*" (Coleman et al., 2005). Consequently, the objectives were defined as reducing the aircraft development lead times and cost and improving the customers focus and product quality (Figure I-3). The main participants were major European aerospace companies.

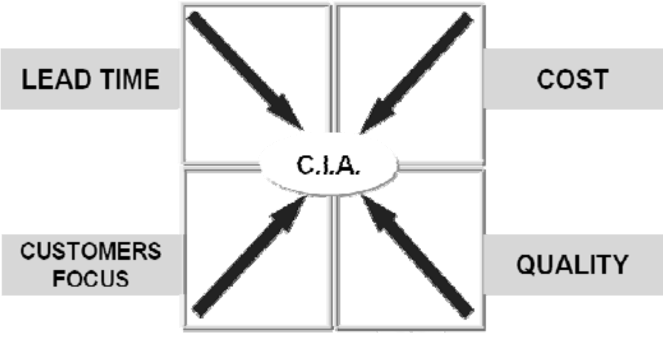


Figure I-3: Change Impact Analysis objectives in VIVACE (Coleman et al., 2005)

The industrial requirements were formulated based on the work previously carried out at the industrial partners (Coleman, 2003) and a review of the state-of-the-art on engineering change theories and practices. The result was the development of a prototype software that could be used to demonstrate and validate a change impact analysis methodology in an industrial context. The contributions from the author focussed on the implementation of algorithms that tracked the propagation of a change and algorithms that could cluster and partition dependency matrices to support robustness evaluation and optimise task sequences.

The proposed methodology presented in this thesis is based upon the author's contributions to the development of the meta-model for storing interdependencies and the propagation algorithm in the CIA task. The methodology was also extended with features that were not included in the CIA approach. Therefore, the CIA prototype software was also extended by the author to enable an evaluation of the proposed methodology.

Use Cases were used by the industrial partners to verify the demonstrator and validate the CIA methodology in the VIVACE project. These were four use cases considering the cockpit architecture, engine pylon and wing architecture (Rutka et al., 2005). However, the author had no access to these use cases. Therefore, the evaluation of the proposed methodology for this thesis was performed separately from the validation studies in the CIA task. This also ensured that it was an independent review of the author's individual work.

4 Research aim, objectives and questions

During the engineering change process, the impact of an EC needs to be identified and subsequently alternative solutions need to be selected and evaluated. Therefore, the research aims to support the engineering change process by investigating and developing methods to simulate and analyse the propagation of changes in an engineering product, process and/or organisation (Figure I-4). These methods should support throughout the product lifecycle the identification of the possible extent of the EC impact across multiple domains such as the physical product architecture, design parameters, requirements and the organisational break-down. They should also support the decision-maker in selecting feasible solutions by identifying possible sets of items that need to be changed. As a result, a more integrated and shared approach to investigate EC across an organisation should be possible.

The development of a methodology that supports the prediction of the impact of engineering changes.

Figure I-4: Research Aim

To enable a global shared view in a distributed design environment, the first objective (Figure I-5) is the development of a generic approach to elicit knowledge about the logical and physical interdependences between the constituent parts within systems and their related information in multiple domains across the product lifecycle. This can come from existing knowledge repositories or can be captured from system experts. Furthermore, the captured knowledge needs to be maintainable, i.e. it must be possible to review, modify and validate it. The method needs to be scalable which means it needs to be applicable to different product sizes and different levels of detail.

The development of meta-model to capture interdependencies within a complex product.

Figure I-5: Research Objective 1

Subsequently, the second objective (Figure I-6) is to optimally exploit the captured knowledge in order to identify the potential extent of the impact of an EC. Therefore, a method should be developed that can trace the propagation of ECs and which considers the appropriate level of detail, limits redundant information and organises the propagation between different information domains.

The development of an algorithm to trace the propagation of ECs and identify the potential extent of their impact.

Figure I-6: Research Objective 2

The third objective (Figure I-7) is to analyse the identified impact of an EC in order to subsequently identify possible groups or sets of affected items, referred to in this thesis at 'impact sets'. These impact sets should support the decision-maker with the identification feasible solutions for implementing the proposed change.

The development of a method to identify possible impact sets.

Figure I-7: Research Objective 3

A key measure for the success of the undertaken research would be that any developed methodology will be beneficial to the aerospace industry and be applicable in an operational aircraft development environment.

5 Thesis Report structure

The structure of this thesis is as follows. Chapter II reports on an extensive review of the state-of-the-art (SoA) of both engineering change theories and practices. This has been carried out at the beginning and throughout the research project and aimed to provide a better understanding of the causes and effects of ECs and identify limitation of current EC management and analysis methods. The following three chapters discuss the methodology that has been developed. In Chapter III, a meta-model is proposed to capture dependencies which formed the basis for the development of an algorithm to trace ECs. This algorithm is discussed in Chapter IV. A method for analysing the change propagation results in order to identify impact sets is described in Chapter V. The presented methodology is evaluated and discussed in Chapter VI. Chapter VII provides conclusions together with future directions for the research.

6 Summary

This introduction chapter demonstrated the importance of engineering changes to products because these can have many different sources, can occur at any point in the product lifecycle and can have a profound effect on product cost and time to customer. In additional, the consequences of proposed ECs are difficult to predict, particularly for complex products. Current practices rely mainly on human communication, the knowledge and experience of system experts. However, there appears to be a need for a more integrated and shared change impact analysis approach within organisations and across their supply chains to support the decision-making in the EC processes. The research in this thesis builds upon recent academic and industrial research which investigated the use of knowledge models to predict the impact of an EC. The aim is the development of a methodology that can support the development and change processes of complex products, particularly the aircraft development process. The research focuses on 3 aspects of the EC process: capturing of knowledge into connectivity models, the exploration of the connectivity models to identify the possible extend of the impact of an EC and the supporting the discrimination of concept alternatives.

CHAPTER II:

State-of-the-Art of Engineering Change Theory and Practices

This chapter reviews the current state-of-the-art of academic research on engineering changes and their practices in industry. The outcome of this review will provide direction for the development of a methodology that can improve the support for the prediction of the impact of engineering changes.

The chapter is structured as following. First, a general overview is given of research published on engineering changes and definitions that have been used for ECs. In addition, ECs and its relation with product complexity, configuration management and product lifecycle is reviewed. Next, existing categorisations of EC causes are collated. This is followed by a discussion of the consequences of ECs and different methods that have been proposed to manage and control ECs. In addition, an overview is drawn up of qualitative dependency models have been used for various methods. Also a more detailed discussion is included of existing EC impact analysis methods which are particularly relevant to the research in this thesis. Finally, the EC processes used in Airbus and Westland Helicopters are summarised together with discussion of commercial software application that currently supports the investigation of ECs in industry.

1 Engineering change as a research topic

Early research on engineering changes was focussed mainly on improvements of project management techniques and optimisation of design processes. Wright (1997) published an extensive review of this early research into engineering change management. Also, Inness (1994) states in one of the few books published on product changes that "complex changes are best controlled using project management techniques". The focus for supporting the EC process in this book is on information management, integration of design and production processes. Other books on product design also include chapters on management of ECs. For example, in 'Engineering Design for Profit', Leech and Turner (1985) discuss the "Management of engineering design change". Huang et al. (1998; 1999; 2000; 2001) also focussed their research into the management of EC processes and the development of software tools to support EC management. Terwiesch and Loch (1999) outlined a process-based view of engineering change orders (ECO) management which aims to reduce the ECO lead times by identifying the key contributing factors. Additionally, Fricke et al. (2000) at the Technical University of Munich did extensive research in collaboration with industry to identify problems associated with ECs and proposed 5 key strategies to cope with changes. Other research based on industrial case studies of ECs have been undertaken by Coughlan (1992), Pikosz and Malmqvist (1998), Hsu (1999) and Huang and Mak (1999).

In recent years, the focus of the research has shifted from methods to manage the EC process to methods and models that aims to predict the impact of an EC. A general framework (Figure II-1) for EC impact analysis based on an integrated design information model has been proposed by Ma et al (2003). This model combines product data, process data and (organisational) resource data but does not propose any dependency models in detail.

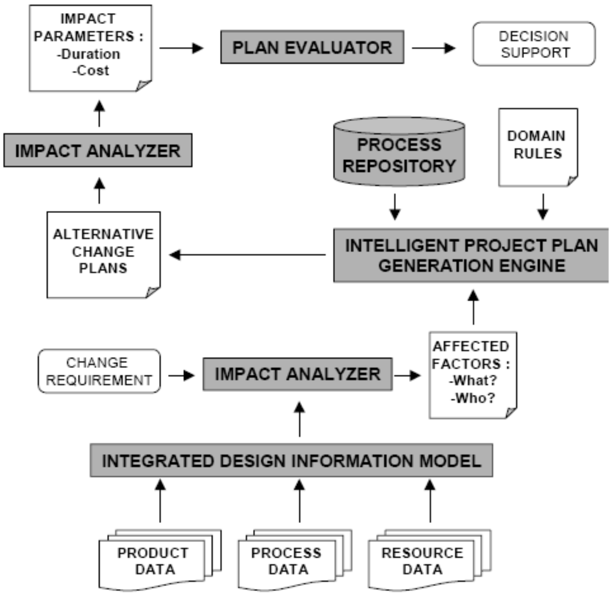


Figure II-1: EC impact analyses framework (Ma et al., 2003)

One approach is to use quantitative models (Sutinen et al., 2002; Kirby & Mavris, 1999) which can automatically identify how much affected design parameters will vary as a consequence of a given change. The main limitations of these methods are that they can only model specific aspects of a product design because they are only applicable where mathematical relations can be established. Furthermore, executing quantitative analysis can be very time-consuming although response surfaces and neural networks have been used to speed up these analyses.

On the other hand, methods have been developed that use qualitative connectivity models often represented with a design structure matrix (DSM) (Steward, 1981) and networks of directed graphs (Diestel, 2005). These connectivity models represent information items related to a product development and the relations or dependencies between these items. The advantages of these methods are that they can handle very diverse types of information and analyses can potentially be performed rapidly.

However, capturing the relations and maintaining the connectivity model need to be updated continuously throughout the product development process.

In 1996, Guenov modelled the knock-on effects of design changes and used digraphs diagrams for representing the connectivities between items. Extensive research by Clarkson et al. (2000; 2001) has been conducted over the past decade in the development of connectivity models to predict the impact of ECs in the product architecture (Clarkson et al., 2001) and optimise the design processes. Other methodologies to predict the impact and propagation of ECs in the product architecture using qualitative connectivity models where developed by Cohen et al. (1998; 2000) and by Rivière et al. (2003). Also previous work at Airbus (Coleman, 2003) was based on qualitative dependency models. Work carried out by Martin and Ishii (2002) resulted in the 'Design for variety' method which include methods to quantify "the amount of redesign effort required".

Qualitative connectivity models have also been used for investigating product complexity. Of particular interest are Axiomatic Design developed by Suh (1990) and the development of connectivity models by Lindemann and Maurer (2006) to improve the understanding of the complexity of products.

Other methods that could potentially support the analysis of ECs include Petri Nets (Collaine et al., 2000), Bayesian Networks (Rivière, 2004). However these methods rely heavily on probabilities which can be very difficult to model. Finally, use of agent technology in computer networks have been discussed in literature (Guenov & Chao, 1996) to support the investigation of ECs. Particularly, the PACT (Cutkosky et al., 1993) and DOME (Senin et al., 2003) approaches demonstrated the potential of this technology. One limitation is that often not all information related to the development of a product is available in a computer network. A second limitation of this approach is that only the directly affected design objects are immediately visible to the agent that initiates a design change. Hence the agent that initiates a change has not immediate view on the complete impact on the systems.

The remainder of state-of-the-art review will focus on the following topics which are of particular interest to the author's research:

- Definitions for ECs that have been used throughout the literature and their relation to product complexity, product lifecycle and configuration management.
- Categorisation of the causes and impacts of ECs together with strategies to manage and control them.
- Qualitative dependency models that have been used to support a range of analyses.
- Qualitative EC impact analysis methods that have been developed which consider in particular the propagation of changes.
- An overview of change management practices in industry and commercial software applications that can support EC impact analyses.

2 Engineering changes in product design

2.1 EC definitions

Engineering change management deals with "the organisation and control of the process of making alterations to products" (Jarratt, 2004). It should not be confused with 'change management' that is common in business and management literature. The latter deals with the implementation of changes in business processes (Kettinger, 1997).

Throughout the literature, authors have been using slightly different terms for modifications or changes to a product. Terms that have been used include:

- Engineering design change (Leech & Turner, 1985)
- Product change (Inness, 1994)
- Design change (Guenov, 1996)
- Product design change (Huang & Mak, 1998)
- Redesign (Ollinger & Stahovich, 2001)
- Engineering change (Rivière et al., 2002a)

Although these terms general refer to the same phenomenon, often different interpretation are been used.

The US Standard 480b (1988) definition of an engineering change, which has been adopted by Rivière (2002a), is "an alteration in the approved configuration of a product related item". An item here is specified as a document or a product component which can be real or virtual depending on the product life cycle stage.

Inness (1994) distinguishes between a product change and an engineering change. He defined the former as "a change to the configuration of an existing product which alters its form, fit or function" while the latter is defined as "a revision to a document or design released by engineering".

Wright (1997) restricts the meaning of an engineering change to "a modification to a component of a product after that product has entered production". This follows a common conception that engineering changes and there associated processes occur after design has been completed and hence the production has been started. While design alterations which occur before the start of the production are seen as design iteration. Huang and Mak (1998) make distinctions similar to Innes (1994) between product design changes and engineering changes. They refer to product design changes as "changes or modifications in forms, fits, materials, dimensions, functions etc of a product or part before the design is released" while they consider engineering changes as changes after a product or part has been released. Hence they also make a distinction between changes before and after part of a product have been completed, but are less restrictive. Terwisch and Loch (1999) use also a similar definition for engineering changes. However, they specifically include changes to software. Also Jarratt (2004) highlights the necessity to include software changes.

In this thesis, a less restrictive view on engineering changes has been used. An EC is considered to be any alteration of an item related to the design of product that needs to be investigated, either formal or informal, at any stage of the product life cycle. These items can be a component of a product, software as well as a requirement, regulation, design parameter, etc. The reason why no distinction is made between changes before or after product release is that they can have the same source and same consequences and hence are treated equally.

2.2 ECs and product complexity

Research on complexity, product complexity in particular, is vast. Therefore, this section gives a brief overview of finding on ECs in relation to product complexity.

According to Earl et al. (2005), product development occurs through interaction of the 4 elements of design (Figure II-2). These elements are the product itself, the design processes, the designer with his/her knowledge and capabilities and the user with its product requirements. Their conjecture is that the change complexities arise from “the relations between these four elements”.

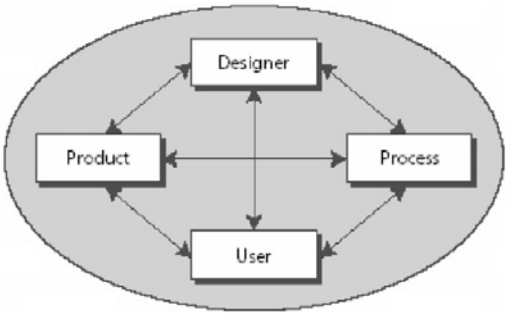


Figure II-2: Elements of design (Earl et al., 2005)

Furthermore, they relate to complexity in other research areas. Wiener (1948) in relation to cybernetics describes complex systems as systems which are “dynamic, changing and evolving over time”, but their behaviour cannot be predicted completely. Simon (1969) instead considers products or systems as complex if they are not fully decomposable into separate independent parts due to the interdependencies in a design. In addition, Axiomatic Design (Suh, 2001) views these interdependencies or connectivity and the uncertainty to achieve a system’s functional requirements as an information complexity.

Also Maurer and Lindemann (2006) have been investigating product complexity. Their understanding is that complexity depends on “the kind and variety of its elements, their number and the inhomogeneity of their distribution", "the kind and the variety of its dependencies between the elements and the system environment, their number and the inhomogeneity of their distribution" and "the number of different conditions and the dynamic behaviour of the system". They report that the key problems resulting from product complexity "may be characterised by attention (because of information overload), perception (concerned to interpretation of available information), memory (not being available in a reasonable way within the given situation) and logical reasoning (failing because of complexity)".

Research by Eckert et al. (2004) concludes that a product design can be considered as complex when no single person has the full understanding of all the design aspects of a product in detail and hence the detailed design knowledge is distributed across the organisation. As a result, it becomes difficult to predict the complete impact of a change.

2.3 ECs and Configuration Management

Configuration Management aims to maintain integrity of the product throughout its lifecycle by ensuring that the used information represents always the current configuration. It encompasses the control of changes by recording and reporting the change processes and the implementation status to ensure product integrity. In his book on product change, Inness (1994) summarises Configuration Management as "the definition and communication of an item (entity) and the control and incorporation of changes to that item throughout its life-cycle".

Rivière et al (2003) report that Configuration Management plays a particular role during the aircraft development process where design and manufacturing occur concurrently by several business entities in different geographic locations. The authors state that an efficient control of ECs is important as most changes to the design of aircraft occur at the development phase and the cost of changes increases over the course of the lifecycle. In addition, the aircraft industry operates in a highly competitive market where the customisation of a product can provide a competitive advantage. Finally, a transparent and efficient change processes can enhance the process for achieving the airworthiness requirements and hence reduce the time to market.

The recent development in the management of ECs has been driven by industry needs to implement Configuration Management and Quality Management procedures and comply with their respective standards (Jarratt, 2004). Standards which are reported (Rivière, 2004) to be specifically relevant to the aerospace industry include ISO 10007 (2003), RG AERO 00023 (2003), MIL-HDBK-61B (2002), ANSI / EIA 649 (2004). These standards provide some recommendations and guidelines for the implementation of configuration management best practices. They specify some generic change processes and highlight the need to identify and control the impact of change requests although they do not provide any models or methods of how to do this.

2.4 ECs during product lifecycle

After the requirements are defined, a product lifecycle starts with the design process which is composed of a feasibility phase, a conceptual design phase and a detailed design phase, and subsequently, the product is manufactured and goes finally into service. A major factor in determining the cost of a change is the point in the lifecycle the change occurs. The cost to implement the change increases as the product design process progresses and the product design becomes more defined and more interfaces appear between constituent parts and systems of the product. Reference (Fricke et al., 2000) has been made to the “Rule of Ten” to qualify this increase in cost. It postulates that changes in a later phase are ten times more expensive than a change in a previous phase.

At the same time, the potential cost reduction to the final product that changes can offer decreases as the design process progresses. As a result, the number of ECs increases rapidly during the initial phases of the product design process when the potential cost savings are considerable and the implementation cost the ECs is limited. However, the number of ECs start to decrease as the implementation cost rise and the potential cost saving become less (Rivière, 2004). This evolution of the implementation cost of ECs, their potential cost saving and their number of occurrences throughout the product lifecycle is shown in Figure II-3.

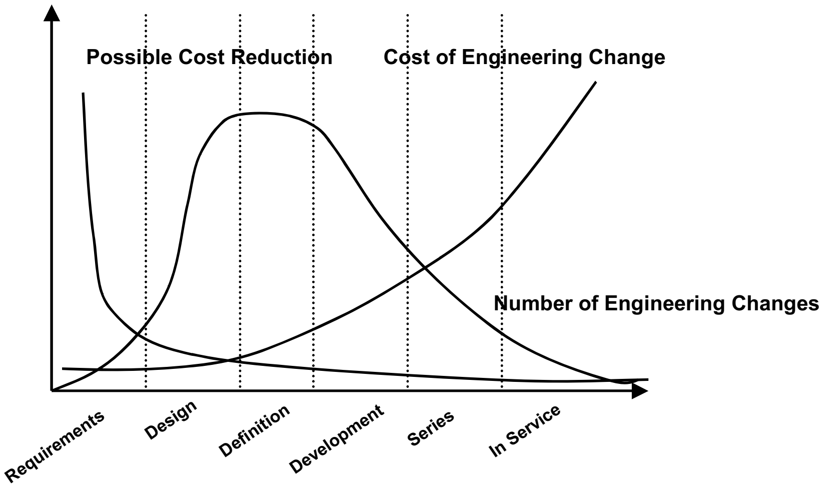


Figure II-3: ECs and cost throughout lifecycle (Rivière, 2004)

In order to reduce the number of possible ECs as the design process continues and hence to control the development cost, part and system designs are ‘frozen’. This is referred to as the status of the part or system. Furthermore, design freeze can also help to structure and schedule the design process, i.e. ‘down-stream’ design aspects can be finalised when key design variables are frozen, or the manufacturing process can start when product parts are frozen.

Even though design freeze is a common practice in industry, little research has been carried out in this subject until recently. However, Eger et al. published in 2005 interesting findings on design freeze in product development. In this research, a design freeze is defined as “a binding decision that defines the whole product, its parts or parameters and allows the continuation of the design based on that decision”. This definition also refers to the different levels of detail to which design freeze can be applied, namely product level, part level and parameter level. Additionally, the research categorises the different reasons for design freeze and categorises different types of design freeze that are being used in industry. It was also noted that it can be in some cases beneficial to ‘unfreeze’ compared to alternative solution or not implementing the proposed ECs.

It is concluded that the product lifecycle is an important factor in the investigation of ECs. In addition, design freeze is a key practice for controlling the impact of ECs. Therefore, the status of product items needs to be taking into account during impact analyses of ECs and the identification of their feasible solutions.

3 Causes, consequences and management of ECs

3.1 Causes

Many publications have been produced in recent years that report research into reasons for engineering changes. This resulted in several different categorisations of the causes of ECs. An overview of the major categorisations is given in Table II-1 and will be discussed later in this section.

In addition, Inness (1994) identifies eight contributors (Figure II-4) to a product design, all of which could be a source of changes during the product development. However, the author argues that the involvement of these contributors will minimise the number of changes after the product has been released for manufacturing.

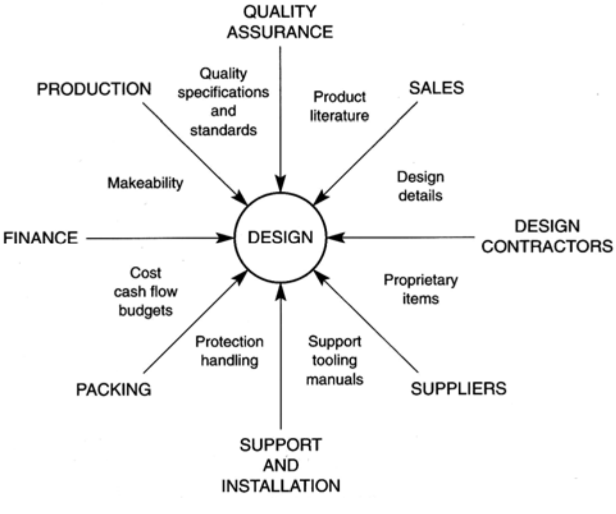


Figure II-4: Contributors to a design (Innes, 1994)

The most fundamental categorisation of causes of ECs has been proposed by Eckert et al. (2004). This categorisation distinguishes between initiated changes and emergent changes. However, for both initiated and emergent changes further subdivisions have been made (Table II-1). Also Jarratt (2004) adapted in his PhD thesis the distinction between initiating changes and emerging changes as reasons for ECs, but uses different subdivisions.

Initiated Changes:

This type of change refers to changes that arise in order to create a new product based on an existing product or to modify an existing product. Reasons for modifying products include addressing customers' needs by making products faster, cheaper or increasing their functionality. Also changes can be initiated to bring products in line with new regulations or industry standards. Modifying existing products can further enable a rapid introduction of new products necessary in the current highly competitive markets (Inness, 1994).

Fricke and Schulz (2005) report that another important source of design changes is the need for product variety. They identify three factors that drive product development: the rapidly emerging of new markets, the fast evolution of technology and diversity of systems which need to be integrated in a product. Their proposed approach ('Design for Changeability') to deal with product variety and initiating changes is discussed in section 3.3.

In addition, designing new products by modifying existing products is favoured particularly for products where the safety and reliability is paramount, such as aircraft (Eckert et al., 2006). In order to minimise the risk to customers and to minimise the design effort of the new product, incremental design by reusing tested and validated parts or sub-systems can be reduce the cost and risk.

Emergent Changes:

These changes address weaknesses or deficiencies that arise during the product design process, manufacturing process or even when the product is in service. These changes can result from mistakes or changes to specifications that have happened in the product design. It would be unrealistic to never expect any correction due to deficiencies of previous design activities, particularly in the design of complex product where nobody has a complete understanding of all the design aspects. Eckert et al. (2004) point out that the changes can arise at any level of product integration. Additionally, the cost of the changes increases during the product design process because the process becomes more time critical and the level of integration increases.

The categorisation of the reasons for engineering changes proposed by Eckert et al. (2004) has been represented in terms of their impacts and their occurrence in the product lifecycle in Figure II-5. The lifecycle is represented by the horizontal axis and spans from the start of the investigation of a new product design ('call for tender') until the product is in use. This lifecycle is divided in to three sections. The first section ends when the contact is signed and product requirements are fixed. The second section is the actual design and manufacture phase of the product which includes testing of the product. The final lifecycle section starts from the delivery of the product and covers the period in which the product is in service. Emergent changes are shown above the horizontal axis while the initiated changes are below the axis. The vertical axis represents a measure for the level of impact of a change in terms of cost and rework. The further away from the horizontal axis in either direction, the larger the impact is of the change.

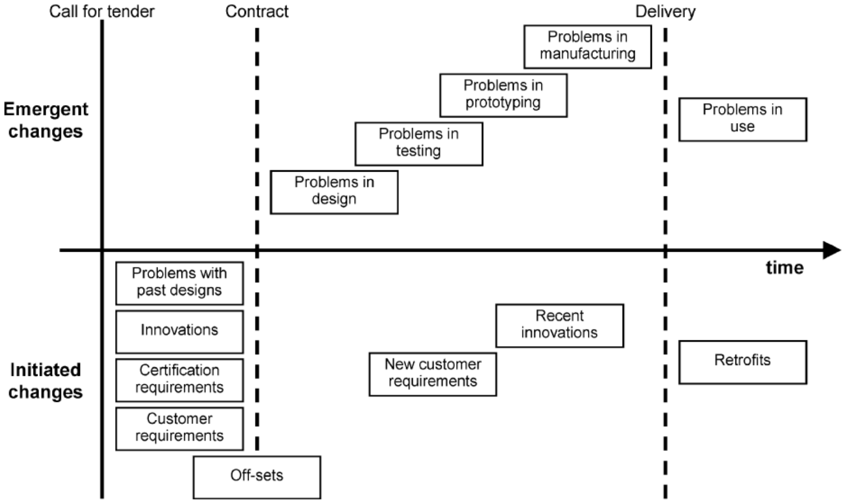


Figure II-5: Sources of change throughout the product lifecycle (Eckert et al, 2004)

Coughlan (1992)	**Hsu (1999)**	**Fricke et al. (2000)**	**Rivière et al. (2002a)**	**Rivière et al. (2002b)**	**Eckert et al. (2004)**
• Cost reduction • Material substitution • Design correction • Design improvement • Documentation change • New feature • Yield improvement	• Requirements definition issues • Changes in needs • Need to fix deficiencies • Government-prime contractor interactions • Program-to-program interactions • Changes in technology • Documentation changes	• Needs and requirements • Feedbacks and complaints • Complexity • Degree of innovation • Change impacts • Communication and coordination • Time • Decision discipline	• Changes in needs and requirements • Programs or projects interactions • Need to fix deficiencies • Technological changes • Legislation changes • Changes in project scheduling	• Changes in needs and requirements • Programs, projects and organisations interactions • Fix deficiencies when the aircraft is still in development or production • Fix deficiencies once the aircraft is in service • Discrepancies between specifications and results • Continuous improvement of products and processes • Changes in contracts • Changes in the documentation • Other Engineering changes	• Initiated changes - Customer requirements - Certification requirements - Innovations - Problems with past designs - New customer requirements - Recent innovations - Retrofits • Emergent changes - Problems in design - Problems in testing - Problems in prototyping - Problems in manufacturing - Problems in use

Table II-1: Overview of categories of EC causes

The other major categorisations that have been proposed (Table II-1) are discussed briefly below.

In 1992, Coughlan made an initial categorisation of reasons for ECs from a manufacturing perspective. Fricke published a number of papers on engineering changes (Fricke et al., 1997; Fricke et al., 2000) and argued that ECs can sometimes be avoided but often not. Moreover, ECs can sometimes be seen as opportunities to improve the quality of the product and are therefore necessary. In the latter publication, Fricke identifies eight categories of causes based on 13 case studies in the German industry.

Hsu (1999) investigated the causes and impacts of ‘Class I’ engineering changes in the context of US defence aerospace product development where the users, acquisition community and contractors are closely involved in the product developments. ‘Class I’ ECs refer to changes that “fundamentally modify the form, fit, and/or function of a product”. Hsu categorises ECs for three defence aircraft acquisition program case studies according to seven primary causes. These primary causes are based on the categorisations by Coughlan (1992) and Fricke et al. (2000) together with a categorisation framework by the US Defence Contract Management Command. The subsequent analysis of the results identified that there were four dominant causes for the three case studies, namely requirements definition issues, changes in needs, changes in technology and the need to fix deficiencies. Hsu’s investigation on the impact of ECs is outlined in section 3.2.

Research by Rivière et al. (2002a; 2002b) extends the categorisation used by Hsu on the causes of ECs from a business perspective. Initially six categories where proposed based on observations in the automotive and aeronautics industry (Rivière et al., 2002a). As Hsu, Rivière recognises that changes to a product design in one project can lead to changes to product design in another project. Product design of earlier projects could be affected as well as future projects in case the change becomes a standard practice. In addition, ECs resulting from changes to project scheduling or planning have also been included as separate category. These changes can occur due to changing customer's demands and due to organisational issues, such as delays. If these new schedules cannot be met with the existing product design, EC have to be introduced.

In a subsequent publication (Rivière et al., 2002b) proposed an extended categorisation based on an investigation of ECs in the aeronautic industry. In this categorisation, a distinction is made between the need to fix deficiencies when an aircraft is in development or production and when an aircraft is in service. In addition, separate categories are specified for changes in contracts and documentation. A final category of 'Other engineering changes' has been included which refers to changes as result of propagation. The latter is discussion in section 3.2. Also Terwiesch and Loch (1999) refer to propagation of changes ('snowballing') as one of the key contributors to long EC (order) lead times. In addition, the latter authors also refer to a complex EC order approval process, capacity and congestion, setups and batching, and organisational issues as contributors to long EC order lead times.

3.2 Consequences

Impact on the cost of the product and impact on the product development schedule are often referred to as the main consequences of ECs (Fricke et al., 2000). Hsu (1999) also considers the performance of products ECs and the organisation and its extended network of suppliers and partners in his investigation into the impacts of ECs. In addition, ECs can affect the organisation and its extended network of suppliers and partners. Furthermore, the other product development project can be affected as already indicated in the section on causes of ECs.

The consequences of ECs, however, can be negative or positive depending on the cause of the change (Fricke et al., 2000; Rivière et al., 2002a). In particular, initiated changes often aim to reduce the cost or improve product performance while emerging changes usually leads to increasing in the costs or delays in the development schedule.

In addition to the four afore mentioned categories of consequences, Rivière et al. (2002a) includes also impacts on the product lifecycle phases and "additional changes resulting of the same issue". The latter category refers to the phenomenon of 'change propagation'. Even though Hsu (1999) observed for the three case studies he investigated that "ECs seldom led to additional, unanticipated engineering changes", other publications (Eckert et al., 2001; Jarratt et al., 2002b; Earl et al., 2005) support the view by Rivière et al. (2002a) on the importance of this phenomenon and investigated it in more detail.

Research by Eckert et al. (2001) classified the behaviour of the EC propagation into 'ending' and 'unending' change processes. For ending change propagation, the distinction is made between ripple and blossom propagation behaviour. In case of the ripple propagation, the initial change causes only small volumes of new changes and decrease quickly or the initiating change occurs regularly and hence the product has been designed to absorb these changes readily. For the blossom propagation, at first, there is a large increase in change but it is brought to a satisfactory conclusion with in the time limit. In this case, one or more major changes result in a considerable amount of redesign effort, but consequences are well understood and can be accommodated. Unending change propagation occurs when a major change initiates more major changes that cannot be brought under control within the given time. This type of propagation behaviour causes the biggest concern and occurs when all the change impacts cannot be predicted and lead to continuous growing number of affected items. Consequently, "the change process can get completely out of control, requiring significant design resources" (Eckert et al., 2004). This propagation behaviour is also referred to as avalanche propagation or the snow ball effect. These three types of change propagation behaviour are shown in Figure II-6.

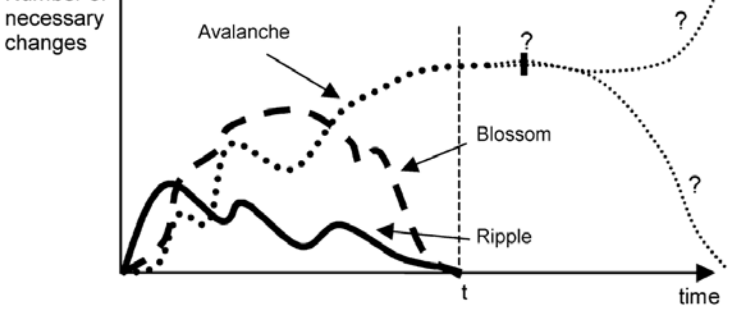


Figure II-6: Change propagation behaviour (Eckert et al., 2004)

Eckert et al. (2001) also included in their research a categorisation of product parts according to their response to changes. The following three categories were proposed:

- **Absorbers:** The number of parts that can affect this part is larger than the number of parts it can be affected by. The term 'total absorber' has been used to indicate parts that will not affect any other parts.
- **Carriers:** These parts can affect the same number of parts as it can be affect by.
- **Multipliers:** These parts can affect more parts than they can be affected by. It is noted that an 'absorber' can become a 'multiplier' once the tolerances of the part are exceeded.

As a result, ECs can impact the product cost and performance, development schedule and extended organisation. However, a major factor that determines that extent of these impacts is the possible propagation of the initial change to other parts. It is concluded that considering the effects of change propagation is essential when analysing the potential impact of ECs.

3.3 Strategies to manage and control ECs

A lot of research on engineering changes has focussed on the managerial aspects in order to minimise their negative consequences and maximise their benefits. Inness (1994) argues that the best way to control complex changes is by using project management techniques. He refers to information management, integration of design and production processes, product change technologies and organisation for product change as key areas for the improvement of product change.

Terwiesch and Loch (1999) proposed 4 improvement strategies to deal with engineering change orders. First, "avoid unnecessary changes" by spending more time on the initial design the parts. Second, "reduce the negative impacts of an engineering change order" by considering the magnitude and the timing of the change and assess the number of parts and tools impacted. Third, "detect engineering change orders early" is related to the product life cycle issues discussed in section 2.4 which included that the cost of implementing ECs is lower early in the design process. Finally, "speed up the engineering change order process" by reducing long response times.

Hsu (1999) concluded that ECs can be reduced by recognising product development schedule as priority, using mature technologies which help to reduce scheduling risk and the proper definition of requirements. He highlighted in particular that the prime contractor's use of Integrated Product Teams, for development-related activities, helped to reduce the proportion of engineering changes that were due primarily to requirements definitions.

Fricke (2000) argues that to stay competitive, it is necessary to have ECs. However, to reduce their costs and delays in schedules, five strategies are proposed which relate to the improvement strategies by Terwiesch and Loch (1999):

- **Prevention** by a more in-depth analysis before design (keep design space open) and the reduction of unnecessary specifications and requirements will lead to a reduction of changes
- **Front-Loading** aims to detect emerging changes earlier. The main rationale behind it is the Rule of Ten (see above).
- **Effectiveness** assesses whether changes are necessary and beneficial
- **Efficiency** aims to optimise the resource such as time and cost when implementing changes. Communication and information tools can help.
- **Learning** to optimise the development process and the product by understand causes and effects (of previous changes)

Designing a product with a more flexible system architecture that can adsorb change better, can also improve the efficiency in dealing with ECs. This has been referred to as 'Design for Changeability' (Frick et al., 1997; Schulz et al., 2000; Fricke & Schultz, 2005). There are four aspects to changeability. First, products with a high degree of 'flexibility' and 'agility' towards ECs will have the ability to be changed with minimal effort and with few negative side effects. In addition, products with a high degree of 'robustness' and 'adaptability' can function under varying operational conditions without the need to be changed or can change themselves to fulfil their newly required functions.

Besides the Collaborative Management of ECs approach discussed in section 5.3, Rivière et al. (2002a) also refers two design strategies to minimise the impact of ECs due to program interactions. First, modular product design makes use of self-contained subsystems with clear interfaces between them to limit the propagation of changes. This concept has been investigated in more detail by Fricke & Schulz (2005). Additionally, using platform-based design to create product families can make it more efficient to investigate and implement ECs on the platform than on the individual product family variants.

The ‘Design for variety’ (Martin & Ishii, 2002) is a method which specifically aims to support during the conceptual design phase the development of platform-based product architectures through standardisation and modularisation of its components and subsystems. Comparable to ‘Design for Changeability’, this method tries to reduce the time-to-market of future generations of a product by designing a product with an architecture that requires less effort to be modified or upgraded. Therefore, two indexes have been defined. First, a ‘generational variety index’ provides a measure for the amount of redesign effort for each component or subsystem based on anticipated future changes to customer requirements. Second, a ‘coupling index’ composed of two values for each component gives a measure of the amount of coupling with the other components in the product model. This index is related to the behaviour of components as absorbers or multipliers for the propagation of ECs as discussed in section 3.2.

Eckert et al. (2004) identify two approaches to changes in industry. On the one hand, a forward redesign process can be used, which follows well-established procedures. These procedures are comprised of an initial study of the change followed by identification of different solutions of which one is selected and subsequently implemented and evaluated. On the other hand, backwards redesign processes are used to response to problems. These do not included include a comprehensive assessment of the impact of the problem but jump straight to a possible solution. Subsequently, this can lead to additional problems which are solved in same fashion. This approach to changes reported to be used mostly to fix small routine problem or when a quick solution is needed.

Finally, Huang et al. (1998; 1999; 2000; 2001) and Pikosz and Malmqvist (1999) have focussed there research efforts on the procedures and software implementations that can improve the management process of the ECs.

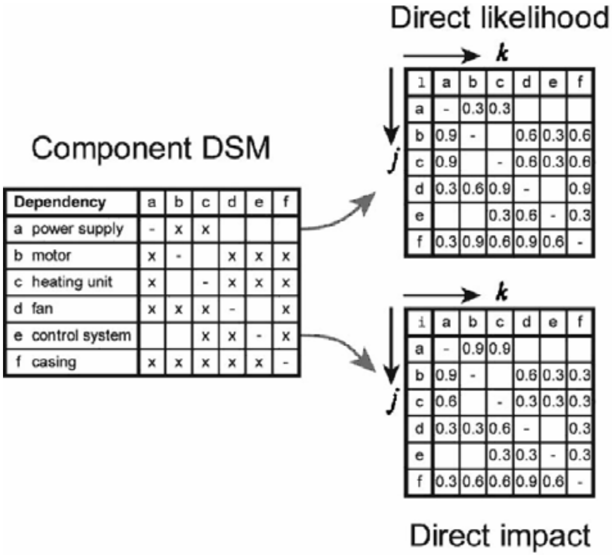
4 Qualitative modelling methods

Since qualitative dependency models are a promising concept to model various types of information and can be applicable at different phases in the product lifecycle, qualitative dependency models that have been developed in the past are reviewed in detail.

Early dependency models for activity scheduling used binary dependencies, i.e. there is a dependency or not between two items, and were represented by digraphs (Moder & Phillips, 1964). More recent binary dependency models are based on matrices. Steward (1981) developed the Design Structure Matrices (DSMs) which can used to model relations between diverse types of information. A DSM is, in essence, a square matrix where the columns and the rows represent the same elements or items. Marks, e.g. 'X' or '1', are places in the matrix cells to indicate that there exists a relation between the item in the column and the item in the row. Henceforth, dependencies in a DSM representation will always be directed from the item in the columns to the item in the row. The major diagonal in DSM representation is not used as it would indicate a relation between the same two items. There is usually a distinction made between product-based DSMs or static DSMs and process-based DSMs or dynamic DSMs (DSM web, 2004). The former models components of a product while the latter models design tasks or activities and hence different analysis methods are often applicable. Besides DSMs to model relations between items that belong the same information domain, also Domain Mapping Matrices (DMMs) (Danilovic & Browning, 2004) have been to model relations between items in two different domains. These DMMs are rectangular matrices because the items in the columns differ from the items in the rows. In other research area, these matrices have been referred to as Incidence Matrices (Kusiak & Wang, 1993). A dependency model based on DSMs and DMMs have been used by Coleman (2003) to elicit features, characteristics and disciplines in the aircraft design process.

The dependency model that is used by the Change Prediction Method (Clarkson et al., 2001), which will be discussed in more detail in section 5.2, associates with each dependency two values between 0 and 1. One of the values is the likelihood of the dependency which is defined as “the average probability that a change in the design of one sub-system will lead to a design change in another by propagation across their common interface”. The other value represents the magnitude of the impact to affected item. This impact value is defined as “the average proportion of the design work that will need to be redone if the change propagates”. These values are derived from previous ECs and experience of designers.

This dependency model in the CPM is often represented with two DSMs, one with the likelihood values and the other with the impact values (Figure II-7).



Dependency	a	b	c	d	e	f
a power supply	-	x	x			
b motor	x	-		x	x	x
c heating unit	x		-	x	x	x
d fan	x	x	x	-		x
e control system			x	x	-	x
f casing	x	x	x	x	x	-

l	a	b	c	d	e	f
a	-	0.3	0.3			
b	0.9	-		0.6	0.3	0.6
c	0.9		-	0.6	0.3	0.6
d	0.3	0.6	0.9	-		0.9
e			0.3	0.6	-	0.3
f	0.3	0.9	0.6	0.9	0.6	-

i	a	b	c	d	e	f
a	-	0.9	0.9			
b	0.9	-		0.6	0.3	0.3
c	0.6		-	0.3	0.3	0.3
d	0.3	0.3	0.6	-		0.3
e			0.3	0.3	-	0.3
f	0.3	0.6	0.6	0.9	0.6	-

Figure II-7: Product model of the Change Prediction Method (Clarkson et al., 2001)

The ‘linkage model’ published by Jarratt et al. (2004) extends the Change Prediction method with the use of different types of dependencies. The case study of a diesel engine included mechanical, electrical and thermal dependencies. Also the Collaborative Management of Engineering Changes (Rivière et al., 2003) uses a qualitative product model with six different types of dependencies. In addition, the components in the product model take into account six different types of information. This approach will be described in more detail in section 5.3.

Also Pimmler and Eppinger (1994) use different types of dependencies (interactions) in their product model of an automotive climate control system. The included types of dependencies are ‘spatial’, ‘energy’, ‘information’ and ‘material’. Each type of association is also scored on a scale from ‘-2’ to ‘+2’, where ‘+2’ means that the relation is necessary and ‘-2’ the relation must be prevented. ‘0’ means there is no dependency.

The ‘Signposting’ method which has been developed by Clarkson and Hamilton (2000), uses a dependency model for design analysis tasks. The input and output parameters of these analyses form the dependencies between the tasks. Each dependency has a value associated which corresponds to the level of confidence of the linking parameter. The ‘Signposting’ method is used to generate an optimal workflow for the design process.

Also Eckert et al. (2004) discusses the use of linking parameter to define the dependencies between product components. Three different types of linking parameters are distinguished:

- **Direct parameters:** they define a product (component) e.g.: geometry
- **Functional parameters:** they arises from the interaction of direct parameters e.g. balance, stress and loads
- **Behavioural parameters:** these are derived from functions and describe the properties of the entire product. I.e. performance parameters

Parashar and Bloebaum (2005) use a comprehensive dependency model for their decision support tool for Multidisciplinary design optimisation. This dependency model includes three domains in the product development, namely components, analyses and tasks. For the component domain, an advanced DSM representation is proposed where each component is broken down in its design variables (Figure II-8). However, different to the approach with linking parameters proposed by Eckert et al. (2004), dependencies are defined from a design variable of an initiating component to an affected component, but the design variable is not associated with the affected component.

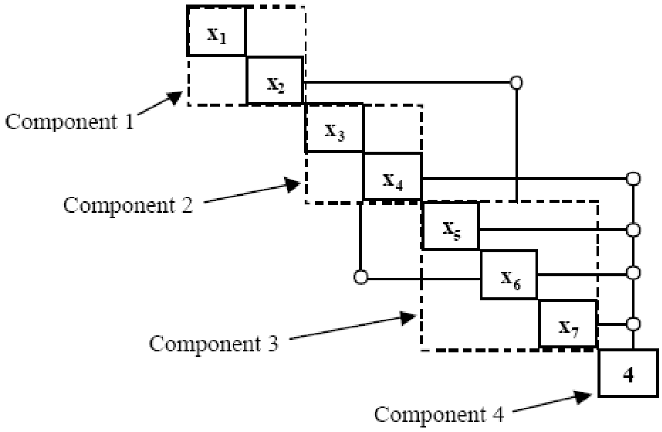


Figure II-8: Component DSM used by Parashar & Bloebaum (2005)

Furthermore, the dependency models for the analysis and task domains are similar to the Signposting dependency model. This means that analyses are linked through their common input and output design variables, while tasks are linked through the design information that is exchanged. Each task has also a cost and time associated with it. Moreover, inter-domain dependencies exist because components can be associated with analyses and task while tasks can be associated with multiple analyses.

The Change Favourable Representation (Cohen & Fulton, 1998; Cohen et al., 2000) also uses a comprehensive dependency model. Here, the dependencies are defined between attributes of the product components and each dependency as an associated linkage value. This method is described in more detail in section 5.5.

The RedesignIT (Ollinger & Stahovich, 2001) method uses a model with dependencies between design parameters. This method will also be discussed in more detail in 5.3. Other dependencies models based on parameters are used by Rouibah and Caskey (2003) which take into account the maturity level (similar to level of confidence in the Signposting method) and parameter status ('in change' or 'released').

5 Qualitative EC impact analysis methods

5.1 Introduction

This section describes existing impact analysis methods for ECs based on qualitative knowledge models which in particular take into account the propagation of changes. The presented methods have been selected because they are seen as most relevant to the research scope of this thesis and can aid with the identification of requirements for a future impact analysis method.

5.2 Change Prediction Method

The Change Prediction Method (CPM) (Simon, 2000; Clarkson et al., 2001) aims to support the decision-maker during the investigation of ECs. Therefore, the method computes for every product component the risk of impact on every other component, where risk is considered as the product of the likelihood with the impact. As described in section 4, the dependencies in the product model (Figure II-7) has each an associated likelihood factor and impact factor.

The likelihood and impact factor that are defined in the dependency model are considered to be the direct likelihood and impact. However, the CPM takes into account also indirect impacts, i.e. different possible propagation paths from one item to another item. Therefore the combined likelihood, combined risk and combined impact between all components are computed. Figure II-9 shows the principle for the computation of the combined likelihood which is based on probability theory.

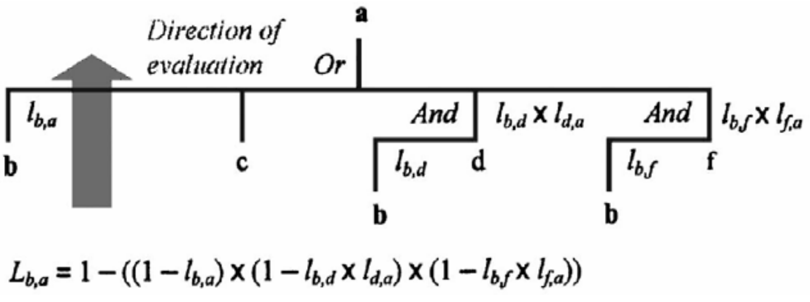


Figure II-9: Computation of combined likelihood (Clarkson et al., 2001)

Separate from the combined likelihood is the combined risk computed. This computation is also based on the combination of propagation paths from one component to another. The risk of each propagation path is computed as the probabilities of the complete propagation path multiplied by the impact value of the penultimate component in the propagation to the final component. The mathematical basis for this approach is not given, only reference is made to "a number of assumptions are involved". Finally, the combined impact is calculated as the combined risk for each component couple divided by their combined likelihood. The results are usually visualised in a reordered risk matrix from the complete product and a logarithmic risk plot of a specific component.

In practice, it is recommended that the product models have not more than 50 components and the propagation paths of no more than 3 – 4 steps are considered by the algorithms.

However, in recent developments of the CPM (Jarratt et al., 2002a), the above described algorithm to compute the combined values have been replace by a Monte Carlo simulation (MCS). This simulation performs a high number of propagations and the continuation of each of the propagation paths is controlled by random numbers. In addition, both the direct impact value and the likelihood value have an uncertainty value associated. This uncertainty value reflects the level of agreement between the experts on the likelihood and impact values. Consequently, the MCS used likelihood and impact values as the nominal value for normal distribution where the standard deviation is controlled by the associated uncertainty value. Comparison between results of original algorithms and the MCS showed the latter is computation efficient for comparable levels of accuracy.

As already described in section 4, in further publications (Jarratt, 2004; Jarratt et al., 2004), the CPM was extended with the inclusion of different types of dependencies. Additionally, the CPM was combined with the Signposting method (section 4) to form a change process planning tool (Eckert et al., 2003). This tool uses the CPM to assess the risk of change propagation for the implementation a design change. Subsequently, the resulting tasks are identified together with relevant generic tasks. The Signposting method then identifies possible implementation schedule (task map) for these tasks.

5.3 Collaborative Management of Engineering Changes

The Collaborative Management of Engineering Changes (CM-EC) (Rivière et al., 2003; Rivière, 2004) is a collection of methods and models which aims to support the management of EC from a business perspective in the aeronautics industry, particularly at the design and definition phases. A prototype software has been developed that is based on four main concepts, namely change process libraries, a change impact analysis method, a solutions assessment method and collaborative workspace.

The product model that is used contains additional information related to ECs to complement the existing information in current Product Data Management (PDM) systems. Hence this model includes information on:

- **Actors involved in the process:** to identify experts and configuration managers relevant to the EC
- **Items lifecycle:** to take into account the maturity of the design and their status (frozen or not)
- **Activities related to a particular milestone:** to identify design activities that can be affected by a change
- **Items requirements:** to identify (frozen) requirement that can be impacted
- **Items behaviours to ECs:** to identify components that cannot be changed for technical or strategic reasons ('blocks')
- **The EC history of an item:** to understand the current state of the design and support the investigation of new ECs

To furthermore support the investigation of the propagation of an EC, also four different types of dependencies are used in the product model to extend relational information that is already in current PDM systems. These types of dependencies are functional, organisational, dimensioning and positioning dependencies.

Consequently, an algorithm was developed to trace the propagation of changes for a single initiating EC taking into account the different types of dependencies in the qualitative dependency model. The results are presented with a propagation tree. An example of change impact analysis result is depicted in Figure II-10.

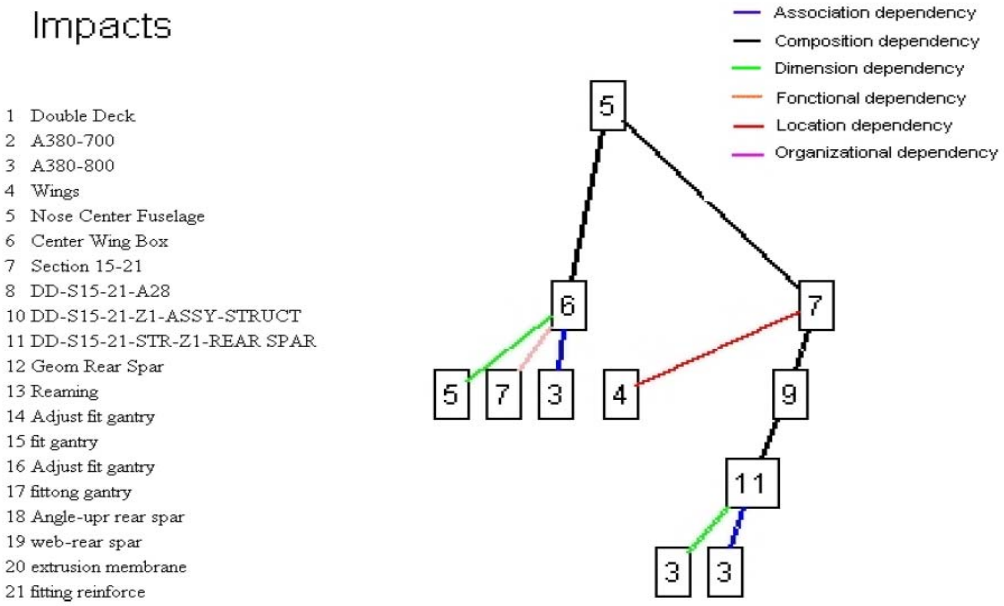


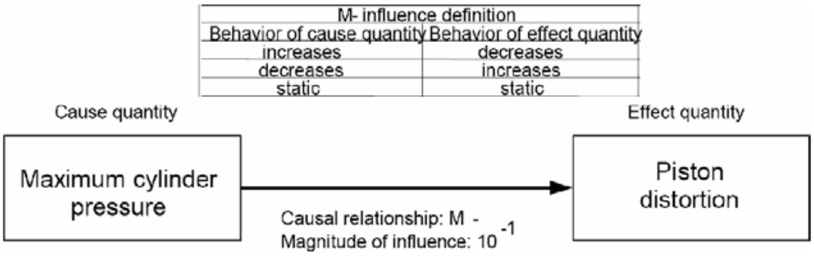
Figure II-10: Example of EC impact analysis result of CM-EC (Rivière, 2004)

Furthermore, there are also 3 different matrices to process ECs more efficiently. First, there is a ‘notification matrix’ which relates different component and systems to their relevant configuration managers. Second, a ‘matrix of needs’ maps the different processes to the relevant experts and specialists. Finally, a ‘matrix of available resource’ links these experts to available ‘actors’ (designers / analyst).

Regarding the assessment and decision-making support concept, this is based on three selected parameters, namely product performances, aircraft operations and implementation cost. Each of the design solution identified by the expert is given a rating from 1 to 5 (5 is best influence) and plotted on a radar diagram. This representation is then used to support the decision-making.

5.4 RedesignIT

RedesignIT (Ollinger & Stahovich, 2001) is based on the semi-quantitative representation of the physical properties (design and behavioural parameters) of a system. This semi-quantitative representation includes the orders of magnitude and positive or negative influence. The order of magnitude can be ‘Low’, ‘Zero’ or ‘High’, i.e. that ratio between the variation of initiating parameter and the variation of impacted parameter is in the order of magnitude of 10^{-1}, 10^{0} and 10^{1} respectively. In addition, four different types of constraints can be specified. These constraints specify if a particular parameter can have only one value (fixed), should be as high as possible (maximise), should be as low as possible (minimise) or can only be within an specific interval (range). Finally, a ‘causal influence’ is associated with the relations between the parameters. These can either be ‘M+’, ‘M– ‘, ‘upper limit’ and ‘lower limit’. Here, ‘M+’ means that an increase in the value of the initiating parameter will lead to an increase of the affected parameter and the same for a decrease, while ‘M–’ means the opposite effect (Figure II-11). The ‘upper limit’ and ‘lower limit’ influences are uses in situations where one parameter imposes an upper or lower limit on the value to affected parameter.



M- influence definition	
Behavior of cause quantity	Behavior of effect quantity
increases	decreases
decreases	increases
static	static

Figure II-11: Dependency definition in RedesignIT (Ollinger & Stahovich, 2001)

To investigate a change of a parameter, the algorithm will identify all possible direct and indirect impacted parameter and whether these impacts are beneficial or adverse. Subsequently, a search will be performed for alternative sets of exogenous quantities (i.e. quantities that the designer can influence directly) that will produce the requested output while minimizing negative consequences. As a result, several possible design plans will be produced. For each produced design plan, also the cost and benefit are calculated. The difference of both is the ‘change value’. The design plan with the highest change value is the considered the best.

5.5 Change Favorable Representation

The Change FAvorable Representation (C-FAR) method (Cohen & Fulton, 1998; Cohen et al., 2000) uses an advanced product model to investigate change propagation. This product model is built with EXPRESS and STEP, which are information modelling languages.

In this product model, relations between entities (components) with associated attributes (e.g. radius, cost, weight) are described. The interactions between attributes of two components are defined in a C-FAR matrix. As a result, each dependency in the model has an associated matrix. Also C-FAR matrices exist for the interactions between the attributes of the same entity. Each element in the C-FAR matrix indicates a linkage value between one attribute of each entities.

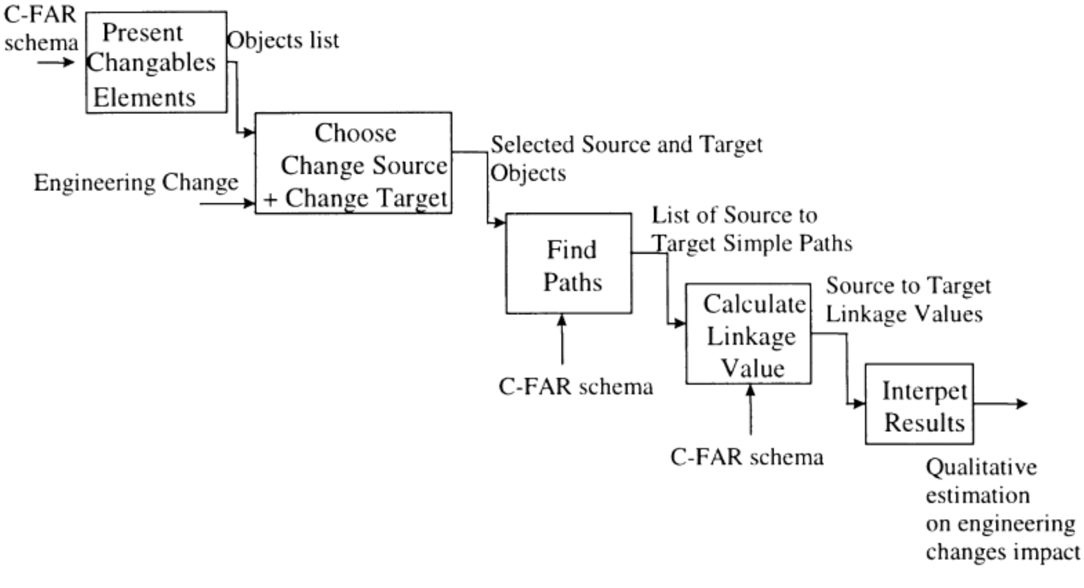


Figure II-12: Process of C-FAR method (Cohen et al., 2000)

The C-FAR method is consequently used to calculate the combined linkage value between two selected attributes in the product model. Therefore, a search is performed to identify the propagation paths between the two attributes. Subsequently, for each of the propagation paths, the (combined) linkage values are calculated, considered the propagation cycles (loops). Finally, a linkage interval is obtained by summing the linkage values of all the propagation paths. The upper bound for the total linkage value interval is a result of the summation, and lower bound of the interval is set to maximum value among the linkage values from the relevant simple paths. As result, the user obtains a value between 0 and 0.9 which indicates the strength of the influence from the first to the second selected attribute.

It is reported the calculation of these final linkage is very computationally complex, which make it difficult to apply to larger models. Case studies of the C-FAR method have included a car bumper and an injection moulding (Cohen et al., 2000).

5.6 Evaluation of qualitative EC impact analysis methods

The Change Prediction Method is a promising method as a result of large research effort in collaboration with industry. However, the interpretation of the results by the decision-maker, in particular the risk percentages, could be difficult and does not provide any immediate explanation of unexpected results. Moreover, due to the computational complexity, the evaluation of many alternative product structures may be hampered and limits the scalability of the method (not more than 50 items).

The CM-EC approach includes a generic EC impact analysis method. However, there is still scope to extend the used dependency model and the visualisation of the propagation paths.

The C-FAR method uses a comprehensive product dependency model but suffers from the same limitation as the CPM. The analysis is computationally complex and the results, a linkage value between two attributes, can be difficult to interpret.

In contrast, the RedesignIT method relies on semi-qualitative dependency model of the physical properties of the product and requires good understanding of their interactions.

As a result, this method can provide more practical solutions to a decision-maker, but on the other hand, the application and scalability is limited.

It is concluded that current EC impact analysis methods have a limited ability for tracing the propagation of ECs and supporting the decision-maker with the identification of feasible solutions. Consequently, there is scope for new EC impact analysis methods which are more scalable and can be used across a wider range of the product lifecycle.

6 Industry practice

6.1 Change management

Current practices for dealing with ECs often use formal configuration management procedures (section 2.3) and rely heavily on human communication, the knowledge and experience of individuals in a specific system area, as well as common sense. The change processes of two major companies in the aeronautics industry are summarised.

In Airbus, a formal and documented change management process (Rivière, 2004; Rutka, 2004) is used throughout the lifecycle of an aircraft, starting from the feasibility phase and into service. However, the change process before the start of manufacturing (milestone 7) is different from the change process after. The first change process until the end of the definition phase takes a more lightweight form and is known as the ‘Change Note’. The process is aimed at changes to the aircraft baseline documents (top level requirements, standard specifications, etc.). Once the manufacturing has started, a more formal change process is followed, known as the ‘Full Change Process’ which also assesses the impact external to the company, e.g. suppliers, sub-contractors and airline customers. For both types of change processes, there are always four stages in a change process, namely, initiate change, evaluate change, investigate change and implement change.

The EC process in Westland Helicopters (Figure II-13) (Eckert et al., 2004) begins with establishing the customer requirements with the Sales and Marketing department. This is followed by a tender process where tender experts together with chief engineers and other experts will made the major design decisions. Subsequently, a proposal is then made to the customer and the contract is signed on agreement. Next, the chief engineer together with the relevant system heads will assess the impact of the change and an approximate schedule is proposed. This is also the beginning of change processes for emergent changes. In the next stage, the system heads and the change engineers investigate the impact of the change in detail will raise a formal engineering change request. Then, individuals or teams are selected for each system involved that will further assess the change and will propose solutions with their cost and implementation planning. The solutions are then discussed in a joint meeting of all involved teams and individual where the preferred solution is agreed upon. Each of the involved teams can then continue with implementation of their part of the change.

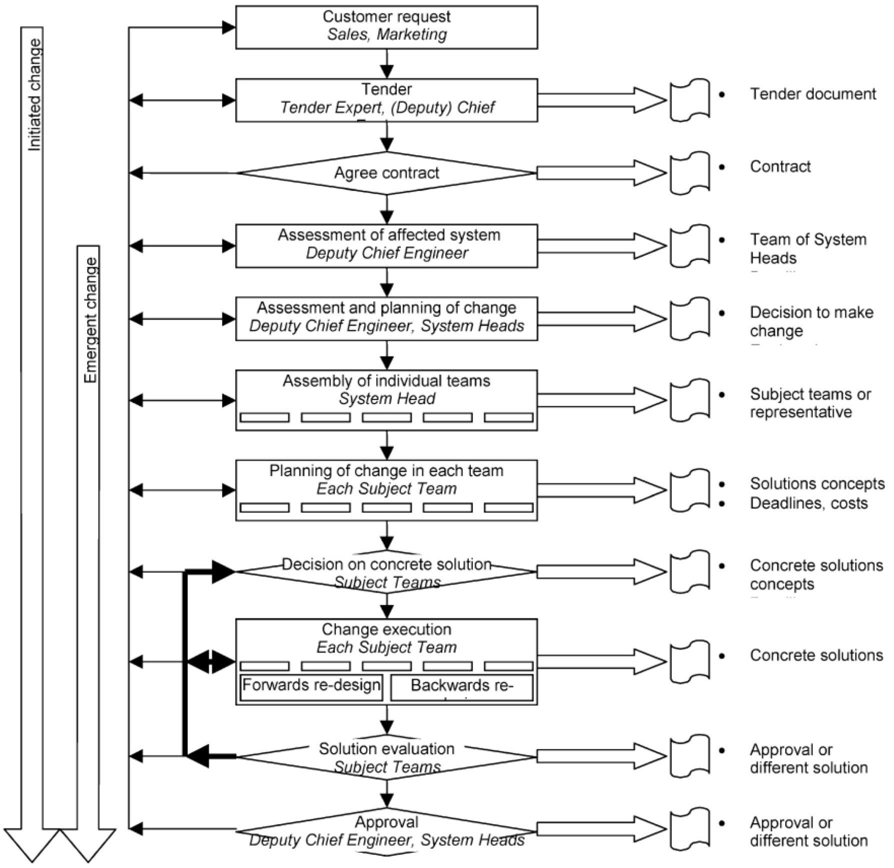


Figure II-13: EC process in Westland Helicopters Ltd.

6.2 Commercial software applications supporting ECs

There are different types of commercial software applications that are currently used in industry and support the analysis of ECs. The main types are discussed briefly to provide an overview of the knowledge they contain which could be used in future EC impact analysis methods.

Current requirement management software is used to manage requirements and their dependencies. Some package offer "traceability" capabilities to identify affected requirements via direct and indirect links for changes to initial requirement. More advanced applications can even be used to decompose a product or system hierarchically into several alternatives (EDS SLATE®, 2004) and link each design object with relevant requirements which can be structured as well.

Configuration Management (CM) software and Product Lifecycle Management (PLM) or Product Data Management (PDM) software (DS ENOVIA®, 2007) are commercial packages that are now generally used in industry to manage all product related data. However, they contain limited relational knowledge, mainly dependencies related to the product hierarchy. Some of these applications can support the communication of changes to the product definition within the extended organisation.

Modern CAD software, such as CATIA (DS CATIA®, 2007), can predict the impact of changing a component by analysing the product geometrically and investigating interferences with neighbouring components, but not more complex interactions. These software packages only enable designers to identify geometry interactions at the assembly or component levels but not at the attributes levels. CAD software based on parametric product modelling allows users to measure the impact of a specific engineering change on predefined dimensional constraints.

7 Summary

The review of the state-of-the-art on ECs aimed to collate the current state of research on ECs and obtain an insight into practices related to ECs in industry. For this purpose, an extensive review was undertaken of major publications in relation to ECs and recent publications on qualitative dependency models and EC impact analysis methods. Additionally, an engineering change was defined in the context of this thesis as any alteration of an item related to the design of product that needs to be investigated.

The review identified that there are many different sources of ECs throughout the product lifecycle. Fundamentally, however, changes are either initiated by designers to modify the product or changes emerge in order to solve deficiencies in the product design. ECs can impact the product, the design process as well as the extended organisation. In addition, ECs can initiate new ECs which in turn can propagate further. This phenomenon is referred to as change propagation. As a result, the extent of the impact can sometimes be difficult to predict, particularly in complex products where the design knowledge is distributed across the organisation.

Current practices in dealing with ECs make use of management procedures to control changes. Configuration management and other standards provide some guidelines for these procedures. However, these standards do not specify any methods to analyse the impact of ECs.

It has been recognised in other research that impact analyses of ECs are necessary to improve the capacity to manage time, cost, resources and quality. Published methods to analyse the impact of ECs are generally categorised as qualitative methods, quantitative methods and other methods. The focus of this research is on the qualitative impact analysis methods because these can be used to model diverse types of information and can be applied at various phases of the product life cycle.

In recent years, academic research has resulted in several promising methods based on qualitative dependency models to investigate ECs. These methods focus on specific analyses of dependency models for particular types of information. The latter are usually either the product architecture or design processes. However, the capabilities of the current dependency models to characterise the impact of ECs are very specific to the related analysis method. In addition, existing EC impact analysis methods have limited capabilities in tracing the propagation of ECs and supporting the decision-maker with the identification of feasible solutions. Hence, there appears to be a need for a more generic and scalable approach to model and analyse qualitative dependencies in support of a more integrated and shared impact analysis approach within organisations. Additionally, any new methods should support an effective visualisation as qualitative analysis methods aim to highlight possible impacts that needs to be further investigated.

CHAPTER III:

Modelling of Dependencies

This chapter is the first of three chapters on the proposed EC impact analysis methodology. The chapter introduces novel versatile meta-model to capture qualitative dependencies between information items related product design and its associated processes. An UML class diagram model of this meta-model is given. Finally, considerations with respect to the elicitation processes that are required to create the dependency models are discussed. The obtained dependencies models will form the basis for a propagation algorithm and impact sets analysis described in Chapters IV and V respectively.

1 Introduction

Qualitative dependency models elicit relations between *items* representing a product design and its associated information at a specific point in its lifecycle and with a certain level of granularity. These items can belong to different viewpoints or *domains* of the engineering system, for example, requirements, product architecture, design processes or activities. The literature review showed that current qualitative relational models focus on one or two specific information domains. Furthermore, some of the current relational models characterise the dependencies between items and associate a likelihood factor and a level of impact with the dependencies. However, these characteristics have a limited ability to characterise the impacts for a particular change.

In order to perform more accurate EC impact analysis, a more precise qualitative description of the changes to items and their dependencies is required. Therefore, a novel generic meta-model has been developed to elicit dependencies for a broad range of items and support the characterisation of the possible changes to affected items. Furthermore, this meta-model considers the product lifecycle by taking into account that some types of items can be frozen from a particular milestone. Additionally, the meta-model contains dependency information that elicits the relations between items. Dependencies can be modelled between items from the same domain or items from different domains. There are two different kind of dependencies included in the dependency models. First, there are the incremental dependencies which capture one change initiating one new change. These dependencies are discussed in section 2 and are equivalent to the dependencies or links used in other related research. Additionally, a new kind of dependency is described in section 3. These dependencies are referred to as combinatorial dependencies because these define an impact resulting from a combination of initiating changes. For the remainder of this thesis, incremental dependencies are inferred for references to dependencies without an ‘incremental’ or a ‘combinatorial’ denotation.

2 Incremental dependencies

2.1 Type of change

In previous research (Jarratt et al., 2004), only dependencies have been characterised, e.g. spatial or electric links. In Figure III-1, a two-step propagation is depicted with traditional dependency definitions between the items ‘A’, ‘B’ and ‘C’. In this example, a ‘geometric’ and a ‘material’ link exist from item ‘A’ to item ‘B’ and from item ‘B’ to item ‘C’.

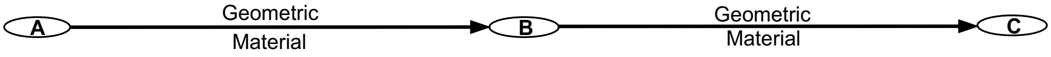
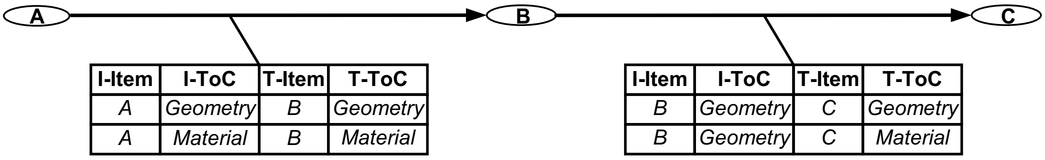


Figure III-1: Propagation with traditional dependency definition

As a result, this example shows that the geometry and material of ‘B’ could be affected due to a change of ‘A’ regardless of the nature of the change to ‘A’. Furthermore, the geometry and material of the item ‘C’ could also be affected. Consequently, this traditional approach based on types of dependencies does not consider the impact of the initiating item.

Therefore, a new approach has been developed which characterises important aspects of the possible change to an item. This approach combines an item with a *type of change* (ToC) during a propagaton. The ToC specifies the property of the item that is changed, e.g. material or geometry. Furthermore, the ToC of the affected item is a function of the ToC of the initiating item. Hence, dependencies are defined between an initiating change composed of an initiating item (I-Item) together with an initiating ToC (I-ToC) and a target change composed of a target item (T-Item) together with a target ToC (T-ToC). Thus, multiple dependencies can exist between two items to define relations between different ToCs. However, in some domains, no relevant types of change can be identified for the items. In that case, a single default ToC can be used for all dependencies.

A two-step propagation example with ToC-based dependencies is shown in Figure III-2. In this example, also two dependencies are defined between items ‘A’ and ‘B’ and another two dependencies are defined between items ‘B’ and ‘C’. The used ToCs are again ‘Geometry’ and ‘Material’.



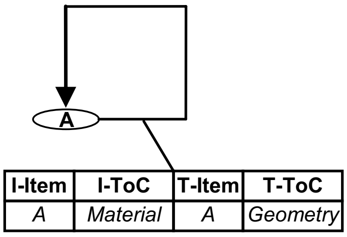
I-Item	I-ToC	T-Item	T-ToC
A	*Geometry*	*B*	*Geometry*
A	*Material*	*B*	*Material*

I-Item	I-ToC	T-Item	T-ToC
B	*Geometry*	*C*	*Geometry*
B	*Geometry*	*C*	*Material*

Figure III-2: Propagation with ToC-based dependencies

In this propagation example, a change to the Geometry of ‘A’ will identify that both the Geometry of ‘B’ and ‘C’ can be affected while a change to the Material of ‘A’ will identify that only a change to the Material of ‘B’ can be affected. In contrast, the example with the traditional dependencies in Figure III-1 will identify that in both cases, both ‘B’ and ‘C’ could be affected. This illustrates the main advantage of using ToC-based dependencies compared to the traditional dependency definition.

An additional advantage of the ToC-based dependencies is that dependencies can be defined between different ToCs of the same item. This is illustrated in Figure III-3. In this example, a change to the Material of item ‘A’ can affect the Geometry of the same ‘A’. This adds another degree of freedom in modelling dependencies.



I-Item	I-ToC	T-Item	T-ToC
A	*Material*	*A*	*Geometry*

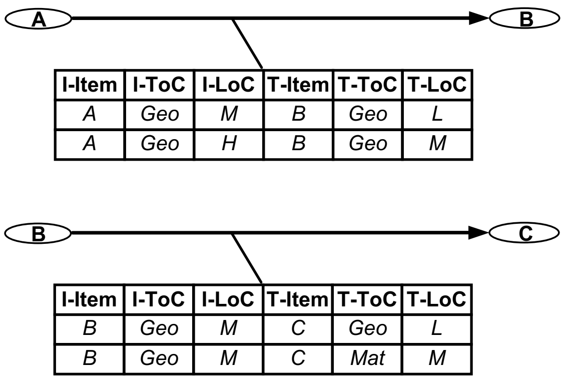
Figure III-3: Dependency between different ToCs of same item

2.2 Level of change

Current dependency models also qualified possible change of an affected item with an impact level. This refers to the amount of rework from the current configuration baseline that could be required for the affected item, which is particularly related to physical components. As with the dependency types, the impact level is independent from the initiating conditions. Therefore to further improve the dependency definition, a change as combination of an item and a type of change is extended with a level of change (LoC). As with the ToC, the LoC of the affected item is a function of the level of change of the initiated item, called *target LoC* (T-LoC) and *initiating LoC* (I-LoC) respectively. Consequently, dependencies are defined between the LoC of the ToC of the initiated item and the LoC of the ToC of the affected item.

The levels of change can be chosen according to the available knowledge about the dependencies and types of changes that are considered even though specifying the levels of change will be in most cases very subjective. Therefore, the conjecture is that ‘Low’ (L), ‘Medium’ (M) and ‘High’ (H) will in most cases be the most appropriate to qualify the change and will be used henceforth. Furthermore, the LoCs can be chosen in order achieve specific propagation behaviours. For example, High LoCs could be used to initiate the worst-case impact while Low LoCs could be used to trigger the best-case impact which could be no impact at all.

Two examples of dependencies with ToCs and LoCs are shown in Figure III-4 to illustrate a change propagation with LoCs and ToCs.



I-Item	I-ToC	I-LoC	T-Item	T-ToC	T-LoC
A	*Geo*	*M*	*B*	*Geo*	*L*
A	*Geo*	*H*	*B*	*Geo*	*M*

I-Item	I-ToC	I-LoC	T-Item	T-ToC	T-LoC
B	*Geo*	*M*	*C*	*Geo*	*L*
B	*Geo*	*M*	*C*	*Mat*	*M*

Figure III-4: Dependency definition with ToCs and LoCs

In the first propagation example based on the above dependency definition, a Medium change to the Geometry of item 'A' can affect the Geometry of item 'B' with Low LoC. As the LoC of 'B' is Low, 'C' will not be impacted and hence the propagation will not continue (Figure III-5).

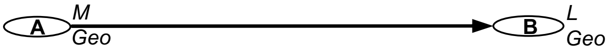


Figure III-5: Propagation example with ToC and LoC (1)

However in a second propagation example, a High change to the Geometry of item 'A' can affect the Geometry of item 'B' with Medium LoC. This impact can in turn affect the Geometry of 'C' with a Low LoC and can also affect Material of 'C' with a Medium LoC (Figure III-6).

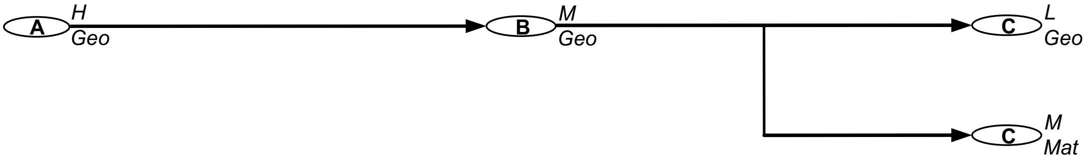


Figure III-6: Propagation example with ToC and LoC (2)

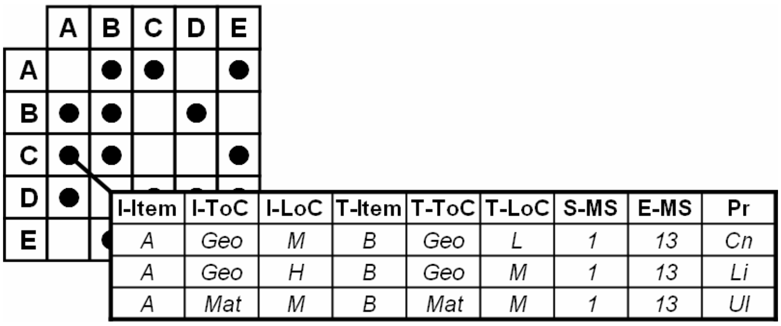
Consequently, as for the use of ToC, dependencies with LoCs further enhance the flexibility to model dependencies between items and enable a better control over the propagation of the ECs.

2.3 Validity range and probability

As discussed above, a dependency is composed of an initiating item, an initiating ToC, an initiating LoC, a target item, a target ToC and a target LoC. However, also lifecycle considerations need to be taken into account with respect to the dependency because a dependency can possibly not always be valid during the product lifecycle. Therefore, each dependency is associated with a validity range between a start milestone (S-MS) and an end milestone (E-MS). Henceforth, a lifecycle with 13 milestones has been used. As a result, different dependencies can be modelled for different phases of the product lifecycle. For example, a change of an item at the beginning of the lifecycle may have a low impact on a cost item while the same change could have a high impact on the same cost item near the end of the lifecycle.

Additionally, a *probability* (Pr) is associated with a dependency in order to perform statistical analyses for possible impact sets discrimination. This probability is the likelihood that the target will be impacted for the initiating conditions. However, it is very difficult to associate a specific probability value with a dependency. Therefore, a scale similar to the LoCs consisting of 'Unlikely' (Ul), 'Likely' (Li) and 'Certain' (Cn) has been proposed. The latter indicates a definite dependency and should be more obvious to elicit. The distinction between an unlikely and likely dependency can be more difficult to make.

As a result, each dependency requires nine attributes to be defined. Figure III-7 shows a regular DSM for a specific domain. A '●' indicates that there exists one or more dependencies from the initiating item in the column to a target items in the row. The inset depicts a table which list the dependencies between the 2 items. Note also that dependencies can exist in the diagonal.



I-Item	I-ToC	I-LoC	T-Item	T-ToC	T-LoC	S-MS	E-MS	Pr
A	Geo	M	B	Geo	L	1	13	Cn
A	Geo	H	B	Geo	M	1	13	Li
A	Mat	M	B	Mat	M	1	13	Ul

Figure III-7: Example of dependency definition

3 Combinatorial dependencies

As described already in the introduction, not only incremental dependencies can exist where one change triggers another change. In engineering design, often step changes occur (Brown, 2004) where the combined effect of a number of changes is different from the effect of each of the individual changes. As step changes often appear unexpectedly, modelling these would be a considerable improvement towards EC impact analyses. To model these step changes, combinatorial dependencies have been introduced. These dependencies define an impact in terms of a target item, a target ToC and a target LoC for a specific set of initiating changes, each of these are composed of an initiating item, initiating ToC and initiating LoC.

The combinatorial dependencies can be used in different ways. First, they can model an impact on an item that the individual initiating items do not impact. Also an impact on additional ToCs can be modelled for an item that can already be impacted with different ToCs by the initiating changes. Finally, the combinatorial dependencies can be used to model an impact with a higher LoC than the target LoCs for each of the individual initiating changes. For example, a high initiating LoC of items A, B and C have individually an impact with a low LoC on item 'D' while a high initiating LoC of items A, B and C all together has an impact with a high LoC on item 'D'.

These combinatorial dependencies cannot be visualised in a dependency DSM and are therefore listed in a table. A table with examples of combinatorial dependencies is shown in Figure III-8. This example includes three items (A, B, C), two ToCs (X, Y) and three LoCs (L, M, H). Each column in this table represents a combination of an I-item, I-ToC and I-LoC while each row is one combinatorial dependency. The different '●' in a row indicate the different initiating changes that are required for the dependency. Hence the same target change can appear in several rows for dependencies with different initiating conditions but with the same impact. Additionally, a start and end milestone together with a probability factor can be defined for each dependency.

							I-Item	A						B						C					
							I-ToC	X			Y			X			Y			X			Y		
							I-LoC	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
N°	*T-Item*	*T-ToC*	*T-LoC*	*S-MS*	*E-MS*	*Pr*																			
1	A	X	L	1	13	Li								●						●					
2	A	X	M	1	13	Li									●						●				
3	A	X	H	1	13	Li										●						●			
4	A	Y	M	1	13	Cn												●						●	
5	A	Y	H	1	13	Cn													●						●

Figure III-8: Combinatorial dependency table

4 UML Model

The complete proposed dependency model has been described in an UML class diagram. This UML diagram reflects the implementation of the dependency model. The diagram is depicted in Figure III-9 and is comprised of 10 types of information represented by classes. Each class and its relations with other classes is described below.

- **Model:** This class contains the references and description of dependency models for different products, product sections or product versions.
- **Domain:** This class contains the possible domains for all the different types of information item that can be included in the models.
- **Milestone:** This class contains the milestones in the product lifecycle
- **Item:** This class contains the items. Each item belongs to one model and one domain. It is also associated with one milestone to specify the moment at which it is frozen in the product lifecycle.
- **ToC:** This class contains the types of change. Each ToC can belong to many domains while each domain can be associated with multiple ToCs
- **LoC:** This class contains the levels of change. Each LoC can belong to many ToCs while each ToCs can be associated with multiple LoCs.
- **Change:** This class contains the possible changes. Each change is composed of one item, one ToC and one LoC.

- **Incr_Deps:** This class contains the incremental dependencies. Each incremental dependency is associated with two Changes, an initiating Change and a target Change. Furthermore, each dependency is associated with two milestones defining the lifecycle validity range and has a probability factor as attribute.
- **Comb_Ini:** This class contains the combinations of initiating changes that can instigate a combinatorial change. Many Changes can belong to each combination while each Change can also belong to many combinations.
- **Comb_Deps:** This class contains the combinatorial dependencies and hence it is associated with a Comb_Ini and a Change as target. Furthermore, each dependency is also associated with two milestones defining the lifecycle validity range and has a probability factor as attribute.

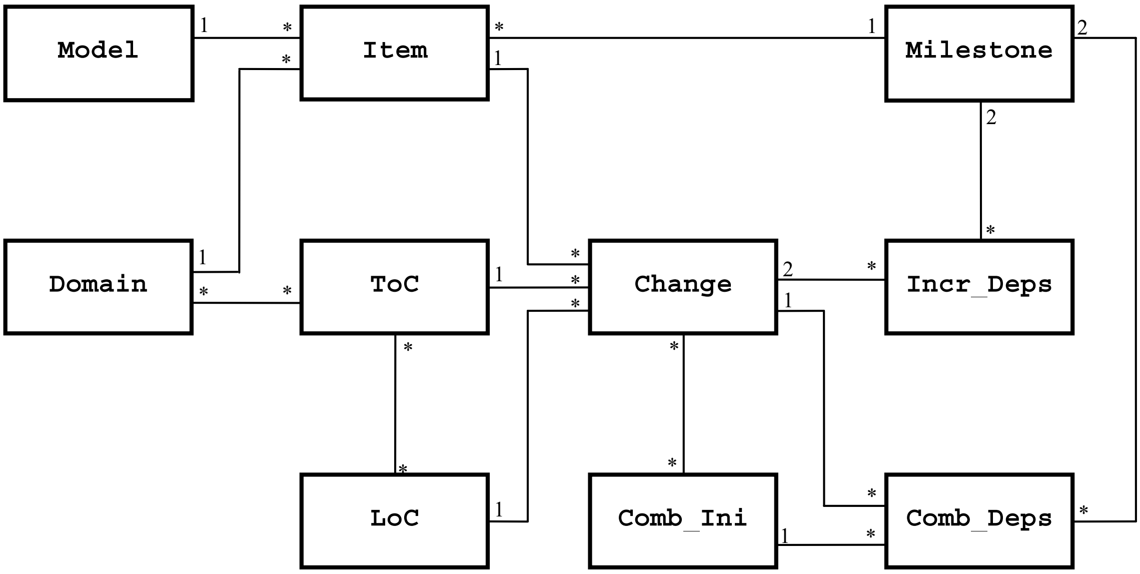


Figure III-9: UML Class Diagram of dependency model

5 Elicitation processes

Capturing all the required information to recreate effective dependency models is a major challenge. There can be two approaches to elicit the required knowledge. First and most of all, the knowledge is obtained from design experts. This can be done through a series of the individual interviews or group discussions which is a time consuming process and the availability of design experts is limited. However, previous research (Jarratt, 2004) indicates that the required elicitation process can be useful in its own right, as it can improve the participants' understanding of the reviewed design areas. Furthermore, capturing knowledge enables it to be stored and distributed across the enterprise. Even though this is beneficial to the company, individuals may be hesitant to share their knowledge for fears that they may become redundant once their knowledge has been stored in a repository. However, qualitative dependency models by their nature do not capture all aspects of a product design, their interdependencies and related information. Consequently, design experts will always be required to interpret the modelled information.

Second, existing knowledge repository could be used to automate the elicitation of items as well as their dependencies. An obvious source of knowledge is the CAD model of the product. For example, components from the physical architecture could be extracted and automatic identification of geometric relations through clash detection methods have been investigated (Rivière, 2004). Other repositories that could be considered are PLM tools and requirement management tools. However, the amount of relevant dependencies that can be obtained automatically is limited. Additionally, these tools can reside on various systems in different locations, integrating these tools with the repository of the dependency models and extracting the right information will not be a trivial task. This will also require many resources and maintenance systems.

Additionally, in order for the dependency models to produce reliable results, the information it contains must be correct. Therefore, a validation process needs to be part of an elicitation process in order to keep a dependency model up-to-date with the current design in the context of a continuously changing and evolving product design.

6 Summary

This chapter described a novel meta-model to capture qualitative dependencies. First, the information items are organised in domains. Second, a change is defined as a combination of an item with a type of change and a level of change. Consequently, dependencies are defined between an initiating change and a target change. As a result, dependencies can be modelled more precisely than with the traditional dependencies and can support a potentially more accurate EC propagation analysis. Additionally, it also improves the ability to model items in terms of their change properties as absorbers, carriers or multipliers (example in Chapter VI section 2.3).

Additionally, combinatorial dependencies have been introduced which define a target change for a specific combination of initiating changes. Hence, these combinatorial dependencies support the prediction of step changes and can enhance the EC propagation analysis results. Also the product lifecycle was taken into account by associating a milestone with items to capture the moment of design freeze and by enabling the definition of a validity range of dependencies between two milestones.

The proposed dependency model is also compatible with various existing EC impact analysis methods in order to support a more integrated and shared impact analysis approach throughout a company and the product lifecycle. For example, CPM could be accommodated by using the probability as the likelihood value and the target LoC as the impact value. The initiating LoC and combinatorial dependencies would be ignored. Also the RedesignIT method could be supported by modelling ‘increases’ and ‘decreases’ to design parameters as ToCs and defining the required dependencies accordingly. The C-FAR dependencies from the corresponding method could be modelled with initiating ToCs and target ToCs.

Regarding the elicitation process that is required, knowledge can be captured from design experts and existing design repositories. This will require a considerable amount of resources and therefore, the right information needs to be elicited at the right moment. Determining these factors was however beyond the scope of this thesis.

CHAPTER IV:
Change Propagation Analysis

A novel meta-model to capture qualitative dependencies in product design and their related information was introduced in the previous chapter. In this chapter, an algorithm, named Change Propagation Analysis (CPA), is presented that can exploit the elicited dependency models in order to identify possible propagation paths. The algorithm can simulate different possible propagation behaviours and limits and filters propagation paths to support an effective visualisation. Additionally, reverse propagation is supported which identifies possible changes that could affect a selected change.

1 Introduction

To analyse the dependency model and identify all relevant propagation paths for an initiating change, a propagation algorithm was developed. This algorithm will start with searching for the dependencies with an initiating item, ToC and LoC that matches the specified initiating change. The matching dependencies will identify the affected items and their affected ToC and LoC. These affected items with their ToC and LoC will become the initiating changes for the next propagation step. The propagation continues accordingly. Consequently, this algorithm produces a propagation tree representing all the propagation paths. It can also be used to support alternative visualisation methods such as networks and visualisation of affected components in the Digital Mock-Up (DMU). In order to support the investigation of the possible extents of the EC impact, the algorithm can execute different types of propagation. Furthermore, it limits the propagation paths in order to reduce redundant impacts and enables the users to filter the propagation according to the domains of interest. These different aspects of the propagation algorithm are described in detail in following sections.

Two simple demonstration models have been used to visualise the resulting propagation behaviour. The first model consists of one domain with 10 items named ‘A’ to ‘K’ excluding ‘H’ (to avoid confusion with ‘H’ as High LoC). There are 3 ToCs included named ‘Green’, ‘Blue’ and ‘Red’ and 3 LoCs named ‘High’ (H), ‘Medium’ (M) and ‘Low’ (L). The complete list of the dependencies for this model is included in Table IV-1. All these dependencies are valid over the complete lifecycle (S-MS = 1 and E-MS = 13) and no probability factor have been included as this is not considered by the propagation algorithm.

I-Item	I-ToC	I-LoC	T-Item	T-ToC	T-LoC
A	Blue	M	B	Blue	H
A	Blue	H	C	Green	M
A	Red	M	D	Red	L
B	Blue	H	C	Blue	M
B	Blue	H	E	Green	M

C	Green	M	D	Red	H
D	Red	M	E	Green	M
D	Blue	H	K	Green	H
D	Blue	H	I	Blue	M
E	Green	M	F	Green	M
E	Green	M	G	Green	M
E	Green	M	G	Blue	M
E	Red	M	I	Blue	M
F	Blue	M	G	Red	M
G	Green	M	B	Red	M
G	Red	M	B	Blue	M
G	Green	M	C	Green	M
K	Green	H	A	Red	M
K	Blue	H	I	Red	M
K	Green	M	J	Green	H
I	Red	M	K	Blue	M
I	Blue	M	J	Green	M
I	Red	M	J	Green	M
J	Green	M	D	Red	H
J	Green	H	E	Green	M

Table IV-1: Single Domain example dependencies

A second model (Figure IV-10) supports the description of the inter-domain propagation and consists of 3 domains: ‘Domain1’, ‘Domain2’ and ‘Domain3’ with 12 items in total. Only one ToC and LoC have been considered hence they are both modelled as ‘Default’.

2 Types of propagation

Since dependencies are defined between the ToC and LoC of the initiating item and affected ToC and LoC of the target item, the CPA can take into account the affected

ToCs and LoCs of the impacted items during the propagation. However, there are occasions when it can be beneficial to ignore the ToC and also the LoC of the dependencies in order to achieve a wider propagation and hence to identify more potentially affected items. Consequently, 3 types of propagations are considered. Each of these propagation types are described in more detail below and an example of a propagation tree is depicted based on a set of dependencies listed in the Table IV-1.

2.1 Simple propagation analysis (SPA)

The SPA only considers relations at item level which means that at every propagation level, all dependencies are taken into account for every initiating item. Hence, only an item needs to be selected as initiating condition. Consequently, the propagation is not influenced by the defined initiating and target ToCs and LoCs. The propagation tree in Figure IV-1 illustrates a SPA with 'A' as initiating item for two propagation levels. As a result, both 'B', 'C' and 'D' are impacted at the first propagation step even though different ToCs and LoCs of 'A' are required. Subsequently, the ToCs and LoCs of the impacted items are ignored for the next propagation step. In Figure IV-1, the name of each affected item and the initiating items is shown in an ellipse. The propagation continues from left to right.

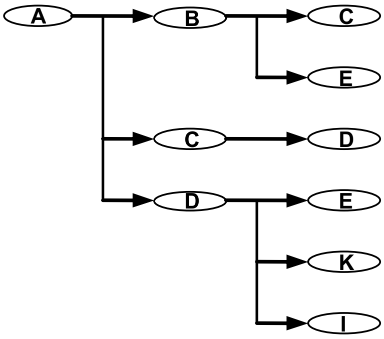


Figure IV-1: Simple Propagation Analysis

This type of propagation analysis can be used to identify the maximum possible extent of the EC impact, particularly in case the considered ToCs do not match the modelled ToCs or the latter are not completely independent. Consequently, this type of propagation analysis identifies rapidly increasing numbers of possible impacts. For example, in case of propagation analysis in a Physical Architecture, all items could eventually be identified as possibly impacted.

2.2 'ToC-only' propagation analysis (TPA)

This type of propagation analysis only considers the ToCs of the relations between items but ignores the LoCs. Therefore, together with the initiating item, also an initiating ToC (I-ToC) needs to be selected. Consequently, all affected ToCs (T-ToC) become I- ToCs for the following propagation level. The propagation tree below illustrates this propagation type with 'A' as initiating item and 'Blue' as I-ToC for two propagation levels. Hence, this time only 'B' and 'C' are identified with the ToC 'Blue' and 'Green' respectively. These ToCs are then taken into account for the next propagation step. In Figure IV-2, the name of the item is shown in the ellipse while the background colour corresponds to the impacted ToC.

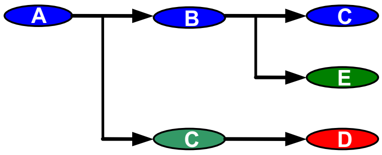


Figure IV-2: 'ToC-only' Propagation Analysis

This type of analysis simulates a propagation behaviour where a change to an item will always affect another item as long as there is a dependency between the relevant ToCs regardless of the magnitude of the change. Hence, different ToCs can be affected for new and already identified items. Consequently, this propagation analysis can also identify large numbers of items as possibly impacted, especially when very generic ToCs are affected or in domains where only one or very few ToCs are used.

2.3 Detailed propagation analysis (DPA)

For this type of propagation analysis, the CPA considers the ToC and LoC of every affected item and takes these into account to identify the relations for the following propagation step. Hence, this type of analysis requires an initiating ToC and a LoC to begin with. The 2-step propagation tree in Figure IV-3 illustrates this propagation type with ‘A’ as the initiating item and ‘Blue’ with ‘Medium’ (M) as I-ToC and I-LoC. Now, only item ‘B’ is identified at the first propagation step. The T-ToC is also ‘Blue’ and the T-LoC is ‘High’. This ‘High’ level of change of ‘Blue’ of item ‘B’ will in turn affected item ‘C’ and ‘D’ with ToC ‘Blue’ together with LoC ‘M’ and ToC ‘Green’ together with LoC ‘M’ respectively. Figure IV-3 uses the same visualisation as Figure IV-2 with the addition that the affected LoC is shown at the top right of the corresponding ellipse.

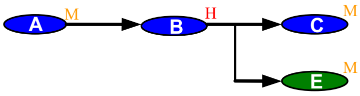


Figure IV-3: Detailed Propagation Analysis

In this case, a specified level of change with the relevant ToC is required for the affected items in order for the propagation to continue. This implies that changes are absorbed by some items when the LoC of the affected items is lower than required in order to affect more items (section 4). Consequently, this type of propagation is more constrained than the previous propagation types and hence fewer items are impacted.

3 Loop detection

To support an effective visualisation of the propagation paths, the algorithm also detects impacted items which have already been impacted at a preceding propagation step. This would result in the repetition of the same knock-on impacts. This in turn could lead to propagation loops and consequently to an infinite propagation. The repeated impacts are considered to add no new information to the propagation results while increasing unnecessarily the size of the resulting propagation tree.

Therefore, loop detection has been included in the CPA. Loop detection works in two ways to recognise when an item has already been impacted. First, the propagation does not continue for an impact which has been identified at previous propagation levels.

Secondly, in case that the same impacts occur multiple times at the same propagation level, the propagation only continues for the first of those impacts. In case of a SPA, loops will be detected when the same items are impacted. During a TPA, loop detection occurs when the same item with same ToC is impacted. Thus the propagation will continue for an impact on a different ToC of an already impacted item. In the case of DPA, the propagation is terminated when the same ToC and LoC is impacted of an item identified before.

Loop detection is illustrated in Figure IV-4 for the second propagation step of the Simple Propagation Analysis shown in Figure IV-1. First, the propagation is not continued beyond the impact on ‘C’ as it has already been impacted on the first step and the same for item ‘D’ (purple arrows). Secondly, ‘E’ is impacted twice at the second propagation step (blue arrow). Only for one first appearance is the propagation continued. Figure IV-5 shows the loop detection at the third propagation step for the same example.

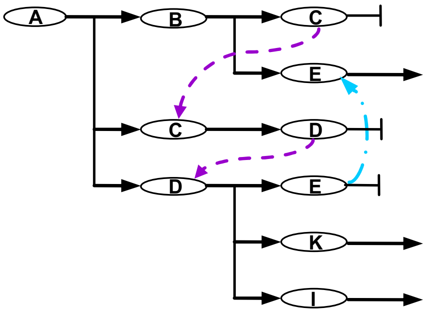


Figure IV-4: Loop detection at step 2

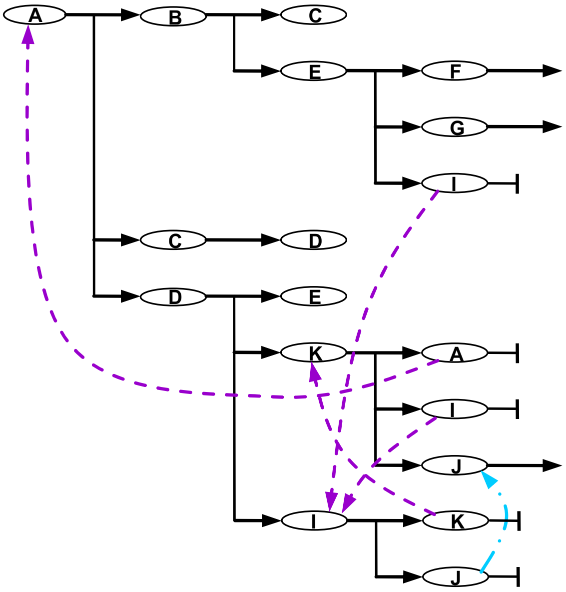


Figure IV-5: Loop detection at step 3

4 LoC propagation management

Unlike ToCs, LoCs are not independent because these are graded and therefore can be ordered. Consequently, this order can be taken into account during the propagation to identify potentially more relevant impacts and to minimise duplicate impacts. Thus, the propagation and loop detection has been extended with three additional rules for Detailed Propagations which consider LoCs. Each of these rules is illustrated with a propagation analysis example based on the dependencies listed in the section 1 of this chapter.

4.1 Rule 1

Besides the selected or identified initiating LoC, also lower LoCs associated with the item need to be taken into account. The rationale is that in case a Low LoC of an initiating item has an impact on an item, a higher level of change of the same initiating item should also identify this impact. The example in Figure IV-6 shows this as ‘K’ which impacts both ‘A’ and ‘J’ while the LoC of item ‘K’ was High but only a Medium LoC was required to impact ‘J’. If this rule was not used only the ‘Medium’ ‘Red’ impact on ‘A’ would have been identified but not the ‘High’ ‘Green’ impact of ‘J’.

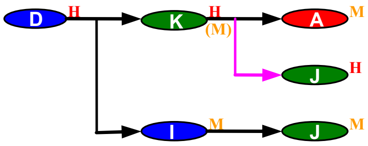


Figure IV-6: LoC Propagation Management - Rule 1

4.2 Rule 2

The propagation should be stopped when an item is impacted which has been impacted before at a higher level (hence not only the same LoC). This is because the impact of the new (lower) identified LoC should already be checked for the previous impact with a higher LoC as a result of the previous rule. This is illustrated in Figure IV-7 where the propagation at the second propagation step for ‘K’ is stopped because the newly identified LoC (Medium) of item ‘H’ had been included at first propagation level with ‘High’ ‘H’ as initiating condition.

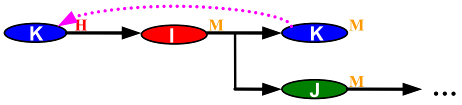


Figure IV-7: LoC Propagation Management - Rule 2

4.3 Rule 3

This rule considers the case when multiple impacts on the same item with different LoCs occur at the same propagation step. It states that in this case the propagation should only continue for the impact with the highest LoC. However, due to Rule 1, also all lower LoCs will be included for that impact. This is illustrated in Figure IV-8 where at the second propagation level a ‘Green’ change of ‘J’ is once identified with a ‘High’ LoC and once with ‘Medium’ LoC. The propagation is terminated for ‘J’ with the ‘Medium’ LoC and only continues for ‘J’ with the ‘High’ LoC but includes also impacts for a lower LoCs (‘Medium’). This means that the ‘Red’ ToC of ‘D’ is shown as impacted by ‘J’ with a ‘High’ LoC and not by ‘J’ with a ‘Medium’ LoC even though the latter is defined in the dependency model.

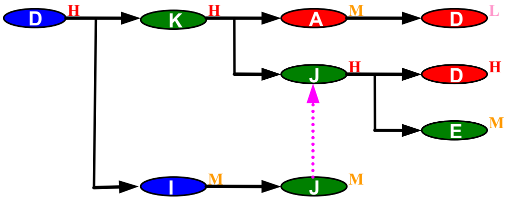


Figure IV-8: LoC Propagation Management - Rule 3

5 Milestone Detection

The algorithm also detects the status of items and the dependencies during the propagation analysis. This requires that a milestone is specified together with the other initiating conditions. As a result, the propagation does not continue for affected items when their status is frozen for the specified milestone. Additionally, the lifecycle validity range of the dependencies is also taken into account. This means that only those relations are considered for which the specified milestone is within their defined lifecycle range (S-MS to E-MS). Figure IV-9 shows the SPA from Figure IV-5 but with item ‘B’ frozen.

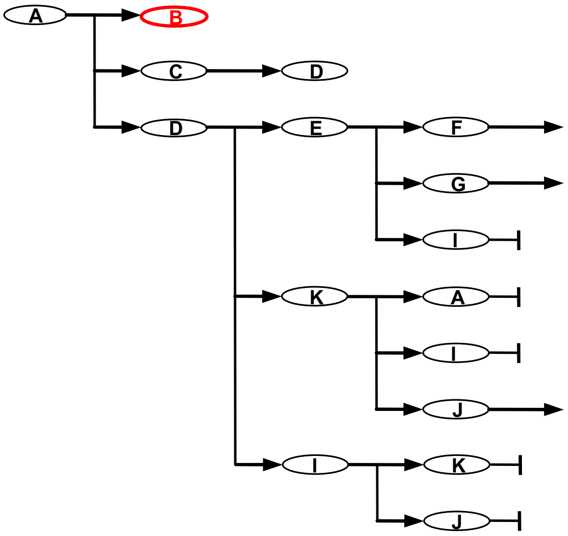
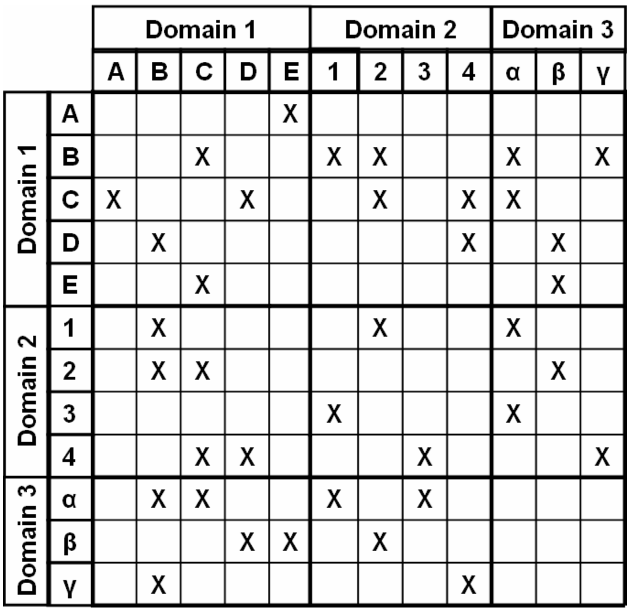


Figure IV-9: SPA example with 'B' frozen

6 Inter-domain propagation filtering

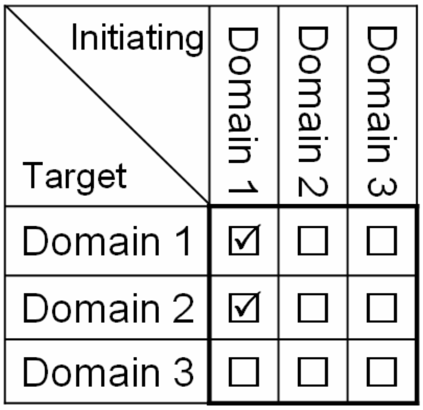
As described in Chapter III, the proposed methodology supports the elicitation of dependencies between items of different types of information organised in domains. All the dependencies, i.e. the dependencies between items of the same domain and between items of different domains, can be visualised in an Inter-domain DSM. This DSM is composed of Single domain DSMs and Domain Mapping Matrices (DMMs). Single domain DSMs contain the dependencies between the items of the same domain. DMMs are used to define dependencies between items in two different domains. All the DSMs and DMMs for all included domains form a square Inter-domain DSM. An example of an inter-domain DSM for three domains is depicted in Figure IV-10.



		Domain 1					Domain 2				Domain 3		
		A	B	C	D	E	1	2	3	4	α	β	γ
Domain 1	A					X							
	B			X			X	X			X		X
	C	X			X			X		X	X		
	D		X							X		X	
	E			X								X	
Domain 2	1		X					X			X		
	2		X	X								X	
	3						X				X		
	4			X	X				X				X
Domain 3	α		X	X			X		X				
	β				X	X		X					
	γ		X							X			

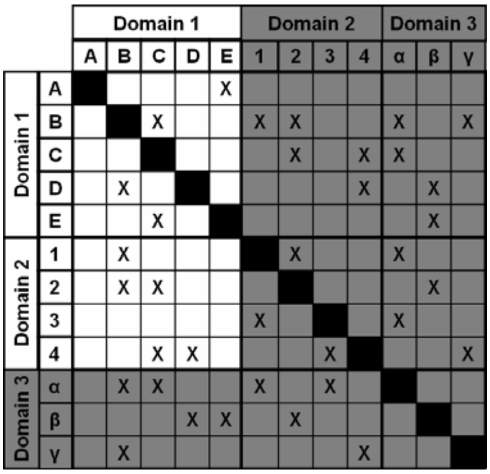
Figure IV-10: Example of Inter-domain DSM

In order to control the identification of cross-domain impacts, special attention has been given to inter-domain propagation. The objective is to give the user a high degree of control over the way the propagation continues between domains. The intention is to provide the decision-maker with a bespoke interface which allows him/her to select specific domain combinations wherefore dependencies have to be considered and ignore all other dependencies for a particular change propagation analysis. This interface constructs a Domain Selection DSM of the available domains, representing the Inter-domain DSM discussed above. Figure IV-11 depicts an example of a Domain Selection DSM with two domain combinations selected. The non-shaded area in Figure IV-12 depicts the corresponding section in the Inter-domain DSM that will be used. This means that the dependencies between the items of Domain 1 and the dependencies from the items in Domain 1 to the items in Domain 2 will be considered during the propagation analysis. As a result, impacts on items of Domain 1 and Domain 2 will be identified at every propagation level. However, only the affected items from Domain 1 will become the initiating items for the following propagation level. This also means that that the initiating item needs to belong to Domain 1.



Initiating / Target	Domain 1	Domain 2	Domain 3
Domain 1	☑	☐	☐
Domain 2	☑	☐	☐
Domain 3	☐	☐	☐

Figure IV-11: Domain Selection DSM



		Domain 1					Domain 2				Domain 3		
		A	B	C	D	E	1	2	3	4	α	β	γ
Domain 1	A	■				X							
	B		■	X			X	X			X		X
	C			■				X		X	X		
	D		X		■					X		X	
	E			X		■						X	
Domain 2	1		X				■	X			X		
	2		X	X				■				X	
	3						X		■		X		
	4			X	X				X	■			X
Domain 3	α		X	X			X		X		■		
	β				X	X		X				■	
	γ		X							X			■

Figure IV-12: Selected section of Inter-domain DSM

Figure IV-13 shows the resulting propagation between the domains. Any required inter-domain flow can be selected as long as every domain is included not more than once in the flow. Furthermore, a finite or an infinite domain flow can be selected. This means that for the infinite flow, at least one loop exist between the domains. In this case, the propagation will continue as long as new items can be identified. In the finite domain flow, the propagation will always end when the impacts in the last domain are identified. Finally, special attention needs to be given that the initiating item belongs to the right domain and that the selected domain combinations result in a consistent domain flow.

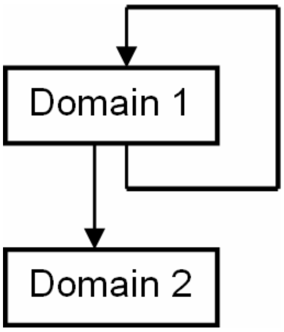


Figure IV-13: Inter-domain Flow

To further demonstrate the inter-domain propagation management, an example of a change scenario is given based on the Inter-domain DSM shown in Figure IV-10. A required inter-domain propagation flow is depicted in Figure IV-14 and the domain combinations in the Domain Selection DSM that need to be selected are shown in Figure IV-15. The propagation between the items in the different domains is depicted in Figure IV-16 in detail and the resulting propagation tree is shown in Figure IV-17.

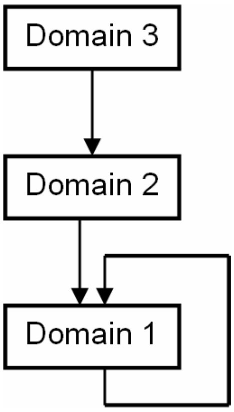
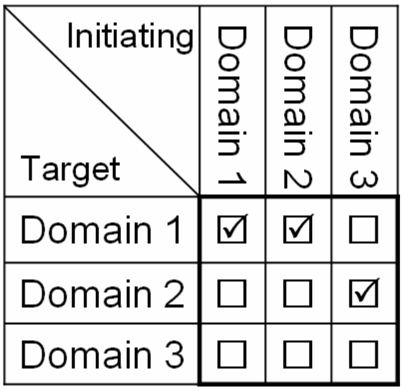
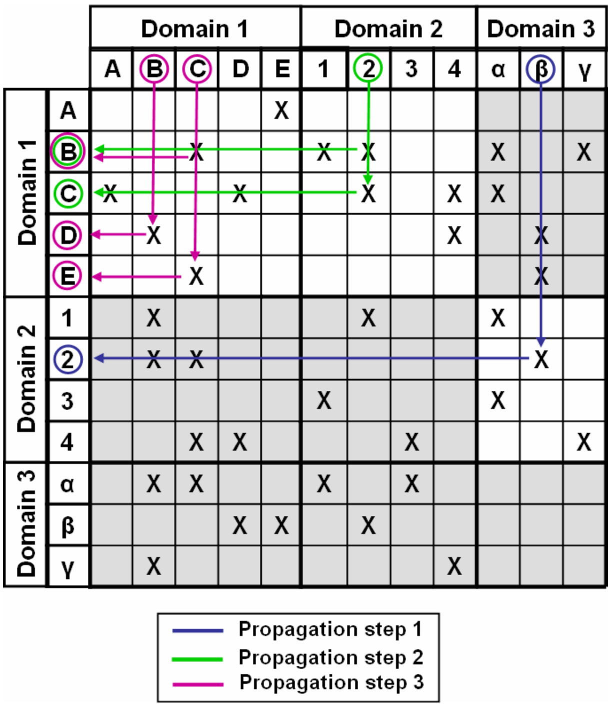


Figure IV-14: Inter-domain propagation overview



Initiating / Target	Domain 1	Domain 2	Domain 3
Domain 1	☑	☑	☐
Domain 2	☐	☐	☑
Domain 3	☐	☐	☐

Figure IV-15: Domain Selection DSM



		Domain 1					Domain 2				Domain 3		
		A	B	C	D	E	1	2	3	4	α	β	γ
Domain 1	A					X							
	B			X			X	X			X		X
	C	X			X			X		X	X		
	D		X							X		X	
	E			X								X	
Domain 2	1		X					X			X		
	2		X	X								X	
	3						X				X		
	4			X	X				X				X
Domain 3	α		X	X			X		X				
	β				X	X		X					
	γ		X							X			

Figure IV-16: Inter-domain propagation in detail

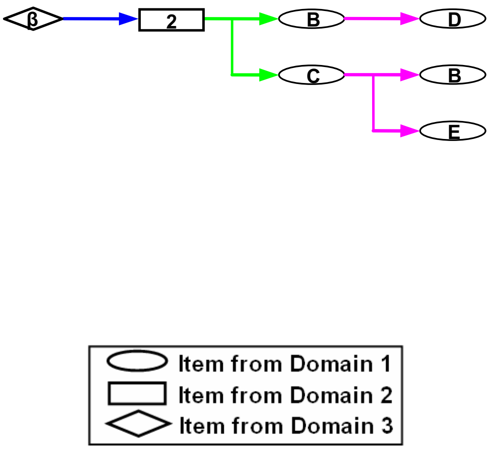


Figure IV-17: Inter-domain propagation tree

This example represents a scenario where a Customer Need (Domain 3) ought to be investigated by identifying related Functional Requirements (Domain 2), the Components (Domain 1) that are affected by these Requirements and any further propagation between the Components.

7 Reverse propagation

Beside forward propagation analyses which identify the possible affected changes for a given initiating change, also reverse propagation analysis can be performed. The aim of a reverse propagation analysis is to identify the possible changes that could affect a given initiating change. Therefore, the algorithm will in this case search for dependencies where the target item, ToC and LoC match the selected initiating change. The identified impacts are then the initiating item, ToC and LoC of the matching dependencies. These identified changes become then the initiating changes for the following propagations steps and the propagation continues accordingly. Consequently, reverse propagation analyses can be performed with the same propagation types as forward propagation analyses. Furthermore, loop detection and inter-domain propagation are equally applicable for reverse propagation analyses.

However, the rules for the LoC propagation managements need to be reversed. This means that for Rule 1 during reverse propagation, all higher LoC need to be taken into account instead of the lower LoC for forward propagation. The rationale here is that in case an item has an impact on another item with high level of change, the first item should also be identified as a possible affecting item for lower levels of change of the second impacted item. Therefore, the algorithm needs to consider not only the selected LoC, but also all higher LoCs. For example, if item ‘A’ affects item ‘C’ with a ‘High’ LoC and item ‘B’ affects items ‘C’ with a ‘Low’ LoC, then the reverse propagation for ‘Medium’ LoC of ‘C’ should identified ‘A’ as a possible affecting item but not ‘B’ as the latter can affect ‘C’ only with a ‘Low’ LoC. Consequently, also Rule 2 and Rule 3 need to be reversed. This means that a loop should be detected when an item is impacted with a higher LoC that previous impact of the same item. In case of multiple impacts on the same item with different LoCs, the reverse propagation should only continue from the item with the lowest LoC, but considering also all higher LoCs for the same item.

An example of a detailed reverse propagation analysis is shown in Figure IV-18 based on the single domain model in Table IV-1. The initiating items is ‘D’ with ToC ‘Red’ and LoC ‘Medium’ which is shown at the right hand side. The propagation continues to the left.

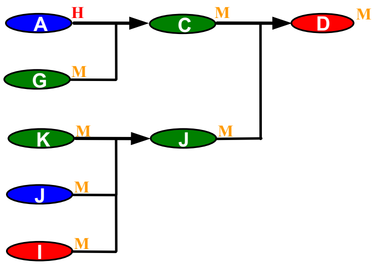


Figure IV-18: Example of reverse propagation analysis

8 Propagation with combinatorial dependencies

So far, only incremental dependencies have been used to discuss the propagation. However, also the combinatorial dependencies can be considered during the propagation. There are two situations that can trigger a combinatorial dependency. First, two or more impacts identified at the last propagation step can initiate a new impact at the new propagation step. This situation is shown in Figure IV-19. Second, one or more new impacts identified at the last propagation step in combination with one or more impacts identified at the earlier propagation steps can also initiate a new impact. This last situation is shown in Figure IV-20.

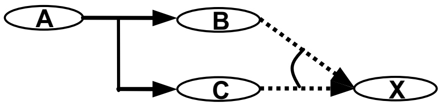


Figure IV-19: Propagation with comb. dependency (1)

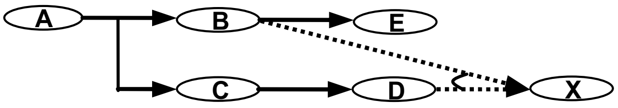


Figure IV-20: Propagation with comb. dependency (2)

Furthermore, the propagation issues discussed above for change propagations with incremental dependencies are equally applicable to change propagations with combinatorial dependencies. This means that the different types of propagation and inter-domain propagation can be used in the same manner with combinatorial dependencies. Also the rules from the LoC propagation management can be taken into account. However, special considerations need to be made regarding loop detection. For incremental dependencies, a loop is detected when an item is impacted which has been impacted before (with the same ToC and LoC) at the same or a previous propagation step. Hence, this new impact is not considered anymore for the subsequent propagation step. In case of combinatorial dependencies, this new repeated impact is also no longer considered to initiate a new impact. However, as combinatorial dependencies consider all affected items of all propagation steps, the initial item will always be considered as an initiating condition for combinatorial dependencies in subsequent propagation steps. Figure IV-21 illustrates this case where items 'B', 'C', 'D' and 'E' impacted at second propagation step do not initiate the combinatorial dependencies which had been used at the previous propagations step. However, the initial impacts of these items at the first propagation steps are still taken into account to identify the impact on item 'K' at the third propagation step.

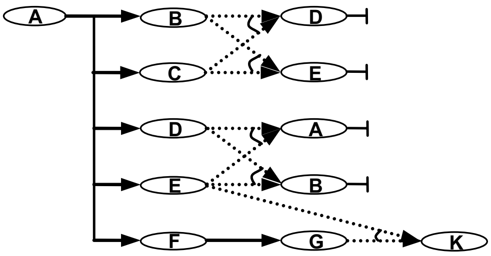


Figure IV-21: Loop detection with combinatorial dependencies

Regarding reverse propagation with combinatorial dependencies, the problem is that different combinations of initiating items can have the same target item. Consequently, the visualisation of all the possible initiating conditions for a target item can become very complex and hence is not included in the CPA algorithm.

9 CPA algorithm

The CPA algorithm brings together all propagation issues that have been discuss in this chapter. The flowchart diagram that is depicted in the following three figures represent the implementation of the CPA algorithm which has been used for the evaluation (Chapter VI). Figure IV-22 shows the overall process. It is at this level that the loop detection, frozen item and LoC management are handled. Figure IV-23 and Figure

IV-24 details the impact identification process for a particular change. The different types of changes are handled as this level together with a part of the LoC management.

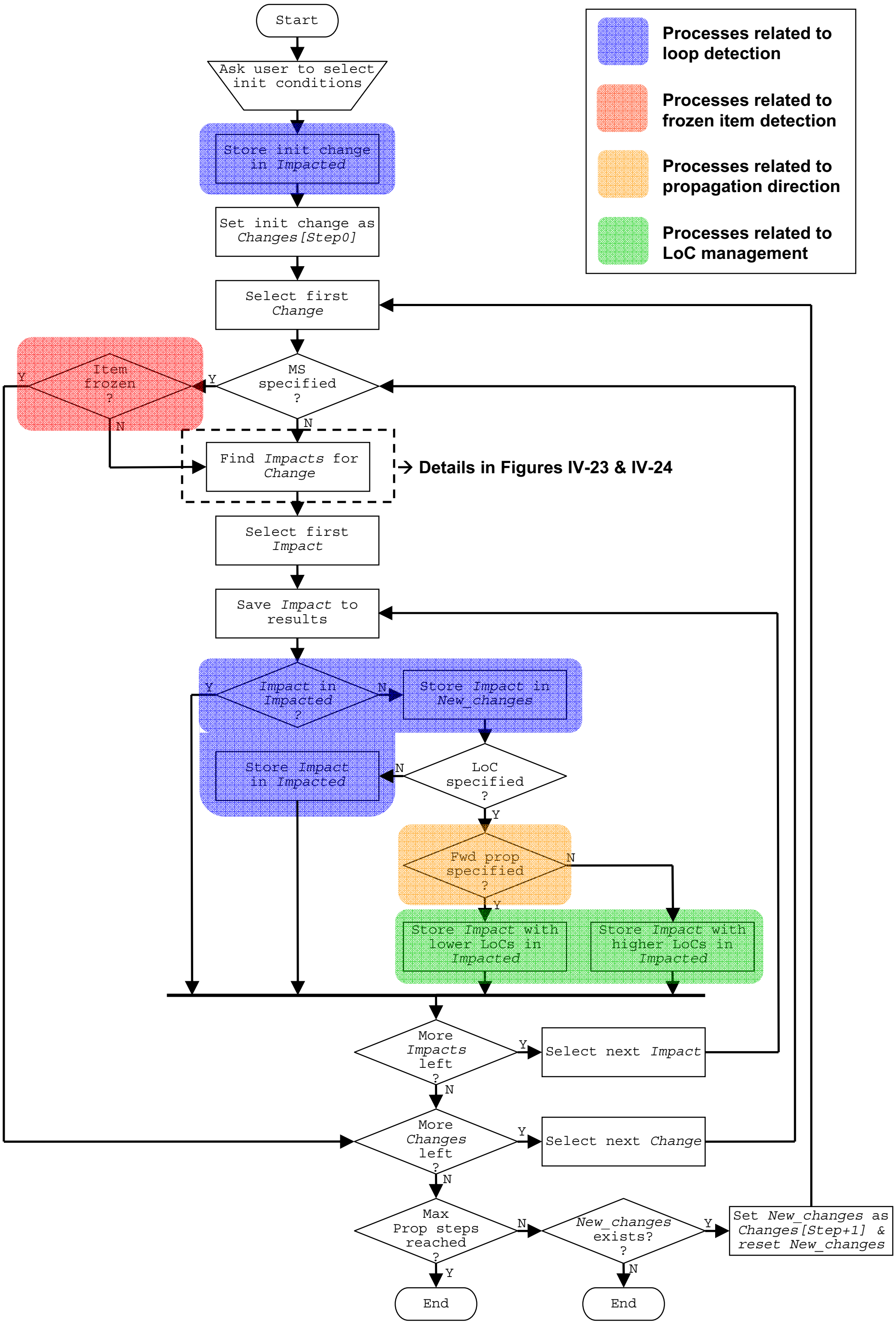


Figure IV-22: Flowchart of overall CPA algorithm

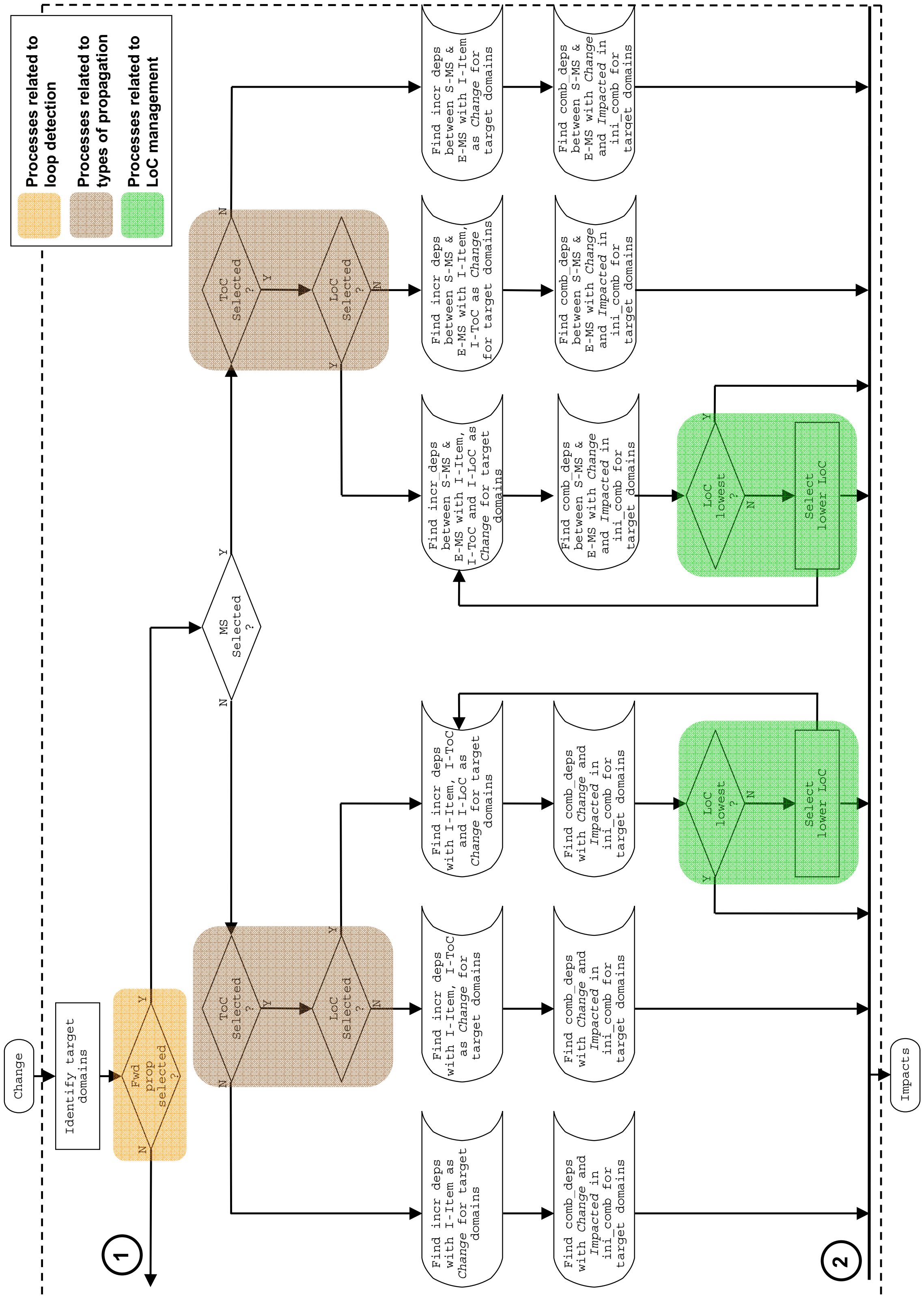


Figure IV-23: Detailed flowchart of 'Find Impacts for Change' process - Part 1

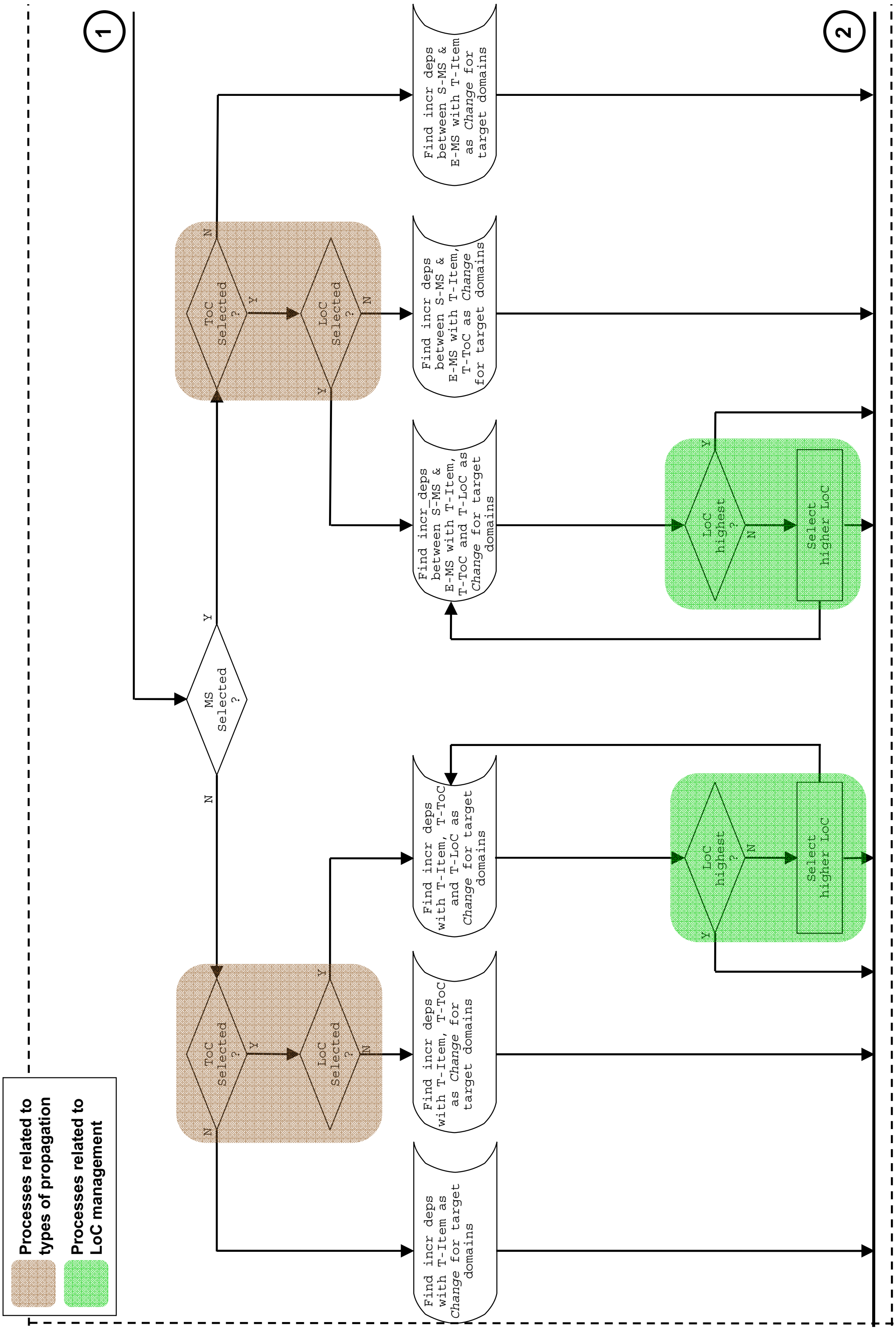


Figure IV-24: Detailed flowchart of 'Find Impacts for Change' process - Part 2

10 Summary

This chapter described a propagation algorithm that analyses the dependency models introduced in the previous chapter. The algorithm can perform three types of propagation simulating different possible propagation behaviour in forward or reverse propagation mode. Furthermore, frozen items and dependency validity is take into account. Finally, loop detection, LoC management and domain-based filtering are included to support an effective visualisation of the propagation paths.

CHAPTER V:

Impact Sets Analysis

This last part of the proposed methodology in this thesis, introduces the Impact Sets Analysis (ISA) algorithm to specifically support the discrimination of concept alternatives during the EC decision-making process. In addition, considerations are made with regard to the computation of the probabilities of these impact sets.

1 Introduction

It was observed in the review of the state-of-the-art of existing qualitative EC impact analysis methods that none of the methods have specific capabilities that support the discrimination of concept alternatives in order to help the decision-maker to identify feasible solutions. However, two publications have been identified that support the discrimination of design concepts. Bryant et al. (2005) developed an algorithm for the generation of concepts during the conceptual design phase. This algorithm generates all possible component combinations for a selected sequence (‘chain’) of functions that are required by a new product. Therefore a matrix is used which maps functions to components. Subsequently, combinations which are not compatible with product dependency models of existing products are eliminated. As a result, a list of viable components sets is obtained. The method was demonstrated with a small case study of a box-labelling device. Also Ulrich and Eppinger (2000) describe an approach to generate concepts based on combinations that can be used during the initial stages of a product development process. This approach also involves the mapping of required functions to possible components. Plausible concepts are subsequently selected using concept screening and concept scoring matrices.

In this research, the Impact Sets Analysis algorithm has been developed to support the decision-maker with the selection of a feasible solution for the required EC which is also based on the generation of concept alternatives through combinations. This algorithm analyses the result of the CPA algorithm (Chapter IV) to identify possible groups of affected items which are referred as ‘impact sets’. The conjecture is that these ‘impact sets’ can help the decision-maker, in addition to the CPA results, with the discrimination of concept alternatives in order find a feasible solution.

2 ISA algorithm

2.1 Impact sets generation

The impact sets generation begins with the propagation tree produced by the CPA. Initially, the impacts at the first propagation level are identified. Additionally, for each of the impacts it is determined if the impact is definite (Probability = 100%) or probable (0% < Probability < 100%). In case of a DPA, only one dependency can exist between the initiating change and each impact and hence the probability factor associated with the dependency will indicate directly if the impact is definite or not. However, there could be multiple valid dependencies between the initiating change and each impact in case of a SPA or a TPA. In those cases, the maximum probability of all valid dependencies will determine if the probability of the impact is definite or probable. The next step generates all combinations for all subset sizes for the probable impacts, including the combination with subset size ‘0’ or no impacts. The impact sets at the first level are then made up by adding the definite impacts to each combination. The number of impact sets that are consequently obtained, can be calculated with Equation V-1.

$$C = \sum_{k=0}^{n} \frac{n!}{k!(n-k)!}$$

Equation V-1: Calculation of number of combination of all subset sizes

Where:

C: Number of combinations
n: Number of impacts or changes
k: Subset size

Subsequently, the procedure is repeated for each identified impact set for the next propagation step. However, as impact sets can be composed of multiple impacts or changes, the impacts that are identified at the next propagation are based on all the changes in the considered impact set. The procedure continues by identifying the maximum probabilities of all the impacts and generating all the combinations of all the probable impacts. Again, the definite impacts are added to each combination but now also the current impact set is added. The procedure continues for all propagation steps in a propagation tree from the CPA. The resulting impact sets are the ones obtained for the last step in each branch.

This procedure is illustrated for the results of a SPA as shown in Figure V-1.

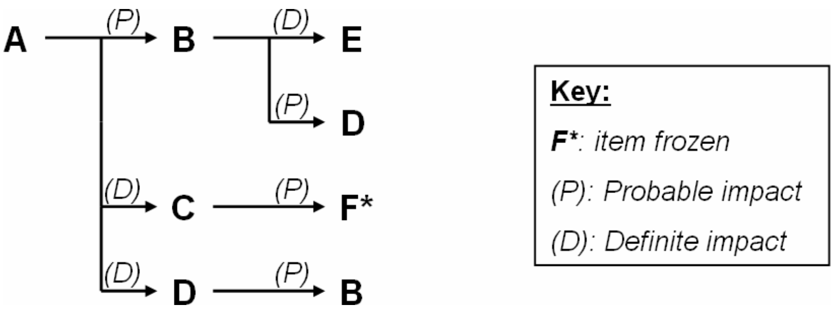


Figure V-1: Example of propagation tree from SPA

The resulting process to identify all impact sets is detailed as follows.

1. Prop. step 1: Identify impacts: ‘B’, ‘C’ and ‘D’
2. Prop. step 1: Identify definite impacts: ‘C’ and ‘D’
3. Prop. step 1: Generate combinations for probable impacts (‘B’):
    a. ‘none’
    b. ‘B’
4. Prop. step 1: Impact sets:
    a. (1) ‘C, D’
    b. (2) ‘C, D, B’
5. Prop. step 2: Select first impact set (‘C, D’)
6. Prop. step 2: Identify impacts: ‘F’, ‘B’
7. Prop. step 2: Identify definite impacts: none
8. Prop. step 2: Generate combinations for probable impacts (‘F’, ‘B’):
    a. None
    b. ‘F’
    c. ‘B’
    d. ‘F, B’
9. Prop. step 2: Impact sets:
    a. (1.1) ‘C, D’
    b. (1.2) ‘C, D, F’
    c. (1.3) ‘C, D, B’
    d. (1.4) ‘C, D, F, B’
10. Prop. step 2: Select next impact set (‘C, D, B’)
11. Prop. step 2: Identify impacts: ‘E’, ‘D’, ‘F’, ‘B’
12. Prop. step 2: Identify definite impacts: ‘E’
13. Prop. step 2: Generate combinations for probable impacts (‘D’, ‘F’, ‘B’)
    a. None
    b. ‘D’
    c. ‘F’
    d. ‘B’
    e. ‘D, F’
    f. ‘D, B’
    g. ‘F, B’
    h. ‘D, F, B’
14. Prop. step 2: Impact sets:
    a. (2.1) ‘C, D, B, E’
    b. (2.2) ‘C, D, B, E, D’
    c. (2.3) ‘C, D, B, E, F’
    d. (2.4) ‘C, D, B, E, B’
    e. (2.5) ‘C, D, B, E, D, F’
    f. (2.6) ‘C, D, B, E, D, B’
    g. (2.7) ‘C, D, B, E, F, B’
    h. (2.8) ‘C, D, B, E, D, F, B’

As a result all identified impact sets are:

- (1.1) ‘C, D’
- (1.2) ‘C, D, F’
- (1.3) ‘C, D, B’
- (1.4) ‘C, D, F, B’
- (2.1) ‘C, D, B, E’
- (2.2) ‘C, D, B, E, D’
- (2.3) ‘C, D, B, E, F’
- (2.4) ‘C, D, B, E, B’
- (2.5) ‘C, D, B, E, D, F’

- (2.6) ‘C, D, B, E, D, B’
- (2.7) ‘C, D, B, E, F, B’
- (2.8) ‘C, D, B, E, D, F, B’

2.2 *Impact set filtering*

In order for the impact sets to support the identification of feasible solution concepts, no impact sets should include frozen items. Therefore, all the generated impact sets are analysed and any impact sets which includes one or more frozen items are removed.

In addition, all duplicate impacts for each impact set is removed. Duplicate impacts are the same items affected with the same ToC. However no distinction is made between impacts which have different affected LoCs. The reason is that it would not be meaningful to have a combination of impacts with the same items and ToCs but different LoCs. For example, if the ToC ‘X’ of item ‘A’ is affected with a ‘High’ LoC through one propagation path and a ‘Low’ LoC through another propagation path, a combination with where the ToC ‘X’ of the item ‘A’ is impacted with ‘High’ as well as ‘Low’ LoC at the same time cannot exist. Hence the LoCs are ignored when duplicate impacts are removed from each impact sets.

Finally, the remaining impact sets are analysed again in order to remove all duplicate impact sets. As a result, only unique impact sets with distinct impacts are kept.

The procedure in this section is further illustrated with example shown in Figure V-1.

15. ‘F’ frozen → remove impact sets: (1.2), (1.4), (2.3), (2.5), (2.7), (2.8)
16. Remove duplicate impacts from each impact set
    a. (2.2) ‘C, D, B, E, D’ → ‘C, D, B, E’
    b. (2.4) ‘C, D, B, E, B’ → ‘C, D, B, E’
    c. (2.6) ‘C, D, B, E, D, B’ → ‘C, D, B, E’
17. Remove duplicate impact sets → (2.2), (2.4), (2.6)

As a result, the remaining possible impact sets are:

a. (1.1) ‘C, D’
b. (1.3) ‘C, D, B’
c. (2.1) ‘C, D, B, E’

This contrasts with the five different possible impacts (‘C’, ‘D’, ‘B’, ‘E’ and ‘F’) that where identified in the propagation tree. If these impacts where completely independent and not frozen, then the theoretical number of combination would be 32 which can be calculated with Equation V-1. However, the Impact Sets Analysis reduced these combinations to just 3 possible impact sets.

2.3 Impact sets analysis algorithm

A flowchart that represents the implemented algorithm of the impact sets analysis is depicted in Figure V-2. The sections that perform the impact sets generation and impact sets filtering are highlighted.

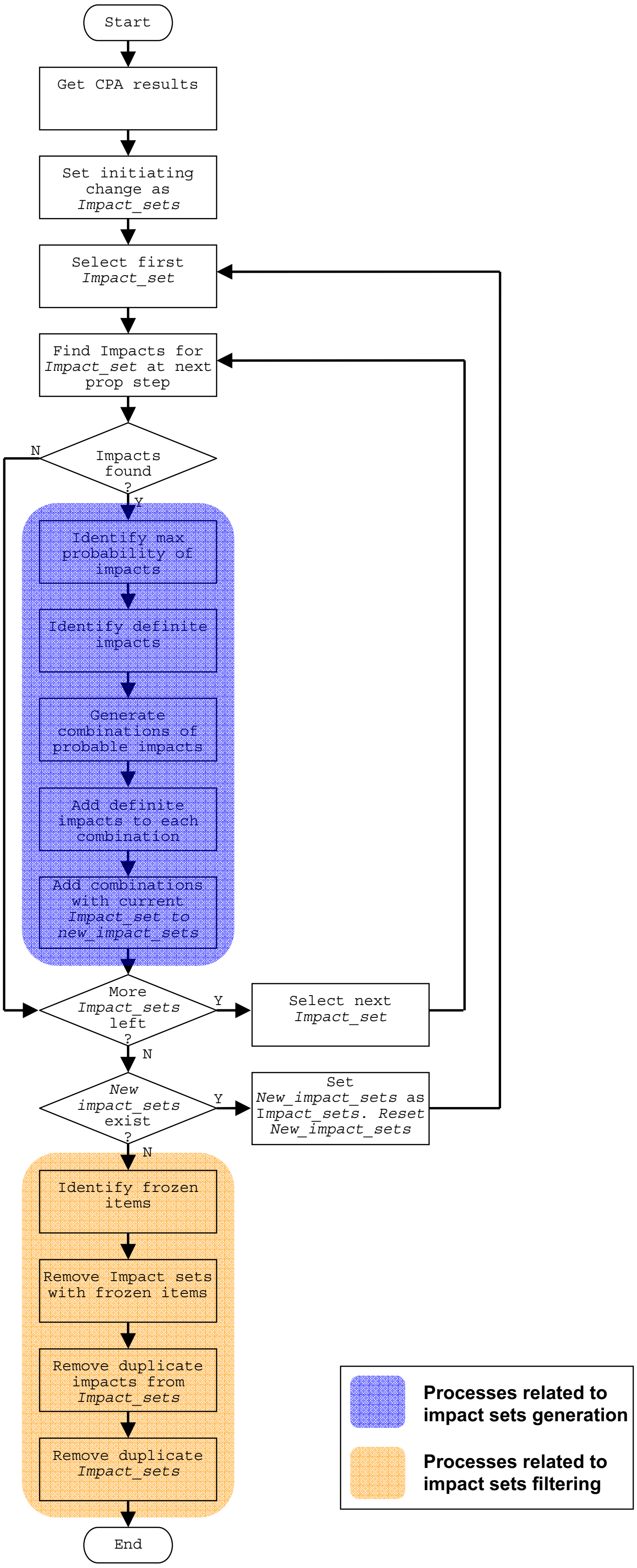


Figure V-2: Flowchart of Impact Sets identification algorithm

3 An investigation into the computation of the impact sets probabilities

3.1 Introduction

A computation of the impact sets probabilities could be envisaged as these may be of interest to the decision-maker in order to discriminate the impact sets. Despite being beyond the scope of this research, an investigation into the computation of the impact sets probabilities has been undertaken. In order to obtain the probabilities of the impact sets, the combined probabilities of occurrence of the individual impacts are required. Previous research, reported in section 5.2 of Chapter II, has proposed two methods for the computation of these combined probabilities. The first method (Clarkson et al., 2001) computes analytically the probabilities of each propagation path with a predefined maximum length. In related research (Jarratt et al., 2002a), a Monte Carlo simulation is used which was found to be more computational efficient for similar levels of accuracy.

The following investigation considers first the applicability of the published methods with respect to the proposed dependency model and the CPA. Second, the calculation of the impact sets based the combined probabilities of the individual impacts is described. Finally, a scheme is proposed for the integration of the CPA, the ISA and a method to compute the combined probabilities of the individual impacts. In addition, a manual example is presented in section 3.6 of Chapter VI as part of the evaluation of the impact sets.

3.2 Considerations with respect to dependency model and CPA

Three considerations have to be made with respect to the previous research on the computation of the combined probability of the individual impacts.

First, the analytical method to compute the probabilities of each of the propagation paths is not valid anymore as these paths may no longer be sequential due to the inclusion of combinatorial dependencies. However, the use of these dependencies poses no additional problems for the Monte Carlo based method.

The second consideration concerns the identification of the propagation paths with the CPA algorithm. However, this algorithm terminates the propagation paths when a repeated impact is identified regardless of the propagation path of the initial impact in order to support an effective visualisation of the impacts. Consequently, the CPA algorithm does not identify all possible propagation paths to every affected item. An example is depicted in Figure V-3. In this example, the CPA algorithm ends the propagation for ‘B’ at the second propagation step because ‘B’ has been impacted before at the first propagation step. The only propagation path identified from ‘A’ to ‘D’ is ‘A’→’B’→’D’. However, ‘D’ can also be affected through the path ‘A’→’C’→’B’→’D’. Consequently, no the loop detection can be used for the identification of the combined impact probabilities.

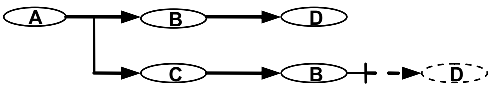
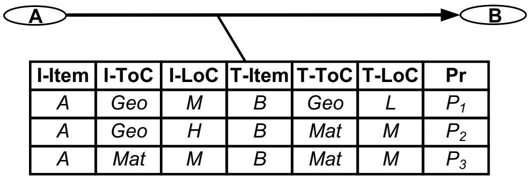


Figure V-3: Propagation paths with loop detection

Finally, multiple dependencies can be valid between an initiating change and a target change for a Simple or ‘ToC-only’ Propagation analysis, therefore the probabilities of all these valid dependencies need to be combined or aggregated. Figure V-4 shows an example of an initiating item ‘A’ and target item ‘B’ with three dependencies from ‘A’ to ‘B’.



I-Item	I-ToC	I-LoC	T-Item	T-ToC	T-LoC	Pr
A	Geo	M	B	Geo	L	P_1
A	Geo	H	B	Mat	M	P_2
A	Mat	M	B	Mat	M	P_3

Figure V-4: Example of multiple dependencies

The aggregated dependency probability from 'A' to 'B' can be subsequently calculated with Equation V-2.

$$P_{agg}(B \mid A) = 1 - \overline{P}_1 \times \overline{P}_2 \times \overline{P}_3$$

Where:

$$\overline{P}_i = 1 - P_i$$

Equation V-2: Aggregated dependency probability of 'A' affecting 'B' directly

These aggregated dependency probabilities differ from the previous discussed combined probabilities as the latter combine the probabilities of all propagation paths between an initiating change and a target change while aggregated dependency probabilities combined the direct valid dependencies between an initiating change and a target change.

3.3 Calculation of impact sets probabilities

Once the combined probabilities of each of the impacts are obtained, the calculation of the probabilities of each of the impact sets is straight forward. The probability of an impact set is the multiplication of the probability (P_i) of each of the impacts in the impact set together with the inverted probabilities ($\overline{P}_i$) of the impacts which are not included in the considered impact set. Equation V-3 is an example for an impact set 'B, C' of a dependency model with items 'A', 'B', 'C', 'D' and 'E' and with initiating item 'A'.

$$P(BC) = P_c(B) \times P_c(C) \times \overline{P}_c(D) \times \overline{P}_c(E)$$

Equation V-3: Example of calculation of Impact Set probability

Where:

$P(BC)$: Probability of impact set 'B, C'
$P_c(B)$: Combined probability of impact 'B'
$P_c(C)$: Combined probability of impact 'C'
$P_c(D)$: Combined probability of impact 'D'
$P_c(E)$: Combined probability of impact 'E'

The summation of the probabilities of all the impact sets equate to 1 because the initiating change will always result in one impact set. Note also that an empty impact set can exist for the case where the initiating change does not impact anything.

3.4 Proposed integration scheme

An integration scheme is proposed in Figure V-5 of the required analyses to compute the impact sets probabilities. In this scheme, the CPA algorithm produces the EC impacts which are used by the ISA algorithm to identify the possible impact sets.

In addition, the computation of the combined probabilities of the individual impacts is required, taking into account the considerations discussion in section 3.2. Finally, these combined probabilities can then be used to compute the probabilities of the impact sets.

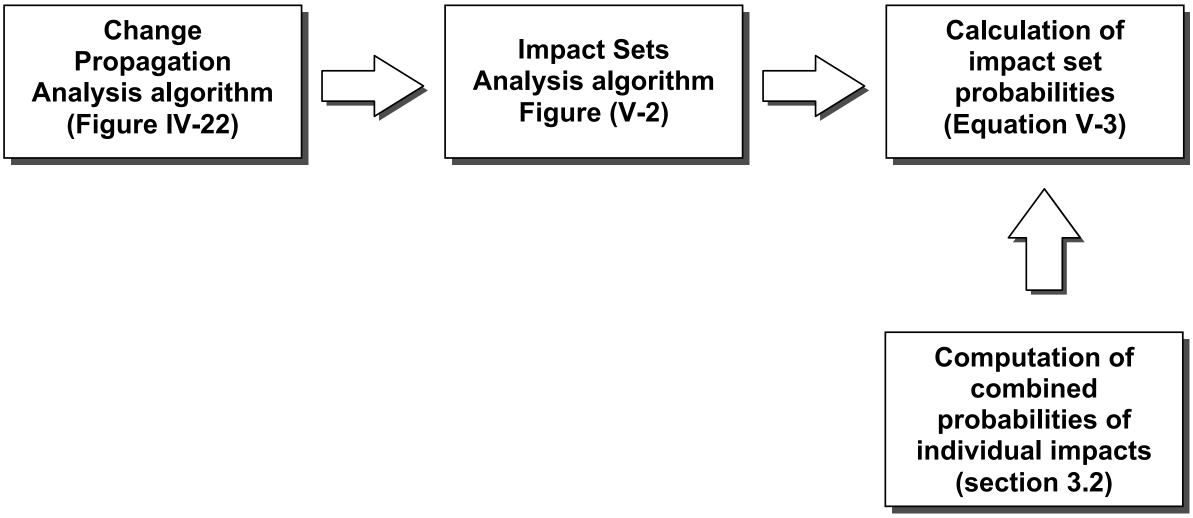


Figure V-5: Proposed integration scheme for calculating impact sets probabilities

4 Summary

This chapter introduced a new algorithm to analyse the results from the CPA algorithm discussed in the Chapter IV in order to support the decision-maker with the discrimination of concept alternatives. This algorithm generates first combinations of the impacted items and their affected ToCs by taking into account the probability of the dependencies and subsequently removes duplicate combinations and combinations with frozen items. The last part of this chapter discusses the considerations that need to be made in order to compute the probabilities of the impact sets.

CHAPTER VI:
Evaluation and Discussion

In this chapter, the methodology presented in Chapters III, IV and V is evaluated and discussed in order to establish the degree of fulfilment of the research objectives. Therefore an evaluation methodology has been introduced. This methodology included a demonstration of the proposed methodology with a case study together with an assessment of the capabilities by academic and industry experts.

1 Evaluation methodology

1.1 Evaluation process

To evaluate the proposed methodology, a case study is created and a set of required capabilities is derived from the research objectives. Subsequently, the level of achievement of these capabilities is demonstrated, evaluated and discussed with the case study. The level of achievement of these capabilities is then used as an indicator for the degree of fulfilment of the research objectives. Additionally, the demonstration and evaluation of the proposed methodology have been presented to external review panels of industry experts and discussed with them. The feedback from these discussions is reported. The case study itself has also been evaluated and discussed with external review panels. The overall evaluation process is depicted in Figure VI-1.

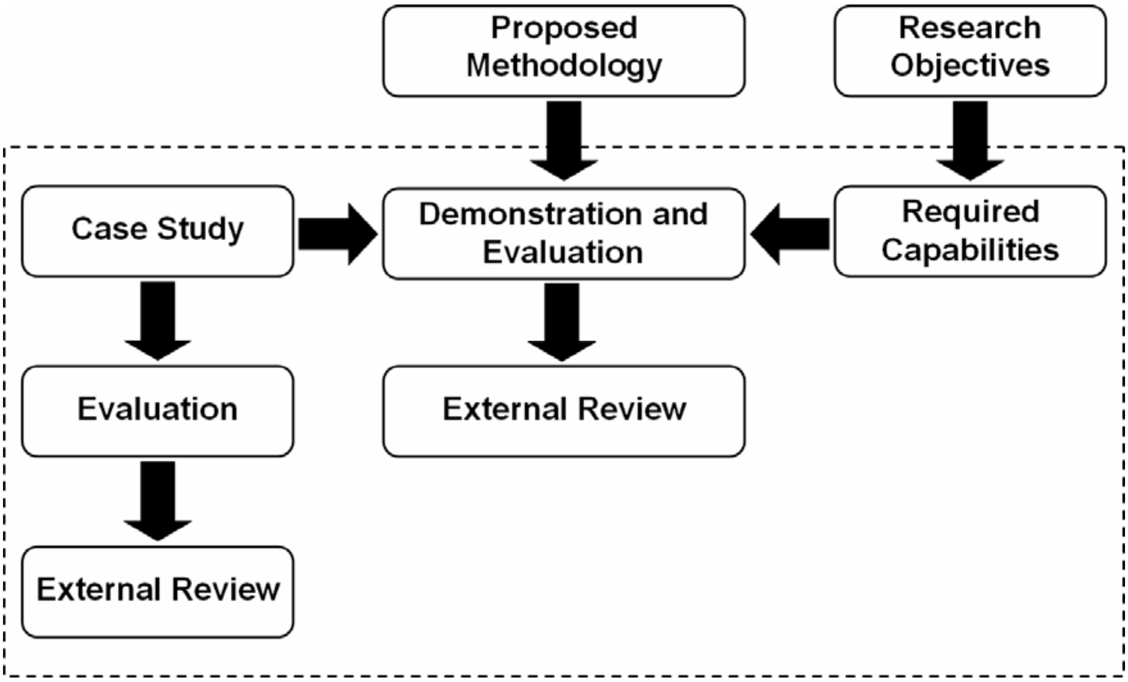


Figure VI-1: Evaluation process

1.2 Case Study purpose and scope

As already discussed in the introduction chapter, the industry Use Cases were kept strictly confidential with only some metrics been published (Rutka et al., 2006). Therefore, a separate case study was developed with the specific purpose to demonstrate the required capabilities in an industrial-like context and consequently facilitate the assessment of their level of achievement. The case study should therefore be representative of a realistic industrial application which means that it should be comparable in size and level of granularity and uses similar types and levels of change.

However, it was beyond the scope of the case study to create a complete dependency model which could be used in future to investigate all possible design changes because the elicitation process was constrained by the available resources in terms of time and man hours. Furthermore, the elicitation process was limited by available design data and knowledge of the author. In order to validate that the case study was sufficiently representative of an industrial application and complete enough to demonstrate the required capabilities, additional external reviews with relevant design experts and industrial partners were carried out.

1.3 Required capabilities

Six core capabilities have been identified as relevant to the proposed methodology based on requirements from industry (Rivière, 2004; Rutka, 2004; Coleman et al., 2005). These are considered to be relevant because these relate directly to the 3 research objectives of this thesis. These six capabilities are formulated as following:

Support is required for the:

1. Application on an industrial scale: It is self-evident that any methodology needs to be sufficiently scalable in order to be used for industrial applications. Therefore, the scalability will be evaluated in terms of all research objectives.

2. Elicitation of dependencies over product life cycle: A methodology for eliciting relational knowledge needs to be applicable throughout the product life cycle and should have the ability to consider the life cycle phases.

3. Identification of the possible extent of an EC impact: A methodology should analyse the possible expected change propagation behaviours and consequently identify the possible extent of the impact of an EC.

4. Effective visualisation of propagation paths: A methodology for EC impact analysis needs to support an effective visualisation of all relevant propagation paths.

5. Organising inter-domain propagation: A methodology for EC impact analysis needs to support the propagation between the relevant domains effectively.

6. Discrimination of concept alternatives: A methodology should support the decision-maker with the identification of possible concept alternatives.

As stated above, the purpose is that the level of achievement of these capabilities will indicate the degree of fulfilment of the research objectives proposed in the introduction of this thesis. Table VI-1 maps the required capabilities onto the defined research objectives.

	Research Objective 1: *Development of meta-model to capture interdependencies within a complex product*	**Research Objective 2:** *Development of an algorithm to trace the propagation of ECs and identify the potential extent of their impact*	**Research Objective 3:** *Development of a method to identify possible impact sets*
Capability 1	**X**	**X**	**X**
Capability 2	**X**		
Capability 3		**X**	
Capability 4		**X**	
Capability 5		**X**	
Capability 6			**X**

Table VI-1: Capabilities vs research objectives

1.4 External reviews

The final and probably the most important part of the evaluation methodology are the discussions of the presented methodology with panels of people from relevant fields of expertise. This approach is referred to in qualitative research as focus group studies (Edmunds, 1999). It brings together a small group of relevant people for a face-to-face in-depth discussion on a specific subject. These discussions have a moderator who will structure and guide the discussion to achieve the objectives of the study. Typically, focus group studies are conducted to review new ideas, new concepts or new products. It is a qualitative research approach hence it does not result in percentages or other statistical information, but the results are rather more exploratory. This is at the same time the main limitation of focus group studies. As the outcomes are not quantifiable results, these outcomes can be open to interpretation and may not lead to a clear conclusion on the reviewed subject. The benefits of conducting these studies are that they can capture subjective comments and can "*provide a better understanding of perceptions, feelings, attitudes*" (Edmunds, 1999) towards the discussed subject.

The external review sessions or focus group studies were considered to be suitable to evaluate the methodology because:

- these allow a detailed discussion of the proposed methodology
- the ability to capture and evaluate of specific comments on all aspects of the methodology
- the availability of qualified and interested people through the project partners

Consequently, the objectives of the external reviews were identified as the determination of:

- the level of demonstration of the capabilities
- the level of achievement of the capabilities
- the level of relevance of the capabilities and missing capabilities

Participants were recruited through industrial project partners. However, the partners with a direct involvement in the CIA task had only a limited participation in the evaluation. This ensured a better objectivity of the evaluation and focus on the proposed methodology.

The selection of the participants was based on their experience with:

- current EC processes
- knowledge-based systems
- design of complex products

The main moderator of the studies was the author of this thesis. Although this may be considered biased, it was the only practical solution as only the author was completely familiar with the proposed methodology. Three review sessions where organised to evaluate this methodology. The review sessions were organised at the premises of the industrial participants and began with presentation of the proposed methodology and the case study followed by the discussion of each of the capabilities. The participants of the first session included experts in design integration and engineering tools development. The second review session involved R&D engineers in system simulation and information technologies with their fields of expertise in complex product configuration management and engineering system definition. The last session was included by experts in requirements management, DMU integration, architectural modelling and system engineering.

Beside the sessions to evaluate the methodology, two more reviews were organised to specifically evaluate the case study as a realistic industrial application. The first session was with an aircraft design expert from Cranfield University to assess the level of completeness of the product design of the case study. At the second session, the case study was presented to some of the key industrial partners. These partners were familiar with the industrial Use Cases (UCs) and hence could assess best to which degree the case study was representative of an industrial application.

2 Case Study

2.1 E-5 concept

The case study is based of the detailed design of a supersonic business jet (SSBJ), named E-5 Neutrino. The design of the E-5 was carried out as the Group Design Project 2005/2006 of 30 MSc Aerospace Vehicle Design students at Cranfield University. The preliminary and detailed design of the E-5 was completed over a period of 7 months. The scope of their efforts was broad and intended to provide a complete overview of the aircraft design process (Morency and Stocking, 2006).

The concept the SSBJ follows from observation that due to the retirement of the Concorde airliner in 2003, very fast intercontinental travel ceased to be available for the public. The SSBJ concept aims to fill this gap and expand access to supersonic travel in all corners of the globe. Specifically, the SSBJ concept should enable corporate executives, celebrities and VIPs to be carried anywhere in the world in half the time of current business jets and under a third of the time door to door. Therefore, significant technical challenges had to be overcome. A key to the success of the design is the reduction of the sonic boom characteristics to enable supersonic flight over land while attaining sufficient fuel efficiency to achieve transpacific flight ranges. At the same time, the SSBJ needs to provide all the luxury, looks and comfort that are expected of a small business jet. The E-5 Neutrino design can be considered as a first design iteration for the ambitious goal of the SSBJ concept. It has a kinked delta wing with canard layout configuration (Morency and Stocking, 2006). The surface model is shown in Figure VI-2.

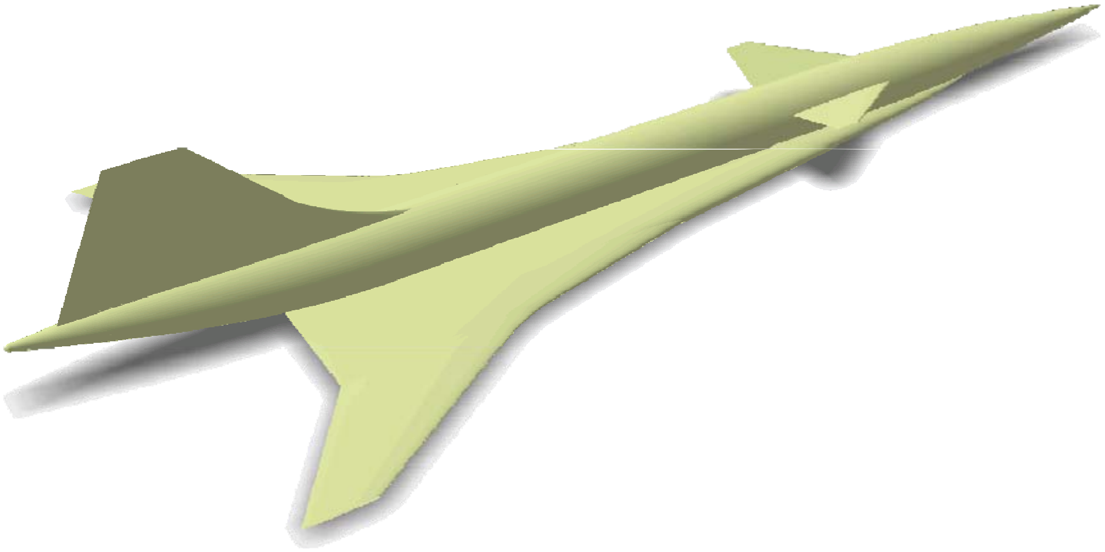


Figure VI-2: E-5 Neutrino (Morency and Stocking, 2006)

The design of the E-5 includes many novel technologies. One of these new technologies is the Hybrid Laminar Flow Control (HLFC) system. The main purpose of this system is to decrease the overall drag of the aircraft, resulting in a reduction of the direct operating costs. The HLFC system employs suction at the leading edges of the inner, outer wing and fin. Another novel technology which has been integrated is a synthetic vision in the cockpit. This means that there are no actually windows in the cockpit but the view from the front of the plane is displayed on screens.

The key design specifications of the E-5 Neutrino are listed below. A full detailed list of the E-5 design specification can be found in the "Design Specification" report (Smith, 2005).

Cruise Speed: 1.8 Mach

Design Mission

- Payload: 6 Passengers + 2 crew and baggage
- Range: 10556 (5700 nm)

Mass

- MTOW: 45454 kg (100209 lbs)
- Empty: 14380 kg (31702 lbs)
- Fuel: 30354 kg (66919 lbs)
- Payload: 720 kg (1587 lbs)

Principal Geometry

- Length: 43.6 m (143ft)
- Wingspan: 16 m (52.5ft)
- Height: 8.87 m (29 ft)
- Gross Wing Area: 175 m2 (1884 ft2)
- Max. Fuselage Diameter: 2.18m (7.15 ft)

2.2 Design Overview

2.2.1 E-5 Design preparation

Even though the design of the E-5 was performed as a group project, the design produced by the students was not always consistent. The main problems lay with the design and integration of the systems. These systems were often designed with different levels of detail and little attention had been paid to the integration in the final version of the design. Consequently, system designs often clashed with the structure and other systems. As a result, considerable time and effort has been spent remodelling some systems and structural components in order to obtain a consistent design. Most of the work was related the HLFC system. This included rerouting parts of the ducting and remodelling of the plenum chambers to fit with the leading edges of the wings. Other work included trimming and extending skin sections to cover the complete structure. Below are the different aircraft sections of the final E-5 design described in more detail.

2.2.2 Structure

The structure that was used for the final design of the E-5 (Figure VI-3) was based upon the metal version produced by the group design project. The structure was divided into fin, fuselage, port wing and starboard wing sections. The fin and wing sections included also the control surfaces. The fin section consisted only of 3 components. Firstly, the fin structure included the spars and ribs for the fin. The second component was the rudder which included the control surface, hinges and hydraulic actuators. The last component of the fin assembly was the skin together with the stringers as for all other skin elements. The second structural section was the fuselage which was divided into four subsections: forward fuselage (FF), centre fuselage (CF), after fuselage (AF) and canard. The first 3 fuselage sections consisted of their respective frames and skin with stringer sections. These were merged as one component each. Furthermore, the CF included the air pressure bulkheads and the AF included walls for the main landing gear (MLG) and a bracket to support the rudder. The canard was split up in its port and starboard side which each included the foreplane and the actuator system. The fuselage contained 14 items in total. The starboard and port wing sections are symmetric and are each further divided into subsections: forward inner wing (FIW), after inner wing (AIW) and outer wing (OW). The FIW sections contain the ribs, spars and skin with stringers forward of the main landing gear (LG) front spar. This included also the complete porous leading edge of the inner wing. The OW sections consist of the wing structure outside the wing kink. Again this includes the ribs, spars, skin with stringers and the porous leading edge beyond the wing kink. Also the low speed or outboard ailerons and the high speed or inboard ailerons are part of the OW section. The remaining structure forms the AIW sections, i.e. the structure behind the front LG spar and inside the wing kink although the kink rib and some of the other AIW ribs extend forward of the LG front spar. The flaps together with their mounts and actuator are also part of this section. As a result, each wing was composed of 27 individual components.

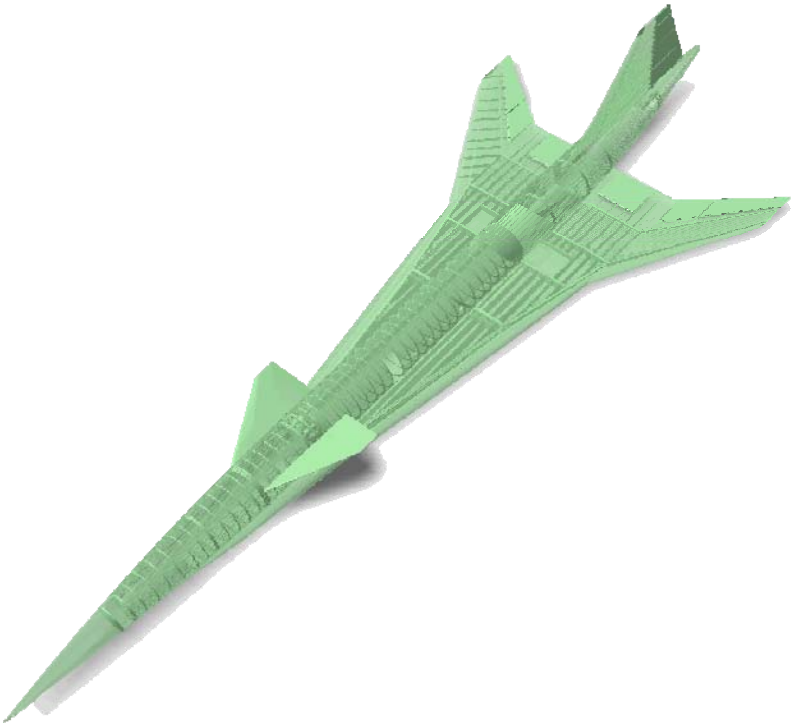


Figure VI-3: E-5 Structure

2.2.3 Systems

All major systems have been developed as part the group design project. However, the detailed geometric model of all the developed systems was not always created. Consequently, systems without a geometric model were not included and the geometric models of other systems were extended in order to include their major components. As a result, in the final design of the E-5 nine systems were included (Figure VI-4). The avionics system included mainly sensors, e.g. radar and GPS, but also the HLFC computer. In total 6 components are distributed around the plane, however wiring has not been included. Another system is the cockpit which consists of 10 parts. Particular about the cockpit is that it does not have any windows but uses as synthetic vision. The cockpit is located forward of the cabin and behind the avionics bay in the centre fuselage. The cabin itself was also included as a separate system with a total of 9 items. The major components that were modelled were the interior shell, partitions, toilet, galleys and emergency hatch. The entry door was not modelled. The environmental control system (ECS) was represented by 2 cold air units and 2 compressor units.

The fuel system was one of the systems that were modelled most extensively with 17 components. It consists of 12 fuel tanks together with elaborate transfer, feed, vent and jettison subsystems. However, the hybrid laminar flow control (HLFC) system was the largest system modelled. It contains no less than 34 components and consists of 7 almost separate suction subsystems. One suction subsystems draws air from the leading edge of the fin and 3 suction subsystems deal each with the leading edges of one wing. For each wing, one subsystem draws air from the outer wing leading edge while leading edges of the inner wings are divided in two parts with a suction system each. Each suction subsystems has therefore its own pump and electrical motor. Furthermore, it includes ducting which leads the air from the plenum chamber to the pump. The plenum chambers distribute the negative air pressure evenly over the porous leading edge section. The common parts of the HLFC system are the joint exhaust duct and the control computer.

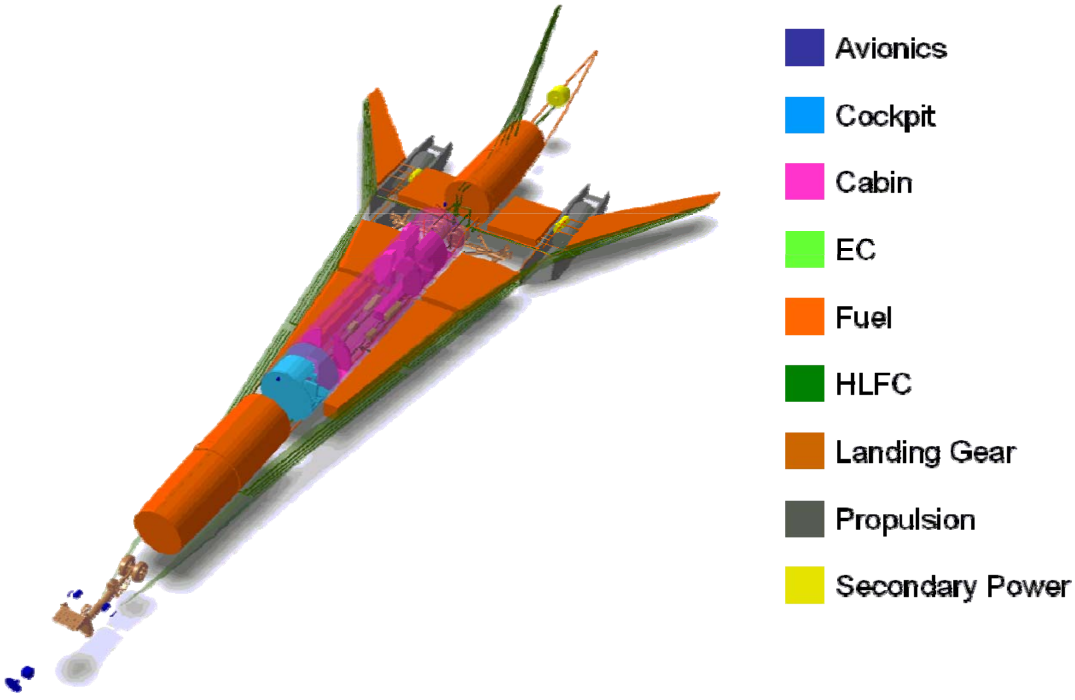


Figure VI-4: E-5 Systems

Another system is the landing gear. This system consists of the nose landing gear and the starboard and port landing gear. Hence, just 3 parts were modelled for the landing gear system. The propulsion system contains both engines and their nacelles, i.e. 4 parts. The final system that was included was the secondary power (SP) system. This included two generators attached to each of the engines with a gearbox. Also an auxiliary power unit (APU) was modelled but no electrical wiring has been included. As a result, 5 items were included in the secondary power system.

2.3 Dependency model

2.3.1 Physical architecture

The author has created a dependency model for the E-5 aircraft which includes a 'physical architecture' domain comprised of all the 71 structural components and 92 system components, hence containing in total 163 items. Between the components in this domain, 1075 incremental relations and 240 combinatorial relations were modelled. These relations considered the following 6 types of change:

- **Power:** this type of change relates to components that produce or consume power in any form. For example, dependencies exist between the power of a HLFC pump and the HLFC motor that drives the pump. Also, a change to the power of a HLFC motor can have an impact on a generator from the secondary power system.
- **Size:** this relates to the dimensions of standard components. For example, the size of the HLFC ducting has a relation with the size of the plenum chambers. But also a change to the power of a HLFC pump could affect the size of the HLFC ducting and also the size of the HLFC pump itself.
- **Geometry:** this relates to the main dimensions and shape of the bespoke items such as structural components. An example is a change to the size of the fin HLFC ducting can impact the geometry of the fin skin. Furthermore, a dependency exists between the geometry of the fin skin and the geometry of the fin structure.
- **Positioning:** this relates to the location of components or equipment. An example is that a change in size the SFIW ducting can affect the location of the ECS cold air unit located underneath the cabin floor in the centre fuselage.

- **Interface:** this type of change is related to the geometry type of change. However, the interface ToC is used for a local change to the geometry of a component. For example, a change to the size of the ducting that runs through the forward fuselage bulkhead will cause a change to the interface of the bulkhead, but not a change to the overall geometry.
- **Software:** this is related to avionics equipment and particular to the HLFC computer in this case study. This ToC is illustrated with the dependencies between the size of the HLFC flow control valves and the software of the HLFC computer.

These relations considered the following three levels of change:

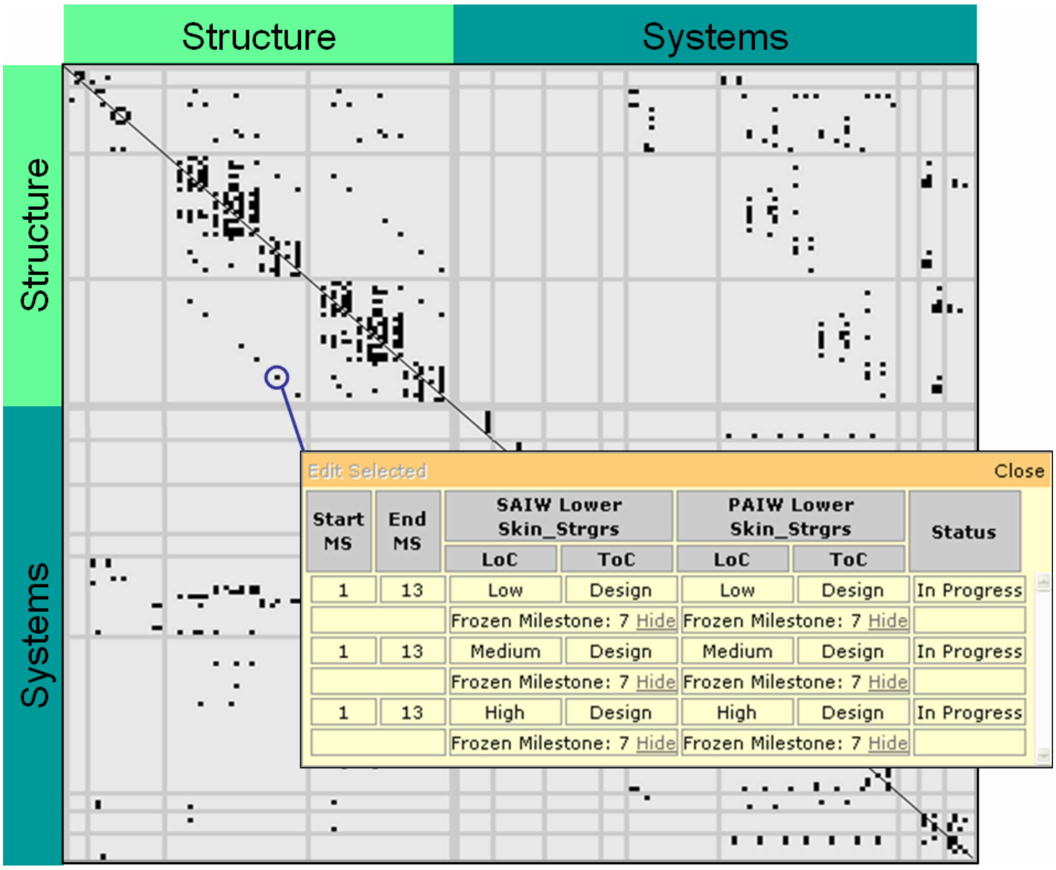
- **Low:** this level of change has been used to model changes that are small enough to be absorbed by design tolerances if there are any. For example, a low level of change to the power of the HFLC SAIW pump could cause a low level of change to the interface with the CF frames where it is mounted on. However, it will have no impact on the size of the communal HFLC exhaust duct.
- **Medium:** this level of change has been used to model changes that exceed any tolerances of the affected item. If there is a tolerance associated with the affected item, the target level of change can be ‘low’. For example, a medium level of change to the power of the HFLC SAIW pump could cause a medium level of change to the power of its motor and can cause a low level of change to the size of the communal HFLC exhaust duct.
- **High:** this level of change has also been used to model changes that exceed tolerances with the affected item, but target level of change will be medium. The target level of change can also be high for closely linked items and low if there is a weak direct impact. For example, a high level of change to the SFIW LG Front Spar will have medium level of impact to the structural elements it is attached to. However, a high level of change to the power of the HLFC SAIW motor can cause a high level of change to the size of the same motor because these are closely related. Additionally, the same initiating level of change can only have a low impact on the power the SP generator 1, since the motor is only one of many energy consumers that the generator supplies.

Consequently, in general, a low change will not affect anything new, while a medium level will affect its immediate components at low level which will not propagate. A high LoC of an item will at least cause a propagation of two steps. Of course, if this is potentially too restrictive for the considered change, a ToC-only propagation can be performed instead. In this case, always all items will be identified with the relevant types of change.

As illustrated above, the multiple dependencies between the same 2 items and dependencies between different ToCs of the same item are very useful. The latter have been used often to model the relation between the power and size of items. Multiple dependencies between the same two items have been used mostly to model relations for different initiating levels of change and target levels of change.

Regarding the combinatorial relations, the dependencies were used to model the combined effect of changes to the power of two or more HLFC motors on the SP generators 1 and 2. The incremental dependencies specified a low impact on the power of the generators for a high level of change to the power of a HLFC motor. While the combinatorial dependencies specified a medium impact on the power of the generators for a high level of change to the power of two or more HLFC motors. As a combinatorial dependency needs to be specified for each combination of initiating item for a specific target item, 120 combinatorial dependencies were required to model all the possible combinations for two or more HLFC motors to impact one of the two SP generators. Hence 240 combinatorial dependencies were required for impacts on both SP generators.

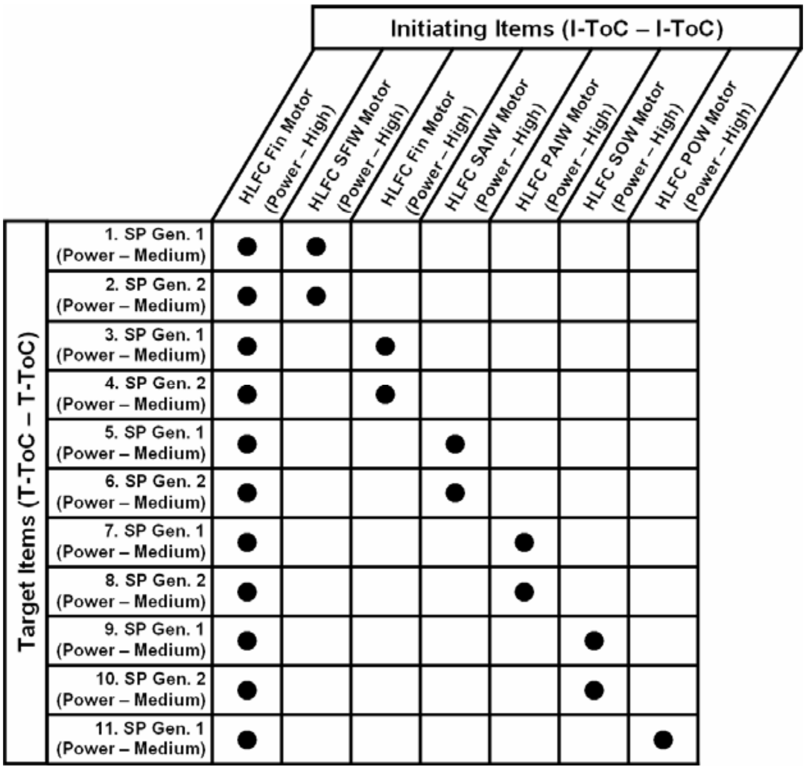
The product life cycle properties have been considered. All skins and spars have been frozen from milestone 7, while all the modelled dependencies in the physical architecture domain are valid from milestone 1 till milestone 13.



Start MS	End MS	SAIW Lower Skin_Strgrs		PAIW Lower Skin_Strgrs		Status
		LoC	ToC	LoC	ToC	
1	13	Low	Design	Low	Design	In Progress
		Frozen Milestone: 7 Hide		Frozen Milestone: 7 Hide		
1	13	Medium	Design	Medium	Design	In Progress
		Frozen Milestone: 7 Hide		Frozen Milestone: 7 Hide		
1	13	High	Design	High	Design	In Progress
		Frozen Milestone: 7 Hide		Frozen Milestone: 7 Hide		

Figure VI-5: Dependency DSM of E-5 physical architecture

Figure VI-5 shows a DSM with the dependencies in the physical architecture domain of the E-5 case study. A dot indicates that there exist one or more dependencies between the initiating items in the columns to a target item in the rows. The inset lists all the dependencies with its properties for a selected initiating and target item. Also the milestones from which the items are frozen are shown. In this DSM only the direct or incremental dependencies are shown. The combinatorial dependencies cannot be included in the representation. Figure VI-6 shows a matrix where examples of these dependencies are specified. In this matrix all the items in the columns that are marked need to be changed in order to trigger an impact on the item in the row.



	Initiating Items (I-ToC – I-ToC)						
Target Items (T-ToC – T-ToC)	HLFC Fin Motor (Power – High)	HLFC SFIW Motor (Power – High)	HLFC Fin Motor (Power – High)	HLFC SAIW Motor (Power – High)	HLFC PAIW Motor (Power – High)	HLFC SOW Motor (Power – High)	HLFC POW Motor (Power – High)
1. SP Gen. 1 (Power – Medium)	●	●					
2. SP Gen. 2 (Power – Medium)	●	●					
3. SP Gen. 1 (Power – Medium)	●		●				
4. SP Gen. 2 (Power – Medium)	●		●				
5. SP Gen. 1 (Power – Medium)	●			●			
6. SP Gen. 2 (Power – Medium)	●			●			
7. SP Gen. 1 (Power – Medium)	●				●		
8. SP Gen. 2 (Power – Medium)	●				●		
9. SP Gen. 1 (Power – Medium)	●					●	
10. SP Gen. 2 (Power – Medium)	●					●	
11. SP Gen. 1 (Power – Medium)	●						●

Figure VI-6: Matrix with combination dependencies

2.3.2 HLFC design process

Beside the physical architecture domain, 3 more domains where modelled in order to capture the HLFC design process as described by Young (2002) and adapted by Pearson (2006). The design process (Figure VI-7) consists of 7 of design activities, represented by boxes, and 10 design characteristics that link the design activities together. However, the 'range' is modelled as a requirement. 'Input' and 'output' are used as types of changes of the design activities. The ToC that was used for all the design characteristics is 'N/A'. Furthermore, no levels of change were considered hence these were all set to 'N/A' as well.

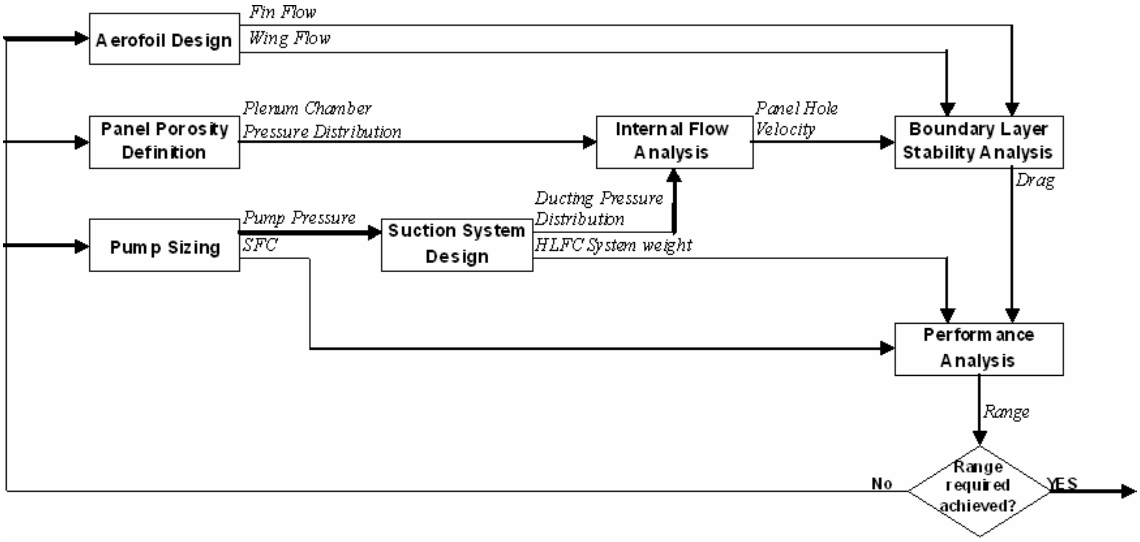
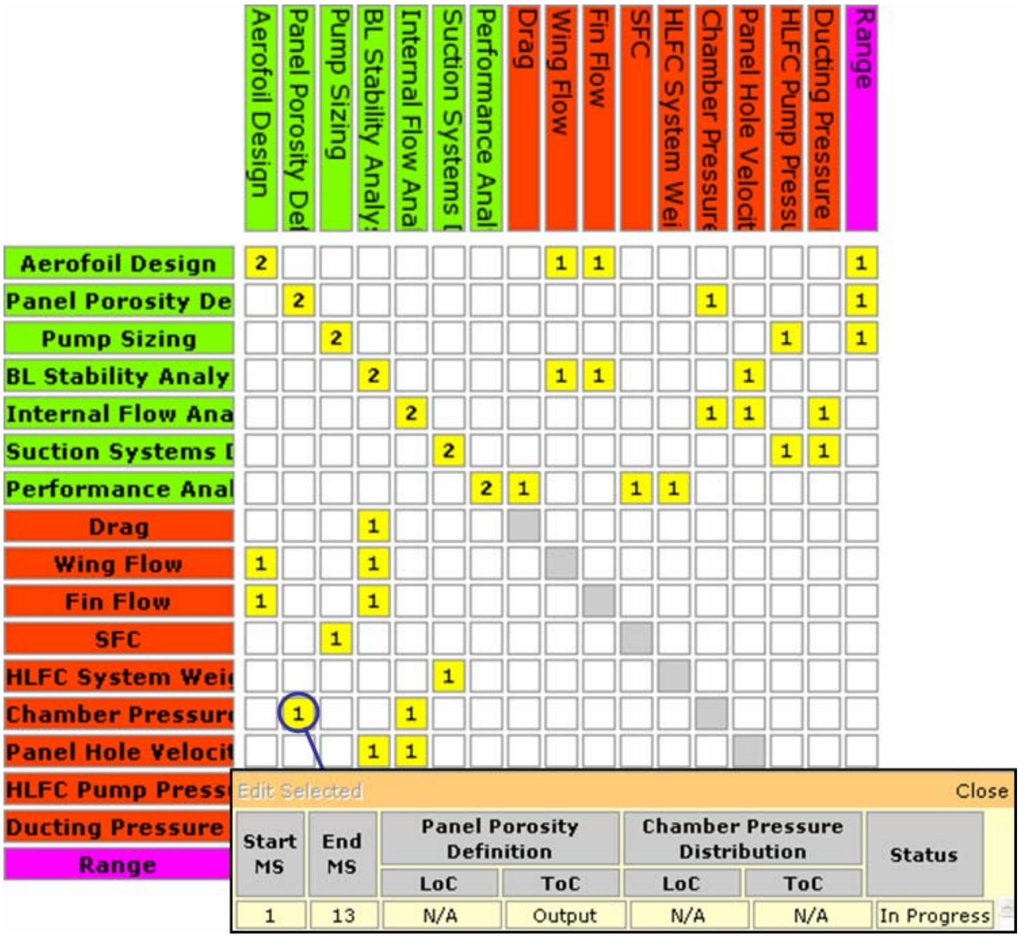


Figure VI-7: HLFC Design process (adapted from Pearson, 2006)



	Aerofoil Design	Panel Porosity Def	Pump Sizing	BL Stability Analy:	Internal Flow Ana	Suction Systems [	Performance Anal	Drag	Wing Flow	Fin Flow	SFC	HLFC System Wei	Chamber Pressure	Panel Hole Velocit	HLFC Pump Pressu	Ducting Pressure	Range
Aerofoil Design	2								1	1							1
Panel Porosity De		2											1				1
Pump Sizing			2												1		1
BL Stability Analy				2					1	1				1			
Internal Flow Ana					2								1	1		1	
Suction Systems [						2									1	1	
Performance Anal							2	1			1	1					
Drag				1													
Wing Flow	1			1													
Fin Flow	1			1													
SFC			1														
HLFC System Wei						1											
Chamber Pressur		1			1												
Panel Hole Velocit				1	1												
HLFC Pump Press																	
Ducting Pressure																	
Range																	

Start MS	End MS	Panel Porosity Definition		Chamber Pressure Distribution		Status
		LoC	ToC	LoC	ToC	
1	13	N/A	Output	N/A	N/A	In Progress

Figure VI-8: Dependency DSM of HLFC design process

In Figure VI-8, the 3 domains are shown together in a dependency DSM. The inset shows the definition of one specific dependency. Note that there are dependencies between the same design activities. These represent that the input (initiating ToC) affects the output (target ToC) of the same design activity. Furthermore, dependencies are modelled from design activities to design characteristics and requirements and vice versa.

2.3.3 Design team

One final domain was added to demonstrate the versatility of meta-model. This domain included 21 members of the design team. Each of them was responsible for a section of the structure or a system. Hence dependencies were modelled from every component in the physical architecture to a member of the design team. These dependencies initiated from any ToC and any LoC of the components to a target ‘N/A’ ToC and ‘N/A’ LoC in the design team domain. In one case, the HLFC computer had a dependency with the person responsible for the HLFC design and a second dependency with the person responsible for the avionics system. In this manner 164 dependencies were captured.

2.4 Evaluation

The dependency model for the physical architecture that was created did not consider all relations for the included items and types of change. It was populated to enable a number of detailed propagation analyses for different initiating conditions. The seven HLFC pumps were selected as possibly initiating items (I-items) and ‘Power’ as initiating ToC (I-ToC). Also all three levels of change (‘Low’, ‘Medium’ & ‘High’) were taken into account. Subsequently, the 1075 dependencies that were elicited enable the complete propagation analysis for these 21 initiating conditions[1]. In other words, the dependency model is complete for 21 different detailed propagation analyses with at least five propagation steps. Beyond the fifth propagation step, dependencies will be missing and consequently not all possibly impacted items will be identified.

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[1] 7 I-items x 1 ToC x 3 LoCs = 21 possible initiating conditions

The ‘ToC-only’ propagation analyses are also considered complete until a propagation depth of 5 steps because all dependencies have been modelled for all initiating LoCs. Simple propagation analyses with any of the 7 HFLC pumps as initiating items will result in near complete set of affected items as not all possible ToCs have been taken into account.

However, all 163 components in the physical architecture domain have dependencies associated for which they are target items. Thus, all components can be impacted by other components. On the other hand, 56 components have no dependencies associated for which they are initiating items. Thus the total dependency model can be considered as approximately 65% complete. However all dependencies are captured for the 21 detailed propagation analyses and 7 ‘ToC-only’ analysis for a maximum of 5 propagation steps and with initiating conditions as described earlier.

2.5 External review

The purpose of this section is to validate the E-5 case study as a realistic representation of an industrial application. Therefore the completeness of the design is evaluated and discussed with a systems design expert from Cranfield University. Secondly, the E-5 design and its dependency model were presented and discussed with the industrial partners that are familiar with the industrial use cases.

2.5.1 Evaluation with aircraft design expert

As described above, the structure of the E-5 is represented by 71 components plus 92 components of the 9 systems. This design was reviewed by a systems design expert in Cranfield University who was familiar with the E-5 Neutrino design project. Based on the discussion, the structural design was considered to be complete for the level of granularity that was used. The modelled systems on the other hand were not complete. Major components that are missing in the modelled systems are:

- **Avionics:** flight control system, flight management system, navigation system, communication system
- **Cabin:** windows, entry door, seats, in-flight entertainment systems

- **Cockpit:** pilot helmets, synthetic vision displays
- **ECS:** electrical motors, ducting, sensors, valves, control computer
- **Fuel:** control computer
- **HFLC:** pressure release valves,
- **Landing gear:** LG doors, shock absorbers, tires, sensors
- **Propulsion:** engine mountings, fire walls, fire extinguishers, fire detection sensors
- **Secondary power:** batteries, ram air turbine, control unit, primary distribution system, secondary distribution system, signal cables, power cables (AC / DC)

It was also observed that more conventional aircraft would include pneumatic and hydraulic systems, but these were replaced by electrical systems in the E-5 design. Furthermore, not all types of change have been considered. The following ToCs have been identified for consideration if the E-5 dependency model:

- Temperature
- EM characteristics
- Material
- Conductivity

It was concluded that an additional 50 components and 4 ToCs would need to be added in order to complete the E-5 design with the same level of granularity. Consequently, a dependency model of the complete E-5 design would include then around 210 components in the physical architecture and 10 different types of change.

2.5.2 Evaluation with industrial partners

The E-5 Neutrino case study was presented to the industrial partners which were involved in the elicitation of the dependencies models for the industrial UCs. The meeting participants included the CIA task leader who is also responsible for the industrial UCs and the person leading the interview sessions with the experts to capture the relational knowledge. Furthermore, R&D engineers from other industrial partners who are also familiar with the UCs[2] were present.

It was commented that the number of items in the physical architecture of the E-5 is similar to the number of items in the industrial UCs. However, these UCs only consider section of aircraft (nose, pylon, wing) compared to E-5 case which covers a complete aircraft. On the other hand, the E-5 case study does not include all systems and the included systems are not complete. Hence we can conclude that the model size is broadly comparable to the industrial models, however their level of granularity is relatively higher. Also the ToCs that have been used in the E-5 model are similar to the ToCs used in the industrial UCs. Again in the latter, many more ToCs have been included, for example, up to 50 ToCs in the cockpit UC. From the discussions was concluded that not only did they consider additional ToCs, but also their ToCs are more specific. For example the distinction would be made between 'size increase' and 'size decrease' as separate ToCs. Regarding the LoCs, both in the E-5 model and the UCs, 'Low', 'Medium', 'High' and 'Any' have been used. Furthermore, the industrial UCs focus mainly on the physical architecture domain. However, additional domains have been considered for the wing UCs such as 'design features' and 'disciplines'. The first is similar to the 'design characteristics' domain in the E-5 model while the latter refers to relevant fields of expertise that exist in the organisation. It was concluded that the E-5 case study is similar in size and granularity of current and envisaged industrial applications. Furthermore, the types and level of changes that have been used are equivalent to the ones considered in the industrial use cases. The CIA-task leader commented that the E-5 case study was "close to reality".

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[2] There are four industrial UCs: UC1 models the nose with cockpit structure and systems installation architecture. The wing and landing gear design and integrated development programme analysis are modelled in UC2 while wing concepts analyses considering 3 different aircraft configurations are included in UC3. The engine pylon design architecture behaviour is covered by UC4. Preliminary metrics of these UCs have been published (Rutka et al., 2005). However, the dependencies models where not complete when these numbers were published.

2.5.3 Conclusion

It is concluded that despite the omissions in the dependency model of the case study, this is sufficiently representative of an industrial application to demonstrate and evaluation the proposed methodology and assess its capabilities.

3 Demonstration and evaluation of capabilities

3.1 Application on an industrial scale

The first capability relates to the scalability of the proposed methodology. This means that the methodology should be able to be used with different model sizes suitable for industrial applications. The main metric to evaluate the scalability is the time needed to elicit the dependency models. This duration depends heavily on the number of possible dependencies that need to be considered during the elicitation process. This number of dependencies or combinations increases rapidly with higher number of items, ToCs and LoCs. The number of combinations is expressed in Equation VI-1 for an inter-domain dependency model.

$$C = N_{I(ID)} N_{T(ID)} N_{L(ID)} \left(N_{I(TD)} . N_{T(TD)} - 1 \right)$$

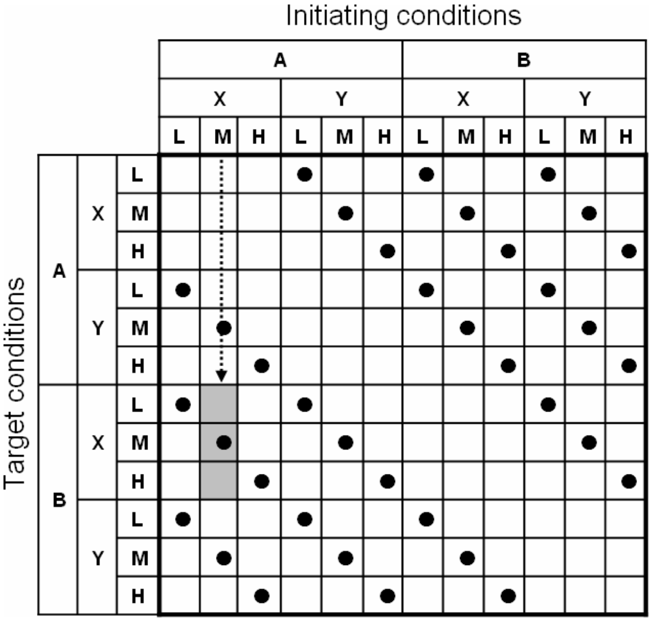
Equation VI-1: Number of combination for dependencies

where:

C: Number of combination or possible dependencies
$N_{I(ID)}$: Number of items in initiating domain
$N_{T(ID)}$: Number of ToCs in initiating domain
$N_{L(ID)}$: Number of LoCs in initiating domain
$N_{I(TD)}$: Number of items in target domain
$N_{T(TD)}$: Number of ToCs in target domain

In case of a single domain dependency model, the initiating domain is the same as the target domain hence $N_{I(ID)} = N_{I(TD)}$ and $N_{T(ID)} = N_{T(TD)}$. Subsequent discussion focussed on a single domain dependency model. However, it is equally valid for inter-domain dependency models.

Equation VI-1 takes into account that the dependencies can be defined between different ToCs of the same item. Furthermore, it is only meaningful that for every initiating item, ToC and LoC combination, just one target LoCs can be impacted for each target ToC and target item. This is illustrated in Figure VI-9 with the dependency DSM with items 'A' & 'B', ToCs 'X' & 'Y' and LoCs 'L', 'M' & 'H'. Here, initiating item 'A' with initiating ToC 'X' and initiating LoC 'M' can only impact one LoC (e.g. 'M') for the target item 'B' and target ToC 'X'. Hence, this is only considered as one possible dependency or combination in Equation VI-1.



			A						B					
			X			Y			X			Y		
			L	M	H	L	M	H	L	M	H	L	M	H
A	X	L				●			●			●		
		M					●			●			●	
		H						●			●			●
	Y	L	●						●			●		
		M		●						●			●	
		H			●						●			●
B	X	L	●			●						●		
		M		●			●						●	
		H			●			●						●
	Y	L	●			●			●					
		M		●			●			●				
		H			●			●			●			

Figure VI-9: Dependency DSM with possible dependencies

This means that for the physical architecture domain of the E-5 case study with 163 items, 6 ToCs and 3 LoCs, almost 2.9 million combinations or possible dependencies exist. The total time to create the E-5 dependency model is estimated as 50 hours although this is closely related to the efficiency of the interface of a software implementation and the experience of the user in creating the dependency models. Hence, the time could be considerably lower in an operational environment. However, the dependency model of the E-5 physical architecture is not complete, as discussed in section 2.5.1. It was estimated that only 65% of dependencies are modelled for the considered components, ToCs and LoCs. Additionally, some major components and

ToCs were missing (section 2.5.1). For a complete aircraft E-5 design with 200 components, 10 ToCs and 3 LoCs, Equation VI-1 results in 12 million possible dependencies that would need to be considered. Hence, if the 50 hours required for eliciting the current E-5 dependencies model is extrapolated linearly, 318 hours[3] would be needed for a complete dependency model as complete E-5 design.

Furthermore, the dependencies in the case study are solely elicited by the author and are based on the author's knowledge of the available CAD models and design reports on the different structural sections and systems. Hence every possible dependency is only considered once. In an industrial environment, the elicitation process will involve all relevant design and system experts who need to validate all the dependencies that are modelled. Hence, the possible dependencies will need to be considered by all relevant experts, requiring much more time. Comparing the published metrics of the industrial UCs (Rutka et al., 2006) with the elicitation during of the E-5 case study, thousands of hours could be needed for the industrial UCs. However, as mentioned before, more efficient tool interfaces and increased experience with the elicitation process can drastically reduce the required time.

So far, only the incremental dependencies that can be visualised in the dependency DSM have been considered. Also combinatorial dependencies have been included in case study. However, these have not been included in the industrial UCs. As the combinatorial dependencies in the E-5 use case demonstrate, a large number of these dependencies can be required in order to model all possible combinations for a given set of initiating items. The equation to calculate the number of combinations is as follows:

$$C = \frac{n!}{k!(n-k)!}$$

Equation VI-2: General formulation for calculation of number of combinations

Where: C: Number of combinations
n: Number of all possible initiating items
k: Number of elements in subset

---

[3] $(50 \times 12 \times 10^6) / (0.65 \times 2.9 \times 10^6) = 318$

For the combinatorial dependencies with impact on the SP generator 1 in the case study, the total number of possible combinations for the 7 HLFC pumps with subset size ranging from 2 till 7 can be calculated as follows:

$$C_T = \sum_{k=2}^{7} \frac{7!}{k!(7-k)!} = 120$$

Equation VI-3: Calculation of total number of combinations for 7 initiating items

As a result, the number of combinatorial dependencies required can increase rapidly for increasing number of initiating items. However, it is envisaged that an intelligent interface of a software tool could automate the creation of combinations for a selected set of initiating items, hence reducing the time needed to create all the possible combinatorial dependencies

An additional approach to evaluate the scalability of the proposed methodology is to investigate this computational complexity. However, the computational complexity is low for both the algorithms as they consist of queries and filtering. The implementation of the change propagation algorithm indicates execution times of less than 10s for analyses with the E-5 case study. Execution times of changes in the industrial UCs are reported to take up to a few minutes which are considered acceptable. Finally, the scalability can also be limited by the visualisation of propagation results. Very large propagation trees or networks can be difficult to be interpreted, consequently limiting the size of feasible models.

Feedback from external reviews

Discussion in the external reviews indicated that the elicitation times for the dependency models are critical. Besides the time needed to create new dependency models, future investigations into the time required to modify the dependency model, e.g. as a result of the addition of a new component or the relocation of existing component would also be useful to evaluate the scalability.

Furthermore, even though it was commented that the proposed methodology impose "no major barriers for scalability", the amount of available data is probably too much to be modelled after Maturity Gate (MG) 4, i.e. the design and development phase, particular in the physical architecture where more than 100,000 components can exist. It was anticipated that the methodology would be best used for the "Overall Aircraft Design" before MG 3 where the level of granularity is more similar to the E-5 case study, even though this needs to be further investigated. However at that phase, many different design solutions still exist that need to be modelled and hence also Variant Management will need to be considered. Additionally, further research will be required to determine what information is useful to be modelled. The CIA-task leader summarised that level of granularity of the model and consequently its size is crucial. Too much detail in terms of the number of items, ToCs or LoCs will require too many resources but not enough detail will give meaningless results. The optimal level of granularity and hence model size are being investigated with the industrial UCs.

3.2 Elicitation of dependencies over product life cycle

The meta-model that has been proposed should be flexible enough to be used throughout the product life cycle. One reason is that it can be used in conjunction with very different kind of information items organised in separate domains. This is illustrated with the case study where the detailed design of the physical architecture (Figure VI-3) is included as well as the HLFC design process (Figure VI-7) which consists of a requirement, design characteristics and design activities that are defined early in the design life cycle phase. A second reason is the ability to define a milestone from which an item is frozen. Finally, alternative dependencies can be modelled for different stages in the design life cycle because each dependency can have a validity range between specified product life cycle milestones. Although not demonstrated in the case study, a typical use would be to capture the low impact on a cost item of a change to a physical component in the early design stages, while the same change has a high impact on the cost item in the late design stages.

Feedback from external reviews

It was commented that there are no limitations in principle in using the dependency models at every stage of the design life cycle. At the conceptual design stages, the dependency models could focus on functional architecture. However, due to scalability as discussed previously, it is anticipated that the application of this methodology would be very difficult post – MG4.

Furthermore, it was acknowledged that it is important to capture the milestone or MG from which an item is frozen in the product lifecycle and the lifespan of a dependency. Also, it would be interesting to be able to track the evolution of dependencies over the lifecycle. Additionally, it was pointed out that the dependency models could be useful during the product lifecycle to ensure that intended independence between functions or components is maintained, as these items get defined in more detail.

3.3 Identification of the possible extent of an EC impact

The possible extent of the impact of an EC is identified through the CPA algorithm as described in Chapter IV. To evaluate the differences between these alternative propagation modes, the distribution of newly affected items as a function of the propagation depth, or the propagation distribution in short, is investigated for multiple analyses with different initiating conditions.

A comparison of the propagation distributions between a simple propagation analysis (SPA) and the 'ToC-only' propagation analysis (TPA) is made first. Propagation analyses with 2 different initiating items (I-items) have been performed. The initiating items are the HLFC fin pump and HFLC SFIW pump and no initiating ToC was selected for both propagation modes. Furthermore, milestone 8 is selected with the initiating conditions. The analyses are performed for 5 propagation steps as the dependency model is not complete for more than 5 propagation steps for the selected initiating items (section 2.4). For each propagation step, the number of newly identified items is shown together with the total number of affected items.

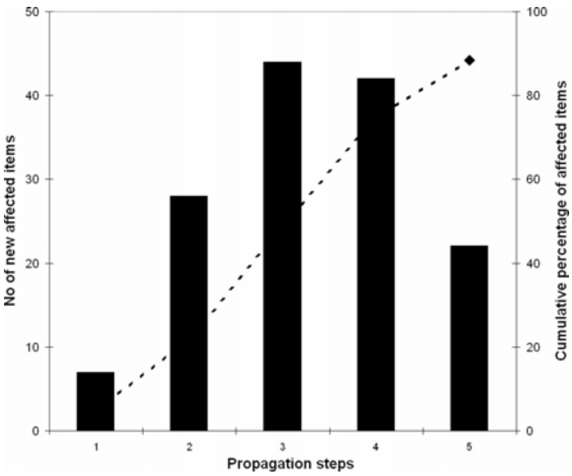


Figure VI-10: SPA with I-item HLFC SFIW Pump

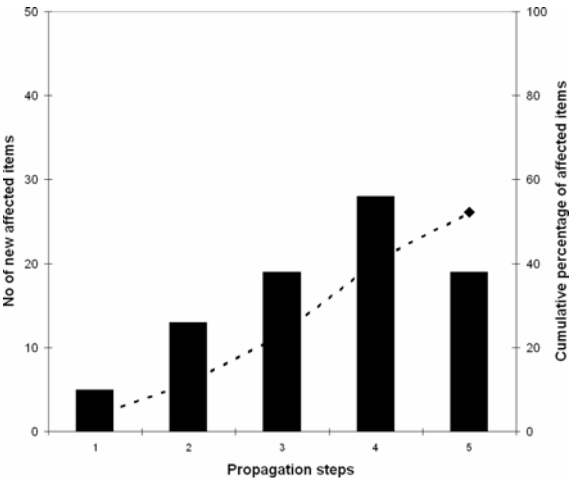


Figure VI-11: SPA with I-item HLFC Fin Pump

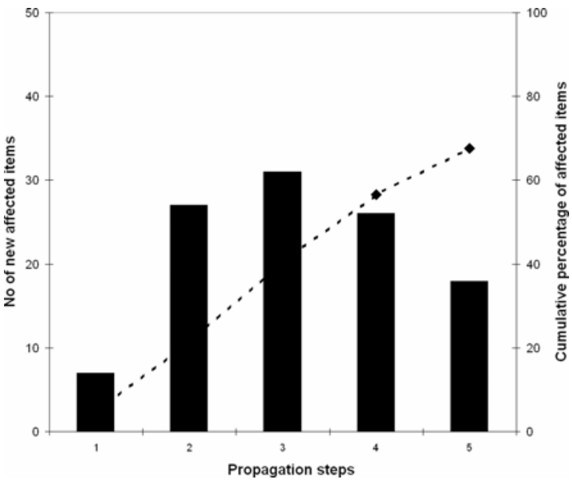


Figure VI-12: TPA with I-item HLFC SFIW Pump

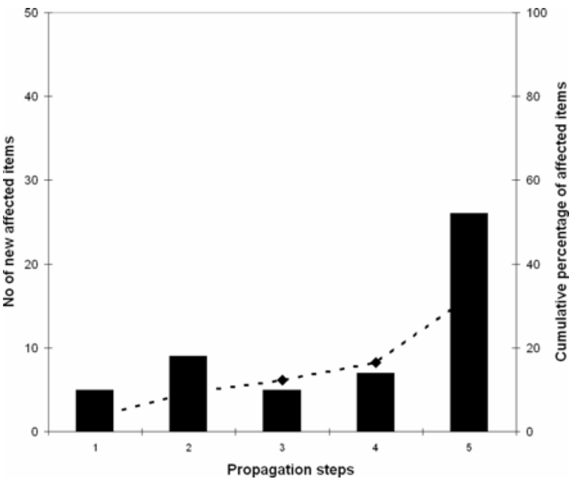


Figure VI-13: TPA with I-item HLFC Fin Pump

Both Figure VI-10 and Figure VI-12 show that for HLFC SFIW Pump as I-item, the number of newly affected items increases for every propagation step until the third step. In case of the SPA, a maximum of 44 new items are impacted out of the 163 items in the physical architecture at the third propagation step. In case of the TPA, only 31 new items are affected. This represents a cumulative impact of respectively 49% and 40% of all items. After the third propagation step, the number of newly affected items decreases because there are now less unaffected items remaining that can be impacted. By the fifth propagation step, 88% of all components in the physical architecture are impacted in SPA mode which ignores the ToCs. While the propagation which considers the impacted ToCs, has only 67% impacted. This means that the TPA can exclude 21% of all items as possibly impacted compared to the SPA. Also Figure VI-11 and Figure VI-13 of the second pair of change propagation analyses show similar results although the distribution of the newly affected impact differs from the first set of results. Particularly the TPA gives in an uneven distribution with a peak of new impacts at the fifth propagation step. However, at this step this TPA only identified 37% of all items while the SPA identifies again 20% more items as possibly impacted.

Secondly, the influence of the initiating level of change is investigated with the HLFC SFIW Pump as initiating item and ‘Power’ as initiating ToC. In the first instance, another TPA is done as reference. Additionally, three detailed propagation analyses (DPA) are performed with I-ToC also ‘Power’ and respectively ‘High’, ‘Medium’ and ‘Low’ as initiating LoC. The propagation distributions of these 4 analyses are shown from Figure VI-14 to Figure VI-17.

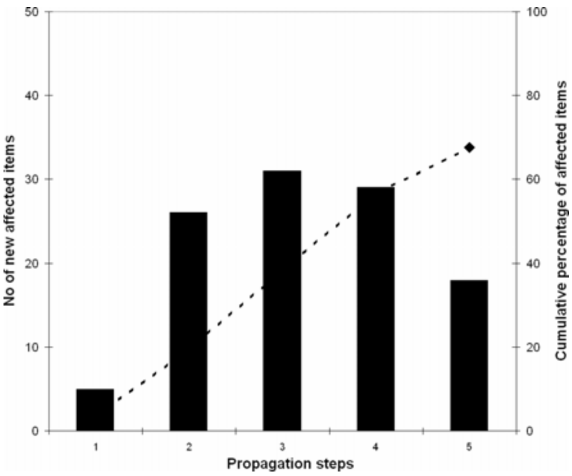


Figure VI-14: TPA with I-ToC 'Power'

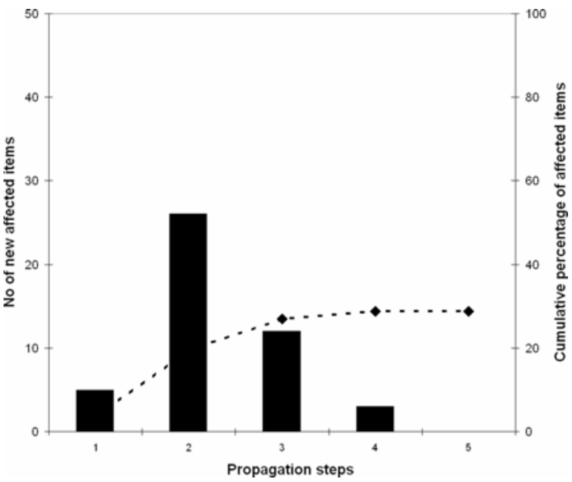
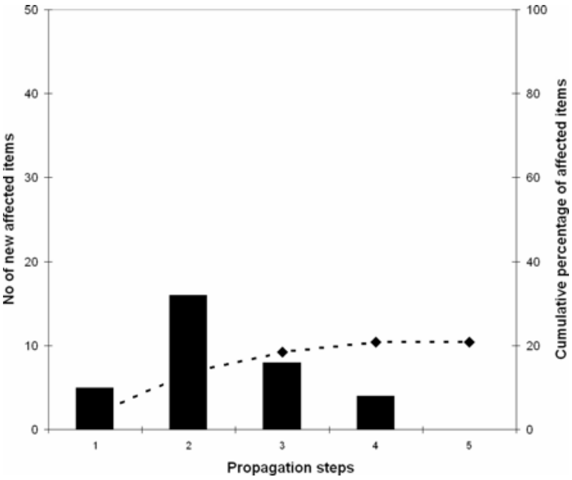


Figure VI-15: DPA with I-LoC 'High'



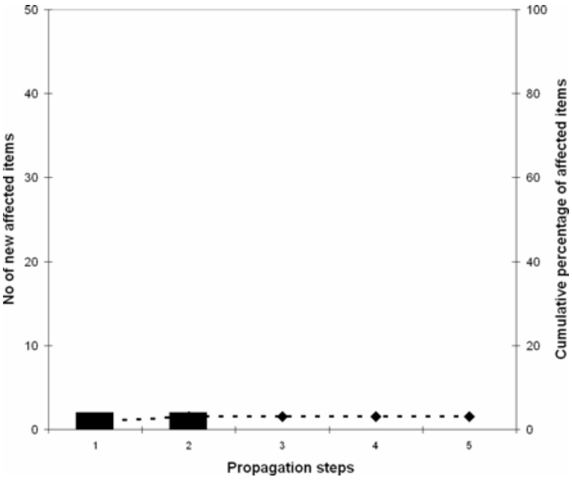


Figure VI-16: DPA with I-LoC 'Medium'

Figure VI-17: DPA with I-LoC 'Low'

The analysis from Figure VI-14 is similar to the analysis with results shown in Figure VI-12. However, the latter is a TPA with all ToCs considered as initiating ToCs while the analysis of Figure VI-14 is a TPA with only ‘Power’ as initiating ToC. Comparing the propagation distribution of TPA with the propagation distribution of the DPA with I-LoC ‘High’ (Figure VI-15), it is clear the number of affected item for the latter is much lower. This propagation distribution indicate that a DPA with I-LoC ‘High’ will propagate to maximum 29% of all the components, compared to at least 67% when the affected LoCs are not considered during the propagation. The DPAs with ‘Medium’ and ‘Low’ as I-LoC will respectively impact 21% and 3% of all components in the physical architecture. Consequently, taking into account the affected ToCs and LoCs can make a huge difference in the extent of possible affected items.

The propagation distributions that have been obtained reflect the different types of propagation behaviours that were reviewed in Chapter II. The SPA propagation distribution and the TPA propagation distribution are similar to the ‘avalanche’ and ‘blossom’ propagation behaviour which are the worst case scenarios. These modes always continue the propagation as long there are dependencies and new components to affect, causing an ‘avalanche’ effect. On the other hand, the propagation distributions obtained from the detailed propagation analyses are more similar to the ‘ripple’ propagation behaviour. This is due to the fact that the LoCs limit the propagation as high LoCs can have lower levels of impact and lower LoCs can have no impact. Thus

DPA simulates more controlled propagations where the changes are absorbed over the propagation steps. Hence the propagation algorithm can emulate to the different possible propagation behaviours that can be expected in reality.

Feedback from external reviews

The evaluation discussion with industry led to the conclusion that the distribution of the number of new impacts is very interesting. However, in order to confirm general trends in the propagation distribution, the propagation distributions for more and very different initiating items and different amount of frozen items needs to be compared. This could also help to identify to which depth propagation analyses are meaningful. However, to perform this investigation, multiple industrial test cases with complete elicited dependencies model need to be available.

Furthermore, it was noted that the CPA algorithm could be used to evaluate the robustness of a design in terms of its level of integration versus modularity. It was also highlighted that this approach could lead to a degree of “deskilling”, i.e., that people may take the CPA result for true without critical evaluation of these results. Hence there is a danger that limitations of the CPA will prevent some solutions to be considered.

Finally, it was concluded that this approach can potentially help to make basic decisions related to ECs which are encountered at every EC process, but is of limited use for the more complex EC-related issues.

3.4 Effective visualisation of propagation paths

As described in the methodology, the CPA algorithm identifies all propagation paths from the initiating conditions. In order to optimise the visualisation of the propagation paths as a propagation tree, loop detection has been introduced. As a result, the propagation will always terminate without ignoring any relevant dependencies. Four examples of CPA results are given to demonstrate the effect the loop detection.

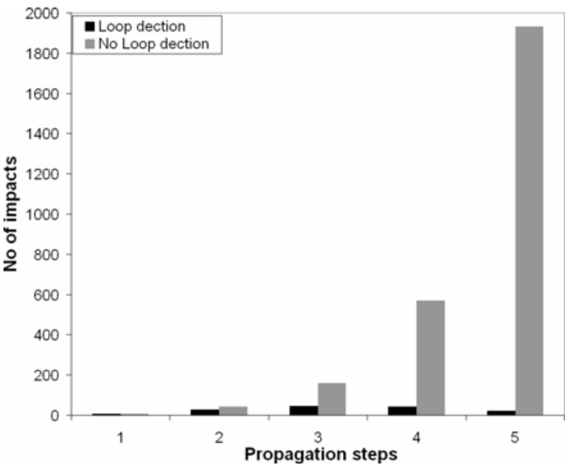


Figure VI-18: Effect of loop detection on SPA

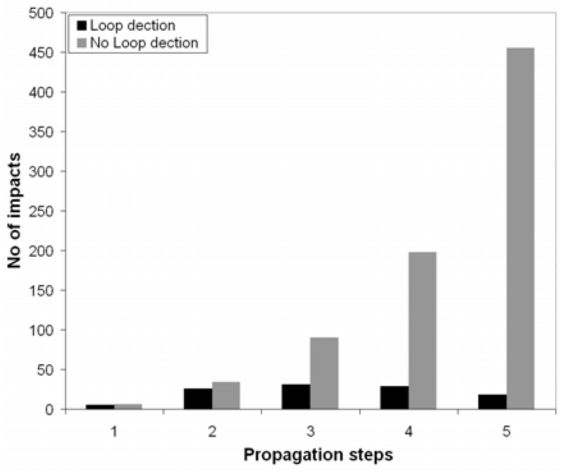


Figure VI-19: Effect of loop detection on TPA

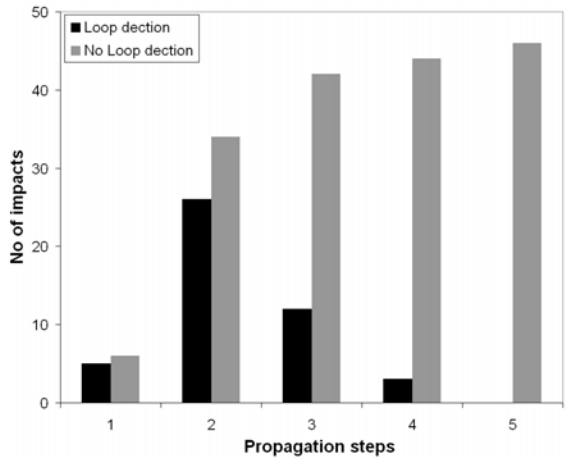


Figure VI-20: Effect of loop detection on DPA (1)

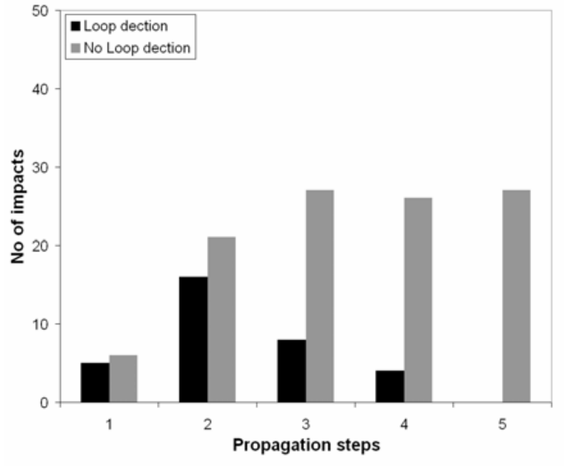


Figure VI-21: Effect of loop detection on DPA (2)

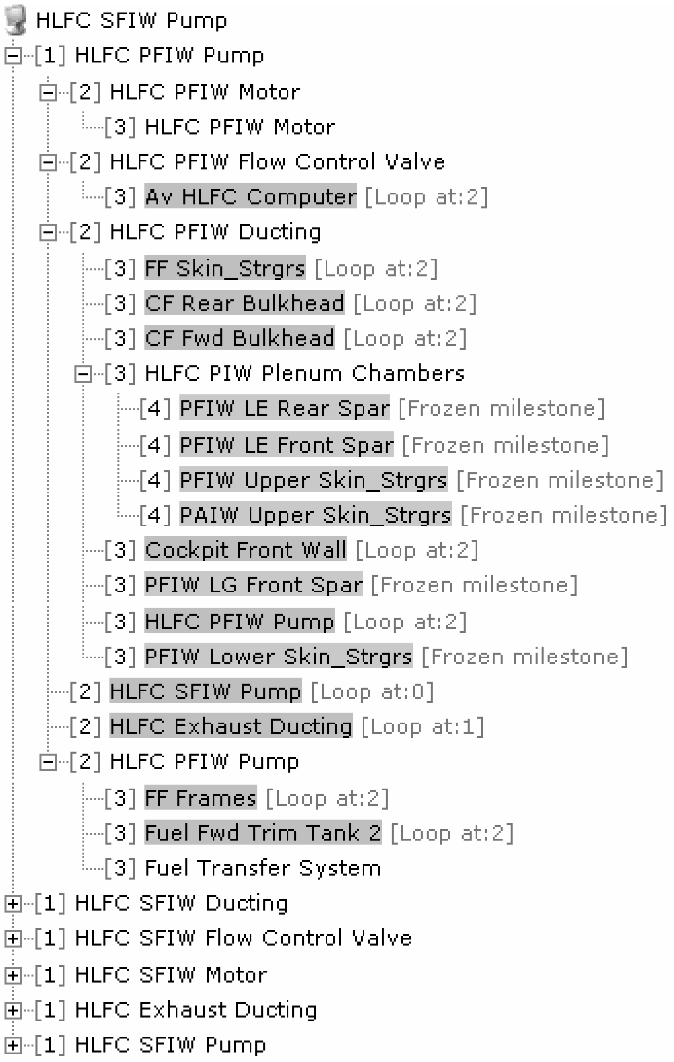
Figure VI-18 to Figure VI-21 show the number of impacts (new and repeated) at every propagation step for HLFC SFIW Pump as initiating item. The black bars indicate the number of impacts for propagation with loop detection while the grey bars indicate the number of impacts with loop detection disabled. The latter means that the propagation continues endlessly when a propagation loop is encountered. In Figure VI-18, a SPA is performed and shows that with loop detection a maximum of 44 impacts are identified at the third propagation step. The number of impact decrease again for the following propagations steps due to loop detection for repeated impacts. However, when no loop detection is performed, the number of impact increases exponentially: the fourth propagations step identifies 568 items and the fifth propagation step not less than 1930.

A similar but a less pronounced effect is shown in Figure VI-19 for a TPA with I-ToC 'Power'. Figure VI-20 and Figure VI-21 show the number of impacts for DPAs with I-ToC 'Power' and I-LoC 'High' and 'Medium' respectively. The expansion of the propagation trees are in these cases considerably lower in the latter case, the number of impacts even stabilises at 26-27 from the third propagation step onwards.

Clearly, without loop detection, the propagation tree can grow very rapidly without providing any new or additional information and consequently constraining the visualisation. However, it is important that the impacts for which the propagation is stopped due to loop detection are highlighted in order to distinguish these from impacts which do not affect any other items or impact on frozen items. An example of partially expanded propagation tree with loop detection and frozen item highlighting is depicted in Figure VI-22 for the same propagation analysis of Figure VI-21.

Figure VI-23 visualise the impacted items from the same analysis in the DMU. The colour of the impacted items indicates the propagation steps at which the items impacted the first time.

It should be emphasised that the obtained propagation paths are not sufficient to be used for the calculation of the combined probabilities of the affected items as required for the discrimination of impact sets. The reason is that due to loop detection, not all propagation paths to every affected item are identified.



```
HLFC SFIW Pump
[1] HLFC PFIW Pump
    [2] HLFC PFIW Motor
        [3] HLFC PFIW Motor
    [2] HLFC PFIW Flow Control Valve
        [3] Av HLFC Computer [Loop at:2]
    [2] HLFC PFIW Ducting
        [3] FF Skin_Strgrs [Loop at:2]
        [3] CF Rear Bulkhead [Loop at:2]
        [3] CF Fwd Bulkhead [Loop at:2]
        [3] HLFC PIW Plenum Chambers
            [4] PFIW LE Rear Spar [Frozen milestone]
            [4] PFIW LE Front Spar [Frozen milestone]
            [4] PFIW Upper Skin_Strgrs [Frozen milestone]
            [4] PAIW Upper Skin_Strgrs [Frozen milestone]
        [3] Cockpit Front Wall [Loop at:2]
        [3] PFIW LG Front Spar [Frozen milestone]
        [3] HLFC PFIW Pump [Loop at:2]
        [3] PFIW Lower Skin_Strgrs [Frozen milestone]
    [2] HLFC SFIW Pump [Loop at:0]
    [2] HLFC Exhaust Ducting [Loop at:1]
    [2] HLFC PFIW Pump
        [3] FF Frames [Loop at:2]
        [3] Fuel Fwd Trim Tank 2 [Loop at:2]
        [3] Fuel Transfer System
[1] HLFC SFIW Ducting
[1] HLFC SFIW Flow Control Valve
[1] HLFC SFIW Motor
[1] HLFC Exhaust Ducting
[1] HLFC SFIW Pump
```

Figure VI-22: Propagation tree for DPA (2)

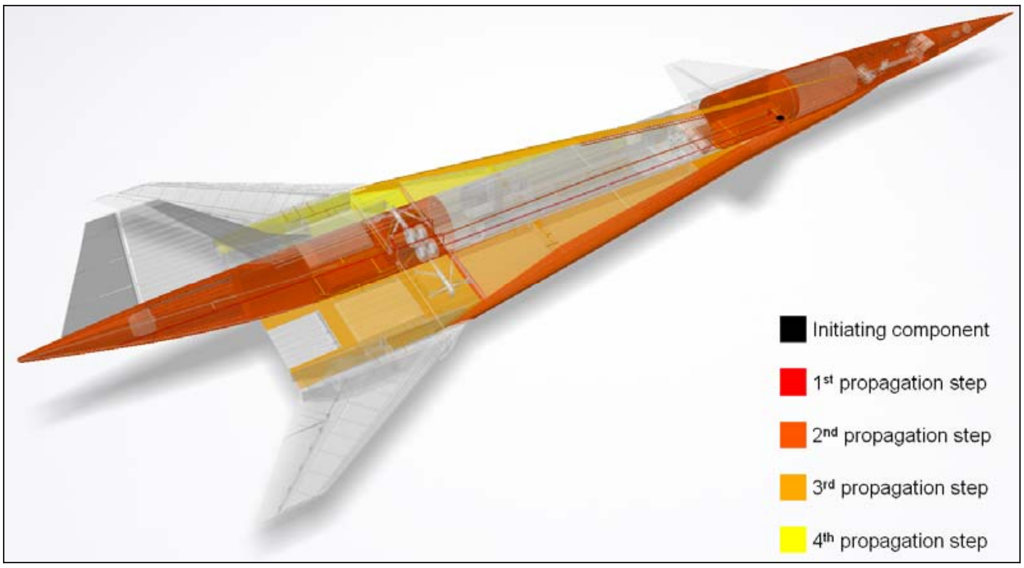


Figure VI-23: DMU visualisation for DPA (2)

Feedback from external reviews

Feedback from the discussions concluded that the loop detection is a valuable capability to improve the visualisation. However, it can still be difficult to find the original impact for a repeated impact where loop detection occurred. Together with the need to highlight the affected ToC and LoC of each item, further advanced interactive tree visualisation methods are required to enable an efficient exploration of the results. Additionally, visualisation of impacts in networks and the DMU does not require loop detection and hence could be alternative visualisation methods for the propagation tree visualisation without loop detection. Furthermore, it was acknowledged that the items "upstream" of frozen items are more important than the "downstream" items, i.e., the items that could be impacted by frozen items. Hence, it was appropriate to terminate the propagation in the algorithm at the frozen items.

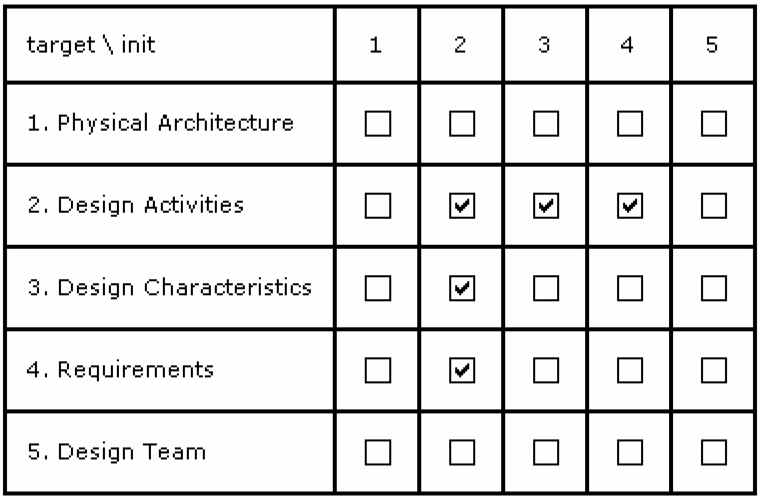
It was also commented that in an industrial situation, multiple ECs often occurs at the same moment. Therefore, it would be interesting to investigate multiple initiating changes in order to identify the overlapping impacts and consequently find the best solution to implement all changes. Furthermore, it was noted that it would be interesting to add parts for particular change scenarios.

3.5 Organising Inter-domain propagation

In order to demonstrate the capabilities of the inter-domain management, a change scenario with 3 DPAs are discussed. This change scenario assumes that an investigation near the end of the detailed design phase has identified that the 'Boundary Layer Stability Analysis' Design Activity underestimates the achieved drag reduction. Consequently, the range requirements for the aircraft will not be met.

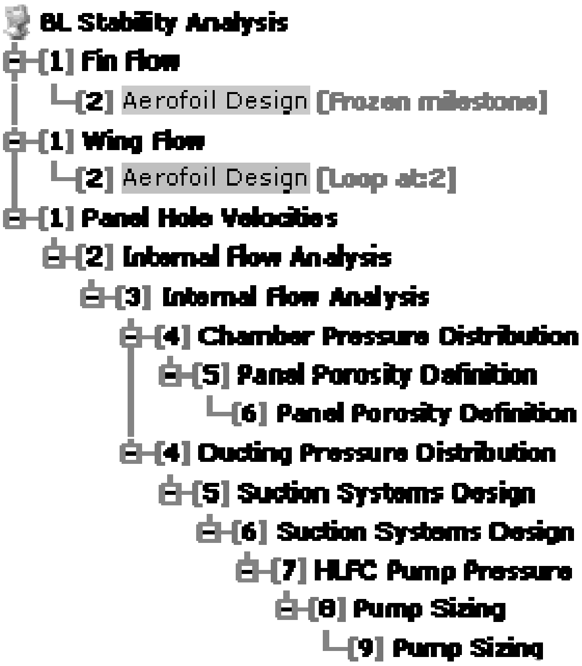
The first DPA, Analysis 1, therefore is to identify all the possible Design Characteristics that could affect the drag in order to achieve the required drag reduction with the updated Boundary Layer Stability Analysis activity. The selected initiating conditions are the 'Boundary Layer Stability Analysis' as I-item, 'Input' as I-ToC and 'N/A' as I-

LoC. The propagation direction is selected as ‘reverse’ in order to identify the items affecting the Boundary Layer Stability Analysis input. The domain combinations that are selected included the dependencies between Design Activities in order to propagate a change from the output ToC to the input ToC of a Design Activity. Additionally, the dependencies from the Design Activities to the Design Characteristics and requirements, and dependencies from the latter two domains again to the Design Activities are also included. This way the propagation can continue from the Design Activities to the Design Characteristics and requirements and back to the Design Activities. This selection of the domain combinations is depicted in Figure VI-24. The resulting propagation tree is displayed in Figure VI-25. It shows that the Boundary Layer Stability Analysis is affected by fin flow, wing flow and panel hole velocities characteristics. These in turn are affected by the Aerofoil Design and Internal Flow Analysis where Aerofoil Design is considered frozen. The propagation continues from the Internal Flow Analysis. Furthermore, the chamber and ducting pressure distribution and HLFC Pump pressure as affecting Design Characteristics are identified.



target \ init	1	2	3	4	5
1. Physical Architecture	☐	☐	☐	☐	☐
2. Design Activities	☐	☑	☑	☑	☐
3. Design Characteristics	☐	☑	☐	☐	☐
4. Requirements	☐	☑	☐	☐	☐
5. Design Team	☐	☐	☐	☐	☐

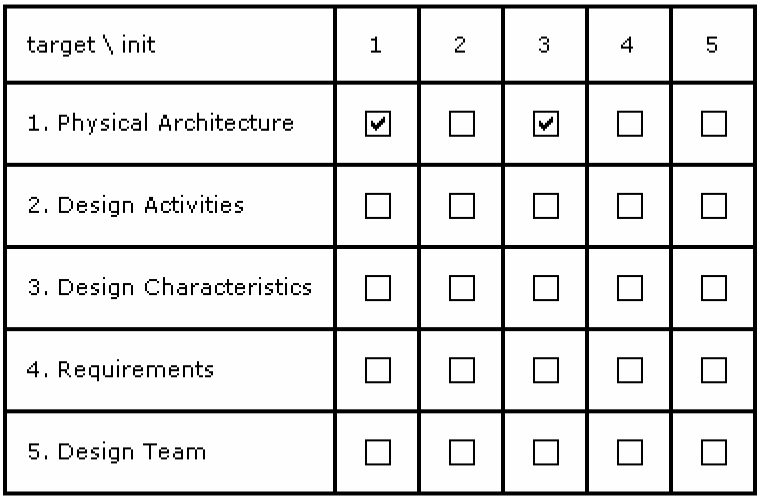
Figure VI-24: Inter-domain combination selection for Analysis 1



BL Stability Analysis
[1] Fin Flow
[2] Aerofoil Design [Frozen milestone]
[1] Wing Flow
[2] Aerofoil Design [Loop at:2]
[1] Panel Hole Velocities
[2] Internal Flow Analysis
[3] Internal Flow Analysis
[4] Chamber Pressure Distribution
[5] Panel Porosity Definition
[6] Panel Porosity Definition
[4] Ducting Pressure Distribution
[5] Suction Systems Design
[6] Suction Systems Design
[7] HLFC Pump Pressure
[8] Pump Sizing
[9] Pump Sizing

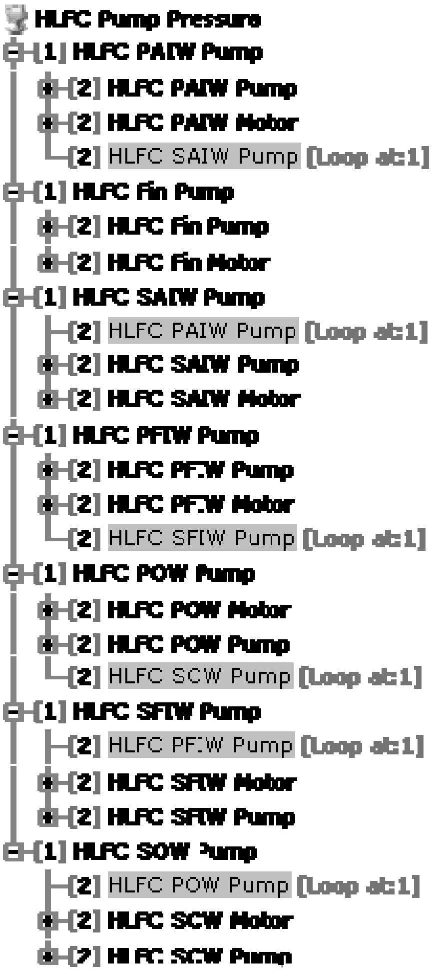
Figure VI-25: Inter-domain propagation tree for Analysis 1

The second DPA, Analysis 2, follows on from Analysis 1. It investigates the possible impact for changing the HFLC Pump pressure on the physical architecture. Therefore, the selected domain combinations (Figure VI-26) are Design Characteristics and Physical Architecture as initiating domains and only the latter as also a target domain. The other initiating conditions are ‘N/A’ as I-ToC and ‘Low’ as I-LoC together with the milestone 8 and forward propagation direction. The obtained propagation tree is depicted in Figure VI-27 for the first two propagation steps. The 7 HLFC pumps are impacted with a ‘Low’ LoC to the ‘Power’ ToC. At the second propagation step, the ‘Power’ of each pump affects the ‘Size’ of the same pump and the ‘Power’ of its motor. Furthermore, each wing pump will affect its opposite wing pump in order to maintain a symmetric drag.



target \ init	1	2	3	4	5
1. Physical Architecture	☑	☐	☑	☐	☐
2. Design Activities	☐	☐	☐	☐	☐
3. Design Characteristics	☐	☐	☐	☐	☐
4. Requirements	☐	☐	☐	☐	☐
5. Design Team	☐	☐	☐	☐	☐

Figure VI-26: Inter-domain combination selection for Analysis 2

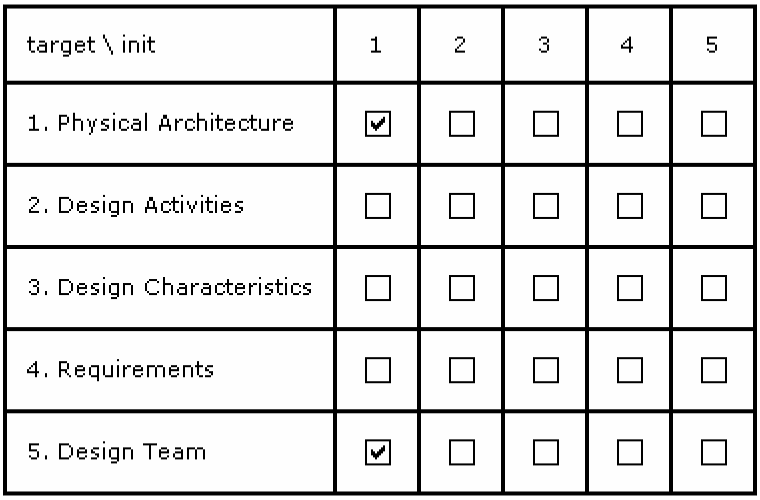


```
HLFC Pump Pressure
⊟-[1] HLFC PAIW Pump
    ⊞-[2] HLFC PAIW Pump
    ⊞-[2] HLFC PAIW Motor
     └[2] HLFC SAIW Pump [Loop at:1]
⊟-[1] HLFC Fin Pump
    ⊞-[2] HLFC Fin Pump
    ⊞-[2] HLFC Fin Motor
⊟-[1] HLFC SAIW Pump
     ├[2] HLFC PAIW Pump [Loop at:1]
    ⊞-[2] HLFC SAIW Pump
    ⊞-[2] HLFC SAIW Motor
⊟-[1] HLFC PFIW Pump
    ⊞-[2] HLFC PFIW Pump
    ⊞-[2] HLFC PFIW Motor
     └[2] HLFC SFIW Pump [Loop at:1]
⊟-[1] HLFC POW Pump
    ⊞-[2] HLFC POW Motor
    ⊞-[2] HLFC POW Pump
     └[2] HLFC SCW Pump [Loop at:1]
⊟-[1] HLFC SFIW Pump
     ├[2] HLFC PFIW Pump [Loop at:1]
    ⊞-[2] HLFC SFIW Motor
    ⊞-[2] HLFC SFIW Pump
⊟-[1] HLFC SOW Pump
     ├[2] HLFC POW Pump [Loop at:1]
    ⊞-[2] HLFC SCW Motor
    ⊞-[2] HLFC SCW Pump
```

Figure VI-27: Inter-domain propagation tree for Analysis 2

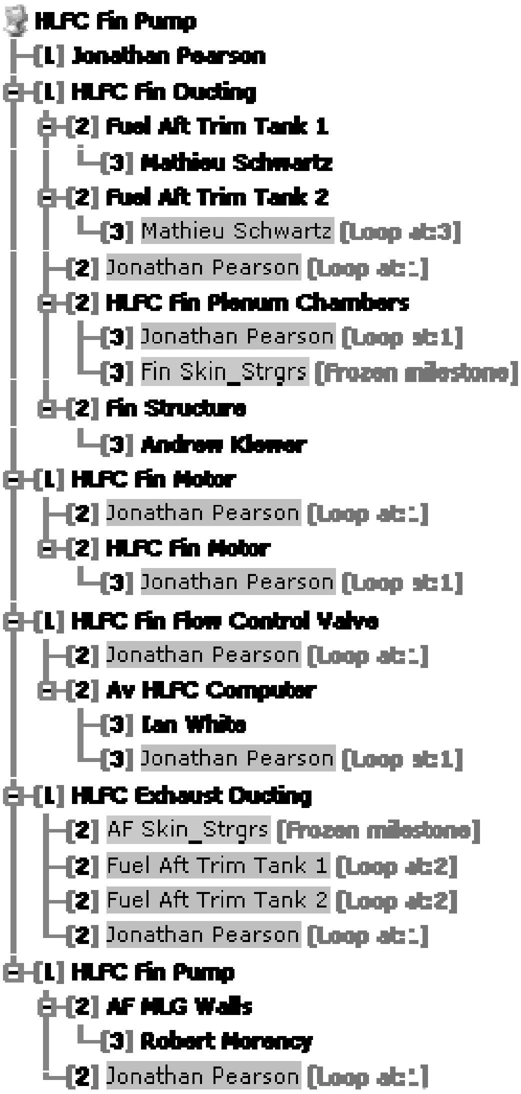
The last DPA, Analysis 3, investigates the propagation of a change to the HLFC Fin Pump in the physical architecture and identifies for each component the person responsible in the Design Team. Therefore, the Physical Architecture is selected as initiating domain and as target domain while the Design Team is also selected as a target domain (Figure VI-28). The initiating ToC is ‘Power’ and the initiating LoC is ‘Medium’. Furthermore, the milestone is 8 and propagation direction is forward. The complete propagation tree is depicted in Figure VI-29. It shows that ‘Jonathan Pearson’ is impacted, i.e. that the latter is responsible to the HFLC Fin Pump. The propagation continues for the affected components.

The examples demonstrate that the management of inter-domain propagation enables the CPA to be used for range of different analyses. However, domains are relative and could be specified at different levels of the product breakdown structure. For example in the E-5 case study, the physical architecture has been modelled as one domain. On the other hand, every system and different aircraft structure sections are modelled as separate domains in the industrial UCs. In an industrial application, many hierarchical levels can exist and different analyses may require the inter-domain propagation management at different levels. Consequently, the functionality of the inter-domain propagation management depends on the level in the product breakdown that is associated with the domains. If this level is chosen too high, then the ability to control the inter-domain propagation is reduced. Instead, if the level is chosen too low, this would result in too many domains and becomes impractical to be used. This also relates to the fact that dependencies for different types of information may need to be modelled at different hierarchical levels which will further complicate change propagation analyses between these different information types.



target \ init	1	2	3	4	5
1. Physical Architecture	☑	☐	☐	☐	☐
2. Design Activities	☐	☐	☐	☐	☐
3. Design Characteristics	☐	☐	☐	☐	☐
4. Requirements	☐	☐	☐	☐	☐
5. Design Team	☑	☐	☐	☐	☐

Figure VI-28: Inter-domain combination selection for Analysis 3



```
HLFC Fin Pump
├─[1] Jonathan Pearson
⊟─[1] HLFC Fin Ducting
│   ⊟─[2] Fuel Aft Trim Tank 1
│   │   └─[3] Mathieu Schwartz
│   ⊟─[2] Fuel Aft Trim Tank 2
│   │   └─[3] Mathieu Schwartz [Loop at:3]
│   ├─[2] Jonathan Pearson [Loop at:1]
│   ⊟─[2] HLFC Fin Plenum Chambers
│   │   ├─[3] Jonathan Pearson [Loop at:1]
│   │   └─[3] Fin Skin_Strgrs [Frozen milestone]
│   ⊟─[2] Fin Structure
│       └─[3] Andrew Klewer
⊟─[1] HLFC Fin Motor
│   ├─[2] Jonathan Pearson [Loop at:1]
│   ⊟─[2] HLFC Fin Motor
│       └─[3] Jonathan Pearson [Loop at:1]
⊟─[1] HLFC Fin Flow Control Valve
│   ├─[2] Jonathan Pearson [Loop at:1]
│   ⊟─[2] Av HLFC Computer
│       ├─[3] Ian White
│       └─[3] Jonathan Pearson [Loop at:1]
⊟─[1] HLFC Exhaust Ducting
│   ├─[2] AF Skin_Strgrs [Frozen milestone]
│   ├─[2] Fuel Aft Trim Tank 1 [Loop at:2]
│   ├─[2] Fuel Aft Trim Tank 2 [Loop at:2]
│   └─[2] Jonathan Pearson [Loop at:1]
⊟─[1] HLFC Fin Pump
    ⊟─[2] AF MLG Walls
    │   └─[3] Robert Morency
    └─[2] Jonathan Pearson [Loop at:1]
```

Figure VI-29: Inter-domain propagation tree for Analysis 3

Feedback from external reviews

Inter-domain propagation filtering was considered as a positive contribution to handle the product information hierarchy. However, it is anticipated that future EC impact analysis methodologies will have to deal with the product information hierarchy in a more generic manner.

It was also noted that the communication or the lack of it between different (system) domains is often a source of EC-related problems. Hence, improving the exchange of information between the domains is valuable. However, the organisation and business issues are very complex and the proposed methodology can only provide limited support in addressing these issues. More investigation is needed into these issues.

3.6 Discrimination of concept alternatives

To demonstrate and evaluate the identification of impact sets, three analyses are performed based on the case study. The first analysis uses the same initiating conditions as Analysis 2 described above. This means the HLFC Pump Pressure (Design Characteristics domain) is selected as initiating item and its impact on the Physical Architecture is identified. The propagation analysis identified 31 unique possibly affected changes. This means that if all these impacts were completely independent, more than 2 billion combinations (Equation V-1) would exist. However, the impact sets analysis identifies only 16 combinations as possible impact sets. These impact sets are listed in Table VI-2.

N°	Impact Set: **Item** (ToC)
1	**'No changes'**
2	**HLFC Fin Pump** (Power&Size), **HLFC Fin Motor** (Power&Size), **AF MLG Walls** (I/F)
3	**HLFC PAIW Pump** (Power&Size), **HLFC PAIW Motor** (Power&Size), **HLFC SAIW Pump** (Power&Size), **HLFC SAIW Motor** (Power&Size), **CF Frames** (I/F)
4	**HLFC PFIW Pump** (Power&Size), **HLFC PFIW Motor** (Power&Size), **HLFC SFIW Pump** (Power&Size), **HLFC SFIW Motor** (Power&Size), **FF Frames** (I/F)
5	**HLFC POW Pump** (Power&Size), **HLFC POW Motor** (Power&Size), **HLFC SOW Pump** (Power&Size), **HLFC SOW Motor** (Power&Size), **AF MLG Walls** (I/F)

6	**HLFC Fin Pump** (Power&Size), **HLFC Fin Motor** (Power&Size), **AF MLG Walls** (I/F) **HLFC PAIW Pump** (Power&Size), **HLFC PAIW Motor** (Power&Size), **HLFC SAIW Pump** (Power&Size), **HLFC SAIW Motor** (Power&Size), **CF Frames** (I/F)
7	**HLFC Fin Pump** (Power&Size), **HLFC Fin Motor** (Power&Size), **AF MLG Walls** (I/F) **HLFC PFIW Pump** (Power&Size), **HLFC PFIW Motor** (Power&Size), **HLFC SFIW Pump** (Power&Size), **HLFC SFIW Motor** (Power&Size), **FF Frames** (I/F)
8	**HLFC Fin Pump** (Power&Size), **HLFC Fin Motor** (Power&Size), **AF MLG Walls** (I/F) **HLFC POW Pump** (Power&Size), **HLFC POW Motor** (Power&Size), **HLFC SOW Pump** (Power&Size), **HLFC SOW Motor** (Power&Size),
9	**HLFC PAIW Pump** (Power&Size), **HLFC PAIW Motor** (Power&Size), **HLFC SAIW Pump** (Power&Size), **HLFC SAIW Motor** (Power&Size), **CF Frames** (I/F) **HLFC PFIW Pump** (Power&Size), **HLFC PFIW Motor** (Power&Size), **HLFC SFIW Pump** (Power&Size), **HLFC SFIW Motor** (Power&Size), **FF Frames** (I/F)
10	**HLFC PAIW Pump** (Power&Size), **HLFC PAIW Motor** (Power&Size), **HLFC SAIW Pump** (Power&Size), **HLFC SAIW Motor** (Power&Size), **CF Frames** (I/F) **HLFC POW Pump** (Power&Size), **HLFC POW Motor** (Power&Size), **HLFC SOW Pump** (Power&Size), **HLFC SOW Motor** (Power&Size), **AF MLG Walls** (I/F)
11	**HLFC PFIW Pump** (Power&Size), **HLFC PFIW Motor** (Power&Size), **HLFC SFIW Pump** (Power&Size), **HLFC SFIW Motor** (Power&Size), **FF Frames** (I/F) **HLFC POW Pump** (Power&Size), **HLFC POW Motor** (Power&Size), **HLFC SOW Pump** (Power&Size), **HLFC SOW Motor** (Power&Size), **AF MLG Walls** (I/F)
12	**HLFC Fin Pump** (Power&Size), **HLFC Fin Motor** (Power&Size), **AF MLG Walls** (I/F) **HLFC PAIW Pump** (Power&Size), **HLFC PAIW Motor** (Power&Size), **HLFC SAIW Pump** (Power&Size), **HLFC SAIW Motor** (Power&Size), **CF Frames** (I/F) **HLFC PFIW Pump** (Power&Size), **HLFC PFIW Motor** (Power&Size), **HLFC SFIW Pump** (Power&Size), **HLFC SFIW Motor** (Power&Size), **FF Frames** (I/F)
13	**HLFC Fin Pump** (Power&Size), **HLFC Fin Motor** (Power&Size), **AF MLG Walls** (I/F) **HLFC PAIW Pump** (Power&Size), **HLFC PAIW Motor** (Power&Size), **HLFC SAIW Pump** (Power&Size), **HLFC SAIW Motor** (Power&Size), **CF Frames** (I/F) **HLFC POW Pump** (Power&Size), **HLFC POW Motor** (Power&Size), **HLFC SOW Pump** (Power&Size), **HLFC SOW Motor** (Power&Size),
14	**HLFC Fin Pump** (Power&Size), **HLFC Fin Motor** (Power&Size), **AF MLG Walls** (I/F) **HLFC PFIW Pump** (Power&Size), **HLFC PFIW Motor** (Power&Size), **HLFC SFIW Pump** (Power&Size), **HLFC SFIW Motor** (Power&Size), **FF Frames** (I/F) **HLFC POW Pump** (Power&Size), **HLFC POW Motor** (Power&Size), **HLFC SOW Pump** (Power&Size), **HLFC SOW Motor** (Power&Size),
15	**HLFC PAIW Pump** (Power&Size), **HLFC PAIW Motor** (Power&Size), **HLFC SAIW Pump** (Power&Size), **HLFC SAIW Motor** (Power&Size), **CF Frames** (I/F) **HLFC PFIW Pump** (Power&Size), **HLFC PFIW Motor** (Power&Size), **HLFC SFIW Pump** (Power&Size), **HLFC SFIW Motor** (Power&Size), **FF Frames** (I/F) **HLFC POW Pump** (Power&Size), **HLFC POW Motor** (Power&Size), **HLFC SOW Pump** (Power&Size), **HLFC SOW Motor** (Power&Size), **AF MLG Walls** (I/F)
16	**HLFC Fin Pump** (Power&Size), **HLFC Fin Motor** (Power&Size), **AF MLG Walls** (I/F) **HLFC PAIW Pump** (Power&Size), **HLFC PAIW Motor** (Power&Size), **HLFC SAIW Pump** (Power&Size), **HLFC SAIW Motor** (Power&Size), **CF Frames** (I/F) **HLFC PFIW Pump** (Power&Size), **HLFC PFIW Motor** (Power&Size), **HLFC SFIW Pump** (Power&Size), **HLFC SFIW Motor** (Power&Size), **FF Frames** (I/F) **HLFC POW Pump** (Power&Size), **HLFC POW Motor** (Power&Size), **HLFC SOW Pump** (Power&Size), **HLFC SOW Motor** (Power&Size),

Table VI-2: Impact Sets of Analysis 1

These impact sets show immediately that no HLFC wing pump can be changed without changing its symmetric pump. It shows further that changing the power of a pump will always affect the size of the pump together with the power and size of its motor and the interface with the structure it is attached to. Hence, the possible impact sets include 'no change', changing the fin pump, any of the 3 symmetric sets of wing pumps or any combination of these four.

The second analysis is based on the analysis 2 discussed in section 3.5. This analysis showed that for a 'Medium' 'Power' change of the HFLC Fin Pump, 14 possible item-ToC combinations can be impacted. The impact sets analysis subsequently identified 6 possible impact sets. The probabilities of the impacts sets were obtained manually (Chapter V, section 2) to demonstrate their potential. These impact sets together with their probability are listed in Table VI-3.

N°	Prob	Impact Set: **Item** (ToC)
1	**11.6%**	**'Definite impacts'***
2	**22.4%**	**'Definite impacts'*, Fin Structure (geometry)**
3	**15.0%**	**'Definite impacts'*, HLFC Fin F-C Valve (size)**
4	**7.4%**	**'Definite impacts'*, HLFC Fin F-C Valve (size), Av. HLFC Computer (software)**
5	**29.2%**	**'Definite impacts'*, HLFC Fin F-C Valve (size), Fin Structure (geometry)**
6	**14.4%**	**'Definite impacts'*, HLFC Fin F-C Valve (size), Fin Structure (geometry), Av. HLFC Computer (software)**

Table VI-3: Impact Sets of Analysis 2

***'Definite impacts': HLFC Fin Ducting (Size), HLFC Fin Motor (Power&Size), HLFC Fin Pump (Power&Size), Fuel Aft Trim Tank 1 (I/F), Fuel Aft Trim Tank 2 (I/F), HLFC Fin Plenum Chambers (Size), AF MLG Walls (I/F)**

Close examination of the impact sets reveals that the 'HLFC Exhaust Ducting' is nowhere included. The reason is that changes to the 'Size' of the Exhaust Ducting will always (probability 'Certain') impact the 'Interface' with the AF Skin. And because the AF Skin is frozen, the Exhaust Ducting cannot be change either. This also reveals a limitation of the methodology. An item that is frozen means that all ToCs of that item are frozen and hence no changes at all are allowed, consequently excluding the item from all impact sets. Additionally, the probabilities of the impact sets indicate the most likely (29%) result for the initiating change is that the size of the HLFC Fin F-C Valve and the geometry of the Fin Structure will be impacted together with the defined impacts. Furthermore, there is an 11% chance that only the ‘definite impacts’-set will be impacted.

The final analysis identifies the impact sets for a ‘High’ level of change to the ‘Power’ of the HLFC SFIW Pump. No impact sets probabilities were computed. Due to the ‘High’ level of change, a large propagation tree is obtained which includes 25 possible resulting changes. This could equate more than 33 million possible combinations (Equation V-1). Although the impact sets analysis reduces this to 192 possible impact sets, this still remains a very high number compared to the 25 possible impacts. Even though only the impact sets with the fewest changes could be used as a starting point to find feasible solutions, evaluating all impact sets would require more effort than evaluating the individual impacts. Hence this example demonstrates a limitation of the impact sets analysis. Table VI-4 lists the ten impact sets with the fewest changes.

N°	Impact Set: **Item** (ToC)
1	**‘Definite impacts’***
2	**‘Definite impacts’*, LG S Main** (Geometry)
3	**‘Definite impacts’*, SFIW Fuselage Rib** (Geometry)
4	**‘Definite impacts’*, Fuel Fwd Trim Tank 2** (Geometry)
5	**‘Definite impacts’*, Cockpit Front Wall** (Geometry)
6	**‘Definite impacts’*, SP Generator 2** (Power)
7	**‘Definite impacts’*, HLFC Exhaust Ducting** (Size)
8	**‘Definite impacts’*, HLFC PFIW Flow Control Valve** (Size)
9	**‘Definite impacts’*, SFIW Fuselage Rib** (Geometry), **LG S Main** (Geometry)
10	**‘Definite impacts’*, Fuel Fwd Trim Tank 2** (Geometry), **LG S Main** (Geometry)

Table VI-4: 10 out of 192 Impact Sets of Analysis 3

***‘Definite impacts’: HLFC SFIW Ducting** (Size), **HLFC SFIW Motor** (Power&Size), **HLFC SFIW Pump** (Size&Power), **HLFC PFIW Pump** (Power&Size), **CF Rear Bulkhead** (Interface), **CF Fwd Bulkhead** (Interface), **Cabin Toilet** (Geometry), **ECS Cold Air Unit 1** (Positioning), **HLFC SIW Plenum Chambers** (Size), **ECS Compressor 1** (Positioning), **Canard S Actuator** (Geometry), **Fuel Transfer System** (Positioning), **SP Generator 1** (Power), **HLFC PFIW Ducting** (Size), **HFLC PFIW Motor** (Power)

Finally, it can be concluded that the impact sets analysis can help the decision-maker to identify alternative concepts or exclude impossible combinations of changes. Furthermore, the computation of the probability of the impact sets can identify the most likely set of impacts where appropriate. However, in case the analysis results in many probable but not definite impacts, the number of impact sets becomes very large and their evaluation can be more time consuming than the interpretation of the propagation tree.

Feedback from external reviews

The discussion indicated that the impact sets analysis is an interesting new concept. It is anticipated that the resulting number of impact sets can be used as an indicator for the number of solutions that would need to be investigated and hence the potential workload for the investigated EC. Furthermore, the impact sets can help to identify the necessary changes and the subsequent favourable changes. However, further investigations with industrial applications will be required to identify the full extent of the potential of impact set analysis.

4 Summary

To evaluate the degree that the research objectives are fulfilled by the proposed methodology, the following six capabilities have been drawn up:

- Application on an industrial scale
- Elicitation of dependencies over product life cycle
- Identification of the possible extent of an EC impact
- Effective visualisation of propagation paths
- Organising inter-domain propagation
- Discrimination of concept alternatives

Furthermore, a case study was introduced based on a student design of supersonic business jet, named E-5 Neutrino. A partial dependency model of the physical architecture was created. This included all the major structural elements together with components from 9 systems. The modelled design was discussed with a design expert from Cranfield University in order to determine the completeness of the design. It was concluded that all major structural components have been included but some of the systems were incomplete. Also 4 major ToC were identified as not being considered in the dependency model. Additionally, a discussion of the case study with the industrial partners concluded that it was similar in size and scope as the industrial UCs.

Subsequently, each of the six capabilities has been demonstrated with the case study in order to assess the level of achievement of these capabilities. Additionally, the level of importance of the capabilities and the level of demonstration by the case study was also assessed. Finally, the results have been presented to industry experts in three separate external reviews sessions. The main conclusions are that the proposed methodology offers good support to model and analyse qualitative dependency models and could provide valuable support to the analysis of EC. However, from a more general perspective, it still needs to be established which information at what point in the product lifecycle is most useful to capture with qualitative dependency models.

CHAPTER VII:

Conclusions and Future Work

This chapter concludes the thesis. It reviews the key conclusions and the research contributions that have been made. Additionally, the limitations of the developed methodology are discussed and areas for future work are identified.

1 Key conclusions

Engineering changes are an integral part of the product design process. Particularly for complex products, the consequences of these changes are often unexpected and unwanted. There is a clear interest from industry in methods to control these changes and predict their impact. Recent research has indicated that the use of qualitative dependency models can increase the understanding of the product design and their associated processes across an enterprise and can support the exploration of the solutions space for ECs.

The proposed CPA algorithm with a novel dependency model can provide improved support to capture dependencies in the product design process and to identify the possible extent of the impact of an ECs. Additionally, the impact sets analysis algorithm can provide useful support for the discrimination of alternative concepts by reducing the solution space or indicate the number of design solutions there could be.

It was found that the elicitation of the dependency models will require a considerable amount of resources. To have effective dependency models, these resources need to be offset by the cost and time savings the dependency models can provide. Therefore, the right information needs to be captured with the right level of detail at the appropriate phases of the product lifecycle. These factors still need to be determined. Finally, experts with additional tacit design knowledge will always be needed to interpret the modelled information and EC impact results.

2 Research contributions

The proposed methodology includes a novel meta-model to capture dependencies. This model differs significantly from the existing qualitative dependency models. Firstly, a more generic approach has been taken to model different types of information items. As a result, the items have been organised in domains. Secondly, ‘types of change’ and ‘level of change’ concepts have been introduced which characterise and qualify a change to an item, respectively. Subsequently, incremental dependencies are defined from an initiating change to a target change. Additionally, combinatorial dependencies have been introduced which are used to model step changes where a specific combination of initiating changes can trigger additional changes. As a result, the proposed dependency model supports on the one hand a more accurate representation of change characteristics, while on the other hand it can support a wider range of product related design information compared to existing qualitative dependency models. Through discussion with industry experts, it is also believed that the dependency model has an improved scalability and hence can support a larger part of the development process of complex products such as commercial aircraft.

Furthermore, the proposed methodology includes a Change Propagation Analysis algorithm which traces the propagation of changes in the proposed dependency models. These analyses include novel methods to identify the possible extent of an EC impact. First, three different types of propagation can be performed to simulate different possible propagation behaviour. Moreover, frozen items and dependency validity is taken into account. Finally, loop detection, LoC management and domain-based filtering were included to support an effective visualisation of the propagation paths. Finally, an additional method was proposed to identify impact sets from the result of the CPA algorithm in order to support the identification of possible solutions for the investigated change. This support can be an indication of possible groups of items that need to be changed together or give an indication of the number of possible design solutions. As a result, the proposed methodology can support a more integrated and shared EC impact analysis approach across an organisation and over the product lifecycle.

The methodology has been tested on a substantial case study and the results have been presented to industry for evaluation. Feedback from industry validated the case study as a realistic application and has provided indications on the phases in the product lifecycle where the methodology could be most suitable. Possible extensions have also been suggested which the proposed methodology could support, such as the analysis of the evolution of dependencies throughout the product lifecycle, the analysis of the levels of modularity or integration of product designs and change propagation analyses for multiple initiating items. Also limitations of the methodology have been highlighted and key areas for future work has been identified which are discussed in more detail in the following sections.

3 Limitations of the research

3.1 Limitations of the proposed methodology

The proposed methodology will not resolve certain complex EC-related issues, such as identifying additional required parts or finding new design solutions. There is also only limited support to consider all aspects of organisational and business issues.

Moreover, the methodology does not support the investigation of multiple initiating changes which often occur during the design process. Also, the addition of parts or new items can not be taken into account for the investigation of specific change scenarios. Furthermore, the use of domains provides only a limited support for the hierarchical modelling of product information.

Regarding the impact sets analysis, in particular, when an analysis results in many probable, but few definite impacts, the number of impact sets becomes much larger than the number of individual impacts and their evaluation can be more time consuming than the direct interpretation of the propagation tree.

3.2 Limitation of qualitative dependency models

The elicitation and maintenance of qualitative dependency models will require considerable resources throughout the product development process, especially as the models continuously need to be updated as a result of product changes. The proposed dependency model in particular requires a high number of combinations to be considered during the elicitation all incremental and combinatorial dependencies.

Furthermore, it is not yet clear what the optimal model sizes are and which are the most appropriate phases in the product lifecycle to benefit most from the proposed methodology. Feedback from industry indicated that for aircraft design processes, the design would become too detailed in the later design phases to capture with the dependency models. However, at earlier design phases, many design solution still exist, all of which would need to be modelled.

There could also be resistance from people to share their knowledge for fears that it could make them redundant. Additionally, as for all knowledge repositories, capturing knowledge could lead to unauthorised use hence access to the dependency models will have to be managed. Moreover, the analyses' results could be taken for true without critical evaluation hence there is a danger that limitations of qualitative impact analysis methodology will prevent some solutions from being considered.

4 Future work

Future work could address the unresolved issues related to the use of qualitative dependency models. In addition, the functionalities of the proposed methodology could be extended to improve the support for the product design process and the EC-processes in particular.

Issues requiring more research in regard to use of qualitative dependency models:

- What are the optimal levels of granularity in term of product information, types and levels of change for qualitative dependency models?
- Which phases in the product development can be most effectively supported by qualitative dependency models?
- What are the most effective approaches to elicit the required knowledge from design experts?
- How can the automatic elicitation of product knowledge from existing repositories be improved to create dependency models?

The proposed methodology could be extended to include support for:

- The investigation of multiple initiating changes and their overlapping impacts.
- Hierarchical product information.
- The addition of parts when investigating changes.
- Organisational and business issues related to ECs.
- The computation of the probabilities of the impact sets.
- The evaluation of impact sets in terms of their impact on decision criteria.

5 Summary

This research has resulted from an industrial need for better methods to support the EC processes. The proposed methodology introduces novel concepts and methods to enable a more precise elicitation of qualitative dependencies in order to achieve a more effective identification of the possible EC impacts and impact sets which can support the decision-maker with the discrimination of alternative solutions.

It was concluded through evaluation and discussion with industry that despite some limitation, the proposed methodology can provide useful support in resolving common issues in the early phases of the EC-processes, such as identifying possibly affected components, components that cannot be changed and associated regulations or requirements.

Future work should concentrate on determining the appropriate product information, level of detail to be modelled and the appropriate product development phase for the most effective application of the methodology.

ABBREVIATIONS

AF: aft fuselage

AIW: aft inner wing

APU: auxiliary power unit

Av: avionics

CAD: Computer Aided Design

CF: centre fuselage

C-FAR: Change Favorable Representation

CIA: Change Impact Analysis

CM-EC: Collaborative Management of Engineering Changes (Rivière, 2004)

Comb: combinatorial

Cn: Certain (probability)

CPA: Change Propagation Analysis
CPM: Change Predict Method (Clarkson et al., 2001)
DMM: Domain Mapping Matrix
DMU: Digital Mock-Up
DPA: detailed propagation analysis
DSM: Design Structure Matrix
EC: Engineering Change
ECS: environmental control system
EM: electro-magnetic
E-MS: end milestone
FF: forward fuselage
FIW: forward inner wing
Fwd: forward
GPS: Global Positioning System
H: High
HLFC: hybrid laminar flow control
I-item: initiating item
I-LoC: initiating level of change
ISA: impact sets analysis
I-ToC: initiating type of change
L: Low
LG: landing gear
Li: Likely
LoC: Level of Change
M: Medium
MCS: Monte Carlo Simulation
MG: Maturity Gate
MLG: main landing gear
MTOW: Maximum Take-Off Weight
N/A: not applicable
OW: outer wing
P: port side

PA: performance analysis
PAIW: port aft inner wing
PDM: Product Data Management
PFIW: port forward inner wing
PLM: Product Lifecycle Management
PPD: panel porosity definition
Pr: Probability
PS: pump sizing
S: starboard side
SAIW: starboard aft inner wing
SFIW: starboard forward inner wing
S-MS: start milestone
SoA: state-of-the-art
SP: secondary power
SPA: simple propagation analysis
SSBJ: supersonic business jet
SSD: suction system design
T-item: target item
T-LoC: target Level of Change
ToC: Type of Change
TPA:’ ToC-only’ propagation analysis
T-ToC: target Type of Change
UC: use case
Ul: Unlikely
VIP: very important person
VIVACE: European sponsor project (Value Improvement through a Virtual Aeronautical Collaborative Enterprise)

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APPENDICES

1. Publications by the author related to this thesis

Rutka A., Guenov M. D., Lemmens Y., Schmidt-Schäffer T., Coleman P., Rivière A. (2006) “Methods for Engineering Change Propagation Analysis” *Proceedings of 25th International Congress of the Aeronautical Sciences*, Hamburg, Germany, September 3-8 2006.

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2. E-5 frozen Item list

List of items with frozen milestone (MS) different from M13 which is the end of considered product lifecycle.

Item Name	Domain	MS
Fin Skin_Strgrs	Physical Architecture	7
AF Skin_Strgrs	Physical Architecture	7
CF Skin_Strgrs	Physical Architecture	7
FF Skin_Strgrs	Physical Architecture	7
PAIW Front Spar	Physical Architecture	7
PAIW LG Rear Spar	Physical Architecture	7
PAIW Lower Skin_Strgrs	Physical Architecture	7
PAIW Rear Spar	Physical Architecture	7
PAIW Upper Skin_Strgrs	Physical Architecture	7
PFIW LE Front Spar	Physical Architecture	7
PFIW Fwd Spar	Physical Architecture	7
PFIW LG Front Spar	Physical Architecture	7
PFIW Lower Skin_Strgrs	Physical Architecture	7
PFIW LE Rear Spar	Physical Architecture	7
PFIW Upper Skin_Strgrs	Physical Architecture	7
POW Front Spar	Physical Architecture	7
POW Lower Skin_Strgrs	Physical Architecture	7
POW Rear Spar	Physical Architecture	7
POW Upper Skin_Strgrs	Physical Architecture	7
SAIW Front Spar	Physical Architecture	7
SAIW LG Rear Spar	Physical Architecture	7
SAIW Lower Skin_Strgrs	Physical Architecture	7
SAIW Rear Spar	Physical Architecture	7
SAIW Upper Skin_Strgrs	Physical Architecture	7
SFIW Fwd Spar	Physical Architecture	7
SFIW LE Front Spar	Physical Architecture	7
SFIW LG Front Spar	Physical Architecture	7
SFIW Lower Skin_Strgrs	Physical Architecture	7
SFIW LE Rear Spar	Physical Architecture	7
SFIW Upper Skin_Strgrs	Physical Architecture	7
SOW Front Spar	Physical Architecture	7
SOW Lower Skin_Strgrs	Physical Architecture	7
SOW Rear Spar	Physical Architecture	7
SOW Upper Skin_Strgrs	Physical Architecture	7
Aerofoil Design	Design Activities	7

3. E-5 dependencies in PA domain

List with all modelled dependencies in the Physical Architecture domain. The validity range of all dependencies is set from M1 to M13.

No	Initiating Item	Initiating ToC	Initiating LoC	Target Item	Target ToC	Target LoC	Pr
1	Fin Rudder	Design	Medium	AF Rudder Bracket	Design	Low	100
2	Fin Rudder	Design	High	AF Rudder Bracket	Design	Medium	100
3	Fin Skin_Strgrs	Design	Medium	Fin Structure	Design	Medium	100
4	Fin Skin_Strgrs	Design	Medium	Fin Rudder	Design	Medium	100
5	Fin Skin_Strgrs	Design	High	Fin Structure	Design	High	100
6	Fin Structure	Design	Medium	Fin Rudder	Design	High	100
7	Fin Structure	Design	Medium	Fin Skin_Strgrs	Design	Medium	100
8	Fin Structure	Design	High	Fin Skin_Strgrs	Design	High	100
9	AF Frames	Design	Medium	Fin Structure	Design	Medium	100
10	AF Frames	Design	Medium	Fuel Aft Trim Tank 1	Design	Medium	100
11	AF Frames	Design	Medium	Fuel Aft Trim Tank 2	Design	Medium	100
12	AF Frames	Design	Medium	Fuel Jettison System	Interface	Medium	100
13	AF MLG Walls	Design	Medium	AF Frames	Design	Low	100
14	AF MLG Walls	Design	Medium	LG S Main	Design	Medium	100
15	AF MLG Walls	Design	Medium	LG P Main	Design	Medium	100
16	AF MLG Walls	Design	Medium	Fuel Transfer System	Interface	Medium	100
17	AF Rudder Bracket	Design	Medium	AF Frames	Design	Low	100
18	AF Rudder Bracket	Design	Low	AF Skin_Strgrs	Interface	Low	100
19	AF Rudder Bracket	Positioning	Medium	SP APU	Positioning	Medium	100
20	AF Skin_Strgrs	Design	Medium	Fin Skin_Strgrs	Design	Medium	100
21	AF Skin_Strgrs	Design	Medium	Fuel Aft Trim Tank 1	Design	Medium	100
22	AF Skin_Strgrs	Interface	Medium	Fuel Aft Trim Tank 2	Design	Medium	100
23	Canard P Actuators	Design	High	Canard P Foreplane	Design	High	100
24	Canard P Actuators	Design	High	FF Frames	Design	High	100
25	Canard P Actuators	Design	High	Canard S Actuators	Design	High	100
26	Canard P Actuators	Design	High	Fuel Fwd Trim Tank 2	Design	High	100
27	Canard P Foreplane	Design	High	Canard P Actuators	Design	High	100
28	Canard P Foreplane	Design	High	Canard S Foreplane	Design	High	100
29	Canard S Actuators	Design	High	FF Frames	Design	High	100
30	Canard S Actuators	Design	High	Canard S Foreplane	Design	High	100
31	Canard S Actuators	Design	High	Canard P Actuators	Design	High	100
32	Canard S Actuators	Design	High	Fuel Fwd Trim Tank 2	Design	High	100
33	Canard S Foreplane	Design	High	Canard S Actuators	Design	High	100
34	Canard S Foreplane	Design	High	Canard P Foreplane	Design	High	100
35	FF Skin_Strgrs	Design	Medium	Fuel SW Vent System	Interface	Medium	100
36	FF Skin_Strgrs	Design	Medium	Fuel PW Vent System	Interface	Medium	100
37	FF Frames	Design	Medium	Fuel SW Vent System	Interface	Medium	100
38	FF Frames	Design	Medium	Fuel PW Vent System	Interface	Medium	100
39	PAIW Kink Rib	Design	Medium	Fuel PIW Tank 3	Design	Low	100
40	PAIW Kink Rib	Design	Medium	PAIW Lower Skin_Strgrs	Design	Low	100
41	PAIW Kink Rib	Design	High	PAIW Lower Skin_Strgrs	Design	Medium	100
42	PAIW Kink Rib	Design	High	PAIW Upper Skin_Strgrs	Design	Medium	100
43	PAIW Kink Rib	Design	Medium	PAIW Upper Skin_Strgrs	Design	Low	100
44	PAIW Kink Rib	Design	Medium	PAIW Rear Spar	Design	Low	100
45	PAIW Kink Rib	Design	High	PAIW Rear Spar	Design	Medium	100
46	PAIW Kink Rib	Design	Medium	PAIW Front Spar	Design	Low	100
47	PAIW Kink Rib	Design	High	PAIW Front Spar	Design	Medium	100
48	PAIW Kink Rib	Design	Medium	PAIW LG Rear Spar	Design	Low	100
49	PAIW Kink Rib	Design	High	PAIW LG Rear Spar	Design	Medium	100
50	PAIW Kink Rib	Design	Medium	PFIW LG Front Spar	Design	Low	100
51	PAIW Kink Rib	Design	High	PFIW LG Front Spar	Design	Medium	100
52	PAIW Kink Rib	Size	High	PFIW LE Rear Spar	Size	Medium	100
53	PAIW Kink Rib	Size	Medium	PFIW LE Rear Spar	Size	Low	100
54	PAIW Kink Rib	Design	Medium	Fuel Transfer System	Interface	Medium	100
55	PAIW Lower Skin_Strgrs	Design	Medium	AF Skin_Strgrs	Design	Low	100
56	PAIW Lower Skin_Strgrs	Design	Medium	PAIW Ribs	Design	Low	100
57	PAIW Lower Skin_Strgrs	Design	Medium	PFIW LE Rear Spar	Design	Low	100
58	PAIW Lower Skin_Strgrs	Design	Medium	PAIW Kink Rib	Design	Low	100
59	PAIW Lower Skin_Strgrs	Design	Medium	LG P Main	Design	Low	100
60	PAIW Lower Skin_Strgrs	Design	Medium	PFIW LG Front Spar	Design	Low	100
61	PAIW Lower Skin_Strgrs	Design	Medium	PAIW LG Rear Spar	Design	Low	100
62	PAIW Lower Skin_Strgrs	Design	Medium	PAIW Rear Spar	Design	Low	100
63	PAIW Lower Skin_Strgrs	Design	Medium	PAIW Flaps	Design	Low	100
64	PAIW Lower Skin_Strgrs	Design	Medium	Fuel PIW Tank 3	Design	Low	100
65	PAIW Lower Skin_Strgrs	Design	Medium	Prop P Nacelle	Design	Low	100
66	PAIW Lower Skin_Strgrs	Design	Medium	PAIW Upper Skin_Strgrs	Design	Medium	100
67	PAIW Lower Skin_Strgrs	Design	High	PAIW Upper Skin_Strgrs	Design	High	100
68	PAIW Lower Skin_Strgrs	Design	Medium	PFIW Lower Skin_Strgrs	Design	Medium	100
69	PAIW Lower Skin_Strgrs	Design	High	PFIW Lower Skin_Strgrs	Design	High	100
70	PAIW Lower Skin_Strgrs	Design	Medium	POW Lower Skin_Strgrs	Design	Medium	100
71	PAIW Lower Skin_Strgrs	Design	High	POW Lower Skin_Strgrs	Design	High	100
72	PAIW Lower Skin_Strgrs	Design	Low	SAIW Lower Skin_Strgrs	Design	Low	100
73	PAIW Lower Skin_Strgrs	Design	Medium	SAIW Lower Skin_Strgrs	Design	Medium	100
74	PAIW Lower Skin_Strgrs	Design	High	SAIW Lower Skin_Strgrs	Design	High	100
75	PAIW Rear Spar	Design	Medium	PAIW Flaps	Interface	Low	100
76	PAIW Rear Spar	Design	Medium	Fuel PIW Tank 3	Size	Low	100
77	PAIW Rear Spar	Design	Medium	AF Frames	Design	Low	100
78	PAIW Rear Spar	Design	Medium	POW Rear Spar	Design	Low	100
79	PAIW Rear Spar	Design	Medium	PAIW Ribs	Design	Low	100
80	PAIW Rear Spar	Design	Medium	Fuel Transfer System	Interface	Medium	100
81	PAIW Ribs	Design	Medium	Fuel PIW Tank 3	Design	Low	100
82	PAIW Ribs	Design	Medium	PAIW Upper Skin_Strgrs	Design	Low	100
83	PAIW Ribs	Design	High	PAIW Upper Skin_Strgrs	Design	Medium	100
84	PAIW Ribs	Design	Medium	PAIW Lower Skin_Strgrs	Design	Low	100
85	PAIW Ribs	Design	High	PAIW Lower Skin_Strgrs	Design	Medium	100
86	PAIW Ribs	Design	High	PAIW Rear Spar	Design	Medium	100
87	PAIW Ribs	Design	Medium	PAIW Rear Spar	Design	Low	100
88	PAIW Ribs	Design	Medium	PAIW Front Spar	Design	Low	100
89	PAIW Ribs	Design	High	PAIW Front Spar	Design	Medium	100

90	PAIW Ribs	Design	Medium	PAIW LG Rear Spar	Design	Low	100
91	PAIW Ribs	Design	High	PAIW LG Rear Spar	Design	Medium	100
92	PAIW Ribs	Design	Medium	PFIW LG Front Spar	Design	Low	100
93	PAIW Ribs	Design	High	PFIW LG Front Spar	Design	Medium	100
94	PAIW Ribs	Design	High	PFIW LE Rear Spar	Design	Medium	100
95	PAIW Ribs	Design	Medium	PFIW LE Rear Spar	Design	Low	100
96	PAIW Ribs	Design	Medium	HLFC POW Ducting	Interface	Medium	100
97	PAIW Ribs	Design	Medium	Fuel Transfer System	Interface	Medium	100
98	PAIW Ribs	Design	Medium	Fuel PW Vent System	Interface	Medium	100
99	PAIW Upper Skin_Strgrs	Design	Medium	PAIW Lower Skin_Strgrs	Design	Medium	100
100	PAIW Upper Skin_Strgrs	Design	High	PAIW Lower Skin_Strgrs	Design	High	100
101	PAIW Upper Skin_Strgrs	Design	Medium	AF Skin_Strgrs	Design	Low	100
102	PAIW Upper Skin_Strgrs	Design	Medium	PAIW Ribs	Design	Low	100
103	PAIW Upper Skin_Strgrs	Design	Medium	PAIW Kink Rib	Design	Low	100
104	PAIW Upper Skin_Strgrs	Design	Medium	PFIW LG Front Spar	Design	Low	100
105	PAIW Upper Skin_Strgrs	Design	Medium	PAIW LG Rear Spar	Design	Low	100
106	PAIW Upper Skin_Strgrs	Design	Medium	PAIW Rear Spar	Design	Low	100
107	PAIW Upper Skin_Strgrs	Design	Medium	PAIW Flaps	Design	Low	100
108	PAIW Upper Skin_Strgrs	Design	Medium	Fuel PIW Tank 3	Design	Low	100
109	PAIW Upper Skin_Strgrs	Design	High	PFIW Upper Skin_Strgrs	Design	High	100
110	PAIW Upper Skin_Strgrs	Design	Medium	PFIW Upper Skin_Strgrs	Design	Medium	100
111	PAIW Upper Skin_Strgrs	Design	Medium	POW Upper Skin_Strgrs	Design	Medium	100
112	PAIW Upper Skin_Strgrs	Design	High	POW Upper Skin_Strgrs	Design	High	100
113	PAIW Upper Skin_Strgrs	Design	Low	SAIW Upper Skin_Strgrs	Design	Low	100
114	PAIW Upper Skin_Strgrs	Design	Medium	SAIW Upper Skin_Strgrs	Design	Medium	100
115	PAIW Upper Skin_Strgrs	Design	High	SAIW Upper Skin_Strgrs	Design	High	100
116	PFIW LE Front Spar	Design	Medium	PFIW LE Rear Spar	Design	Medium	100
117	PFIW LE Front Spar	Design	Medium	PFIW Fuselage Rib	Design	Low	100
118	PFIW LE Front Spar	Design	Medium	PFIW Fuel Boundary Panels	Design	Low	100
119	PFIW LE Front Spar	Design	Medium	Fuel PIW Tank 1	Design	Low	100
120	PFIW LE Front Spar	Design	Medium	PFIW Ribs	Design	Low	100
121	PFIW LE Front Spar	Design	Medium	PFIW Fwd Spar	Design	Low	100
122	PFIW LE Front Spar	Design	Medium	PFIW Lower Skin_Strgrs	Design	Low	100
123	PFIW LE Front Spar	Design	Medium	PFIW Upper Skin_Strgrs	Design	Low	100
124	PFIW LE Front Spar	Design	High	PFIW Fuel Boundary Panels	Design	Medium	100
125	PFIW LE Front Spar	Design	High	PFIW Fwd Spar	Design	Medium	100
126	PFIW LE Front Spar	Design	High	PFIW LE Rear Spar	Design	High	100
127	PFIW LE Front Spar	Design	High	PFIW Lower Skin_Strgrs	Design	Medium	100
128	PFIW LE Front Spar	Design	High	PFIW Ribs	Design	Medium	100
129	PFIW LE Front Spar	Design	High	PFIW Upper Skin_Strgrs	Design	Medium	100
130	PFIW LE Front Spar	Design	High	PFIW Rail Attachments	Design	High	100
131	PFIW Fuselage Rib	Design	Medium	PFIW LE Front Spar	Design	Low	100
132	PFIW Fuselage Rib	Design	High	PFIW LE Front Spar	Design	Medium	100
133	PFIW Fuselage Rib	Design	Medium	PFIW Fuel Boundary Panels	Design	Low	100
134	PFIW Fuselage Rib	Design	High	PFIW Fuel Boundary Panels	Design	Medium	100
135	PFIW Fuselage Rib	Design	Medium	PFIW Fwd Spar	Design	Low	100
136	PFIW Fuselage Rib	Design	High	PFIW Fwd Spar	Design	Medium	100
137	PFIW Fuselage Rib	Design	Medium	PFIW LG Front Spar	Design	Low	100
138	PFIW Fuselage Rib	Design	High	PFIW LG Front Spar	Design	Medium	100
139	PFIW Fuselage Rib	Design	Medium	CF Frames	Design	Low	100
140	PFIW Fuselage Rib	Design	High	CF Frames	Design	Medium	100
141	PFIW Fuselage Rib	Design	Medium	HLFC PAIW Ducting	Interface	Medium	100
142	PFIW Fuselage Rib	Design	Medium	Fuel Transfer System	Interface	Medium	100
143	PFIW Fuselage Rib	Design	Medium	PFIW Upper Skin_Strgrs	Design	Low	100
144	PFIW Fuselage Rib	Design	High	PFIW Upper Skin_Strgrs	Design	Medium	100
145	PFIW Fuselage Rib	Design	Medium	PFIW Lower Skin_Strgrs	Design	Low	100
146	PFIW Fuselage Rib	Design	High	PFIW Lower Skin_Strgrs	Design	Medium	100
147	PFIW Fuselage Rib	Design	Medium	Fuel PIW Tank 1	Design	Low	100
148	PFIW Fuselage Rib	Design	Medium	Fuel PIW Tank 2	Design	Low	100
149	PFIW Fuselage Rib	Design	High	PFIW Rail Attachments	Design	High	100
150	PFIW LG Front Spar	Design	High	CF Rear Bulkhead	Design	Medium	100
151	PFIW LG Front Spar	Design	Medium	CF Rear Bulkhead	Design	Low	100
152	PFIW LG Front Spar	Design	Medium	AF MLG Walls	Design	Low	100
153	PFIW LG Front Spar	Design	High	AF MLG Walls	Design	Medium	100
154	PFIW LG Front Spar	Design	Medium	PFIW Fuselage Rib	Design	Low	100
155	PFIW LG Front Spar	Design	High	PFIW Fuselage Rib	Design	Medium	100
156	PFIW LG Front Spar	Design	Medium	PFIW Ribs	Design	Low	100
157	PFIW LG Front Spar	Design	High	PFIW Ribs	Design	Medium	100
158	PFIW LG Front Spar	Design	Medium	PAIW Kink Rib	Design	Low	100
159	PFIW LG Front Spar	Design	High	PAIW Kink Rib	Design	Medium	100
160	PFIW LG Front Spar	Design	Medium	PAIW Ribs	Design	Low	100
161	PFIW LG Front Spar	Design	High	PAIW Ribs	Design	Medium	100
162	PFIW LG Front Spar	Design	Medium	PFIW LE Rear Spar	Design	Low	100
163	PFIW LG Front Spar	Design	High	PFIW LE Rear Spar	Design	Medium	100
164	PFIW LG Front Spar	Design	Medium	PAIW Upper Skin_Strgrs	Design	Low	100
165	PFIW LG Front Spar	Design	High	PAIW Upper Skin_Strgrs	Design	Medium	100
166	PFIW LG Front Spar	Design	Medium	PFIW Lower Skin_Strgrs	Design	Low	100
167	PFIW LG Front Spar	Design	High	PFIW Lower Skin_Strgrs	Design	Medium	100
168	PFIW LG Front Spar	Design	High	PAIW Lower Skin_Strgrs	Design	Medium	100
169	PFIW LG Front Spar	Design	Medium	PAIW Lower Skin_Strgrs	Design	Low	100
170	PFIW LG Front Spar	Design	Medium	PFIW Upper Skin_Strgrs	Design	Low	100
171	PFIW LG Front Spar	Design	High	PFIW Upper Skin_Strgrs	Design	Medium	100
172	PFIW LG Front Spar	Design	Medium	Fuel PIW Tank 2	Design	Low	100
173	PFIW LG Front Spar	Design	Medium	HLFC PAIW Ducting	Interface	Medium	100
174	PFIW LG Front Spar	Design	Medium	HLFC PFIW Ducting	Interface	Medium	100
175	PFIW Lower Skin_Strgrs	Design	Medium	PFIW LE Front Spar	Design	Low	100
176	PFIW Lower Skin_Strgrs	Design	Medium	PFIW LE Rear Spar	Design	Low	100
177	PFIW Lower Skin_Strgrs	Design	Medium	Fuel PIW Tank 1	Design	Low	100
178	PFIW Lower Skin_Strgrs	Design	Medium	Fuel PIW Tank 2	Design	Low	100
179	PFIW Lower Skin_Strgrs	Design	Medium	PFIW Ribs	Design	Low	100

180	PFIW Lower Skin_Strgrs	Design	Medium	PFIW Fuel Boundary Panels	Design	Low	100
181	PFIW Lower Skin_Strgrs	Design	Medium	PFIW Fwd Spar	Design	Low	100
182	PFIW Lower Skin_Strgrs	Design	Medium	PAIW Kink Rib	Design	Low	100
183	PFIW Lower Skin_Strgrs	Design	Medium	PFIW Fuselage Rib	Design	Low	100
184	PFIW Lower Skin_Strgrs	Design	Medium	PFIW LG Front Spar	Design	Low	100
185	PFIW Lower Skin_Strgrs	Design	Medium	CF Skin_Strgrs	Design	Low	100
186	PFIW Lower Skin_Strgrs	Design	Medium	PFIW Upper Skin_Strgrs	Design	Medium	100
187	PFIW Lower Skin_Strgrs	Design	Low	SFIW Lower Skin_Strgrs	Design	Low	100
188	PFIW Lower Skin_Strgrs	Design	Medium	SFIW Lower Skin_Strgrs	Design	Medium	100
189	PFIW Lower Skin_Strgrs	Design	High	SFIW Lower Skin_Strgrs	Design	High	100
190	PFIW LE Rear Spar	Design	Medium	PFIW LE Front Spar	Design	Medium	100
191	PFIW LE Rear Spar	Design	Medium	POW Front Spar	Design	Low	100
192	PFIW LE Rear Spar	Design	Medium	PAIW Front Spar	Design	Low	100
193	PFIW LE Rear Spar	Design	High	PFIW LE Front Spar	Design	High	100
194	PFIW LE Rear Spar	Design	Medium	PFIW Lower Skin_Strgrs	Design	Low	100
195	PFIW LE Rear Spar	Design	Medium	PFIW Upper Skin_Strgrs	Design	Low	100
196	PFIW LE Rear Spar	Design	Medium	PFIW Fwd Spar	Design	Low	100
197	PFIW LE Rear Spar	Design	Medium	Fuel PIW Tank 2	Design	Low	100
198	PFIW LE Rear Spar	Design	Medium	PFIW Ribs	Design	Low	100
199	PFIW LE Rear Spar	Design	Medium	PAIW Kink Rib	Design	Low	100
200	PFIW LE Rear Spar	Design	Medium	PAIW Ribs	Design	Low	100
201	PFIW LE Rear Spar	Design	High	POW Front Spar	Design	Medium	100
202	PFIW LE Rear Spar	Design	Medium	POW Ribs	Design	Low	100
203	PFIW LE Rear Spar	Design	Medium	HLFC POW Ducting	Interface	Medium	100
204	PFIW LE Rear Spar	Design	Medium	PAIW Lower Skin_Strgrs	Design	Low	100
205	PFIW LE Rear Spar	Design	Medium	PAIW Upper Skin_Strgrs	Design	Low	100
206	PFIW LE Rear Spar	Design	High	PAIW Front Spar	Design	Medium	100
207	PFIW LE Rear Spar	Design	High	PAIW Kink Rib	Design	Medium	100
208	PFIW LE Rear Spar	Design	High	PAIW Lower Skin_Strgrs	Design	Medium	100
209	PFIW LE Rear Spar	Design	High	PAIW Ribs	Design	Medium	100
210	PFIW LE Rear Spar	Design	High	PAIW Upper Skin_Strgrs	Design	Medium	100
211	PFIW LE Rear Spar	Design	High	PFIW Fwd Spar	Design	Medium	100
212	PFIW LE Rear Spar	Design	High	PFIW Lower Skin_Strgrs	Design	Medium	100
213	PFIW LE Rear Spar	Design	High	PFIW Ribs	Design	Medium	100
214	PFIW LE Rear Spar	Design	High	PFIW Upper Skin_Strgrs	Design	Medium	100
215	PFIW LE Rear Spar	Design	High	POW Ribs	Design	Medium	100
216	PFIW Ribs	Design	Medium	PFIW Upper Skin_Strgrs	Design	Low	100
217	PFIW Ribs	Design	High	PFIW Upper Skin_Strgrs	Design	Medium	100
218	PFIW Ribs	Design	Medium	PFIW Lower Skin_Strgrs	Design	Low	100
219	PFIW Ribs	Design	High	PFIW Lower Skin_Strgrs	Design	Medium	100
220	PFIW Ribs	Design	Medium	PFIW Fuel Boundary Panels	Design	Low	100
221	PFIW Ribs	Design	High	PFIW Fuel Boundary Panels	Design	Medium	100
222	PFIW Ribs	Design	Medium	PFIW Fwd Spar	Design	Low	100
223	PFIW Ribs	Design	High	PFIW Fwd Spar	Design	Medium	100
224	PFIW Ribs	Design	Medium	PFIW LE Front Spar	Design	Low	100
225	PFIW Ribs	Design	High	PFIW LE Front Spar	Design	Medium	100
226	PFIW Ribs	Design	Medium	PFIW LG Front Spar	Design	Low	100
227	PFIW Ribs	Design	High	PFIW LG Front Spar	Design	Medium	100
228	PFIW Ribs	Design	Medium	HLFC PAIW Ducting	Interface	Medium	100
229	PFIW Ribs	Design	Medium	Fuel Transfer System	Interface	Medium	100
230	PFIW Ribs	Design	Medium	Fuel PIW Tank 1	Design	Low	100
231	PFIW Ribs	Design	Medium	Fuel PIW Tank 2	Design	Low	100
232	PFIW Upper Skin_Strgrs	Design	Medium	PFIW Lower Skin_Strgrs	Design	Medium	100
233	PFIW Upper Skin_Strgrs	Design	High	PFIW Lower Skin_Strgrs	Design	High	100
234	PFIW Upper Skin_Strgrs	Design	Medium	PFIW LE Front Spar	Design	Low	100
235	PFIW Upper Skin_Strgrs	Design	Medium	PFIW LE Rear Spar	Design	Low	100
236	PFIW Upper Skin_Strgrs	Design	Medium	Fuel PIW Tank 1	Design	Low	100
237	PFIW Upper Skin_Strgrs	Design	Medium	Fuel PIW Tank 2	Design	Low	100
238	PFIW Upper Skin_Strgrs	Design	Medium	PFIW Ribs	Design	Low	100
239	PFIW Upper Skin_Strgrs	Design	Medium	PFIW Fuel Boundary Panels	Design	Low	100
240	PFIW Upper Skin_Strgrs	Design	Medium	PFIW Fwd Spar	Design	Low	100
241	PFIW Upper Skin_Strgrs	Design	Medium	PAIW Front Spar	Design	Low	100
242	PFIW Upper Skin_Strgrs	Design	Medium	PFIW Fuselage Rib	Design	Low	100
243	PFIW Upper Skin_Strgrs	Design	Medium	PFIW LG Front Spar	Design	Low	100
244	PFIW Upper Skin_Strgrs	Design	Medium	CF Skin_Strgrs	Design	Low	100
245	PFIW Upper Skin_Strgrs	Design	Medium	PAIW Upper Skin_Strgrs	Design	Medium	100
246	PFIW Upper Skin_Strgrs	Design	High	PAIW Upper Skin_Strgrs	Design	High	100
247	PFIW Upper Skin_Strgrs	Design	Low	SFIW Upper Skin_Strgrs	Design	Low	100
248	PFIW Upper Skin_Strgrs	Design	Medium	SFIW Upper Skin_Strgrs	Design	Medium	100
249	PFIW Upper Skin_Strgrs	Design	High	SFIW Upper Skin_Strgrs	Design	High	100
250	POW Front Spar	Design	Medium	POW Ribs	Design	Low	100
251	POW Front Spar	Design	High	POW Ribs	Design	Medium	100
252	POW Front Spar	Design	Medium	POW LE Ribs	Design	Low	100
253	POW Front Spar	Design	High	POW LE Ribs	Design	Medium	100
254	POW Front Spar	Design	Medium	POW Lower Skin_Strgrs	Design	Low	100
255	POW Front Spar	Design	High	POW Lower Skin_Strgrs	Design	Medium	100
256	POW Front Spar	Design	Medium	POW Upper Skin_Strgrs	Design	Low	100
257	POW Front Spar	Design	High	POW Upper Skin_Strgrs	Design	Medium	100
258	POW Front Spar	Design	Medium	Fuel POW Tank	Design	Low	100
259	POW Front Spar	Design	Medium	Fuel PW Vent System	Interface	Medium	100
260	POW LE Ribs	Design	Medium	POW Front Spar	Design	Low	100
261	POW LE Ribs	Design	High	POW Front Spar	Design	Medium	100
262	POW LE Ribs	Design	Medium	POW Lower Skin_Strgrs	Design	Low	100
263	POW LE Ribs	Design	High	POW Lower Skin_Strgrs	Design	Medium	100
264	POW LE Ribs	Design	Medium	POW Upper Skin_Strgrs	Design	Low	100
265	POW LE Ribs	Design	High	POW Upper Skin_Strgrs	Design	Medium	100
266	POW LE Ribs	Design	Medium	Fuel PW Vent System	Interface	Medium	100
267	POW Lower Skin_Strgrs	Design	Medium	POW Outboard Aileron	Design	Low	100
268	POW Lower Skin_Strgrs	Design	Medium	PAIW Lower Skin_Strgrs	Design	Medium	100
269	POW Lower Skin_Strgrs	Design	High	PAIW Lower Skin_Strgrs	Design	High	100

270	POW Lower Skin_Strgrs	Design	Medium	POW Wing Tip	Design	Low	100
271	POW Lower Skin_Strgrs	Design	High	POW Outboard Aileron	Design	Medium	100
272	POW Lower Skin_Strgrs	Design	Medium	POW Inboard Aileron	Design	Low	100
273	POW Lower Skin_Strgrs	Design	High	POW Inboard Aileron	Design	Medium	100
274	POW Lower Skin_Strgrs	Design	Medium	POW Rear Spar	Design	Low	100
275	POW Lower Skin_Strgrs	Design	High	POW Rear Spar	Design	Medium	100
276	POW Lower Skin_Strgrs	Design	Medium	POW Upper Skin_Strgrs	Design	Medium	100
277	POW Lower Skin_Strgrs	Design	High	POW Upper Skin_Strgrs	Design	High	100
278	POW Lower Skin_Strgrs	Design	Medium	POW LE Ribs	Design	Low	100
279	POW Lower Skin_Strgrs	Design	High	POW LE Ribs	Design	Medium	100
280	POW Lower Skin_Strgrs	Design	Medium	POW Ribs	Design	Low	100
281	POW Lower Skin_Strgrs	Design	High	POW Ribs	Design	Medium	100
282	POW Lower Skin_Strgrs	Design	Medium	Fuel POW Tank	Design	Low	100
283	POW Lower Skin_Strgrs	Design	High	POW Wing Tip	Design	Medium	100
284	POW Lower Skin_Strgrs	Design	Low	SOW Lower Skin_Strgrs	Design	Low	100
285	POW Lower Skin_Strgrs	Design	Medium	SOW Lower Skin_Strgrs	Design	Medium	100
286	POW Lower Skin_Strgrs	Design	High	SOW Lower Skin_Strgrs	Design	High	100
287	POW Rear Spar	Design	Medium	POW Inboard Aileron	Design	Medium	100
288	POW Rear Spar	Design	Medium	POW Outboard Aileron	Design	Medium	100
289	POW Ribs	Design	High	POW Wing Tip	Design	Medium	100
290	POW Ribs	Design	High	Fuel POW Tank	Design	High	100
291	POW Upper Skin_Strgrs	Design	High	POW Lower Skin_Strgrs	Design	High	100
292	POW Upper Skin_Strgrs	Design	Medium	POW Lower Skin_Strgrs	Design	Medium	100
293	POW Upper Skin_Strgrs	Design	Medium	PAIW Upper Skin_Strgrs	Design	Medium	100
294	POW Upper Skin_Strgrs	Design	High	PAIW Upper Skin_Strgrs	Design	High	100
295	POW Upper Skin_Strgrs	Design	Medium	POW Wing Tip	Design	Low	100
296	POW Upper Skin_Strgrs	Design	Medium	POW Outboard Aileron	Design	Low	100
297	POW Upper Skin_Strgrs	Design	High	POW Outboard Aileron	Design	Medium	100
298	POW Upper Skin_Strgrs	Design	Medium	POW Inboard Aileron	Design	Low	100
299	POW Upper Skin_Strgrs	Design	High	POW Inboard Aileron	Design	Medium	100
300	POW Upper Skin_Strgrs	Design	Medium	POW Rear Spar	Design	Low	100
301	POW Upper Skin_Strgrs	Design	High	POW Rear Spar	Design	Medium	100
302	POW Upper Skin_Strgrs	Design	Medium	POW LE Ribs	Design	Low	100
303	POW Upper Skin_Strgrs	Design	High	POW LE Ribs	Design	Medium	100
304	POW Upper Skin_Strgrs	Design	Medium	POW Ribs	Design	Low	100
305	POW Upper Skin_Strgrs	Design	High	POW Ribs	Design	Medium	100
306	POW Upper Skin_Strgrs	Design	Medium	Fuel POW Tank	Design	Low	100
307	POW Upper Skin_Strgrs	Design	High	POW Wing Tip	Design	Medium	100
308	POW Upper Skin_Strgrs	Design	Low	SOW Upper Skin_Strgrs	Design	Low	100
309	POW Upper Skin_Strgrs	Design	Medium	SOW Upper Skin_Strgrs	Design	Medium	100
310	POW Upper Skin_Strgrs	Design	High	SOW Upper Skin_Strgrs	Design	High	100
311	SAIW Front Spar	Design	Medium	Fuel Transfer System	Interface	Medium	100
312	SAIW Kink Rib	Design	Medium	Fuel SIW Tank 3	Design	Low	100
313	SAIW Kink Rib	Design	Medium	Fuel Transfer System	Interface	Medium	100
314	SAIW Kink Rib	Design	Medium	SAIW Front Spar	Design	Low	100
315	SAIW Kink Rib	Design	High	SAIW Front Spar	Design	Medium	100
316	SAIW Kink Rib	Design	Medium	SAIW LG Rear Spar	Design	Low	100
317	SAIW Kink Rib	Design	High	SAIW LG Rear Spar	Design	Medium	100
318	SAIW Kink Rib	Design	Medium	SAIW Lower Skin_Strgrs	Design	Low	100
319	SAIW Kink Rib	Design	High	SAIW Lower Skin_Strgrs	Design	Medium	100
320	SAIW Kink Rib	Design	Medium	SAIW Rear Spar	Design	Low	100
321	SAIW Kink Rib	Design	High	SAIW Rear Spar	Design	Medium	100
322	SAIW Kink Rib	Design	Medium	SAIW Upper Skin_Strgrs	Design	Low	100
323	SAIW Kink Rib	Design	High	SAIW Upper Skin_Strgrs	Design	Medium	100
324	SAIW Kink Rib	Design	Medium	SFIW LE Rear Spar	Design	Low	100
325	SAIW Kink Rib	Design	High	SFIW LE Rear Spar	Design	Medium	100
326	SAIW Kink Rib	Design	Medium	SFIW LG Front Spar	Design	Low	100
327	SAIW Kink Rib	Design	High	SFIW LG Front Spar	Design	Medium	100
328	SAIW Lower Skin_Strgrs	Design	Medium	SFIW LE Rear Spar	Design	Low	100
329	SAIW Lower Skin_Strgrs	Design	High	SFIW LE Rear Spar	Design	Medium	100
330	SAIW Lower Skin_Strgrs	Design	Medium	SAIW Ribs	Design	Low	100
331	SAIW Lower Skin_Strgrs	Design	High	SAIW Ribs	Design	Medium	100
332	SAIW Lower Skin_Strgrs	Design	Medium	SAIW Kink Rib	Design	Low	100
333	SAIW Lower Skin_Strgrs	Design	High	SAIW Kink Rib	Design	Medium	100
334	SAIW Lower Skin_Strgrs	Design	Medium	SFIW Lower Skin_Strgrs	Design	Medium	100
335	SAIW Lower Skin_Strgrs	Design	High	SFIW Lower Skin_Strgrs	Design	High	100
336	SAIW Lower Skin_Strgrs	Design	Medium	SFIW LG Front Spar	Design	Low	100
337	SAIW Lower Skin_Strgrs	Design	High	SFIW LG Front Spar	Design	Medium	100
338	SAIW Lower Skin_Strgrs	Design	Medium	SOW Lower Skin_Strgrs	Design	Medium	100
339	SAIW Lower Skin_Strgrs	Design	High	SOW Lower Skin_Strgrs	Design	High	100
340	SAIW Lower Skin_Strgrs	Design	Medium	AF Skin_Strgrs	Design	Low	100
341	SAIW Lower Skin_Strgrs	Design	Medium	SAIW Upper Skin_Strgrs	Design	Medium	100
342	SAIW Lower Skin_Strgrs	Design	High	SAIW Upper Skin_Strgrs	Design	High	100
343	SAIW Lower Skin_Strgrs	Design	Medium	Prop S Nacelle	Design	Low	100
344	SAIW Lower Skin_Strgrs	Design	Medium	Fuel SIW Tank 3	Design	Low	100
345	SAIW Lower Skin_Strgrs	Design	Medium	SAIW Flaps	Design	Low	100
346	SAIW Lower Skin_Strgrs	Design	High	SAIW Flaps	Design	Medium	100
347	SAIW Lower Skin_Strgrs	Design	High	SAIW LG Rear Spar	Design	Medium	100
348	SAIW Lower Skin_Strgrs	Design	Medium	SAIW LG Rear Spar	Design	Low	100
349	SAIW Lower Skin_Strgrs	Design	Medium	SAIW Rear Spar	Design	Low	100
350	SAIW Lower Skin_Strgrs	Design	High	SAIW Rear Spar	Design	Medium	100
351	SAIW Lower Skin_Strgrs	Design	Medium	LG S Main	Design	Low	100
352	SAIW Lower Skin_Strgrs	Design	Low	PAIW Lower Skin_Strgrs	Design	Low	100
353	SAIW Lower Skin_Strgrs	Design	Medium	PAIW Lower Skin_Strgrs	Design	Medium	100
354	SAIW Lower Skin_Strgrs	Design	High	PAIW Lower Skin_Strgrs	Design	High	100
355	SAIW Rear Spar	Design	Medium	Fuel Transfer System	Interface	Medium	100
356	SAIW Rear Spar	Design	Medium	SAIW Ribs	Design	Low	100
357	SAIW Rear Spar	Design	Medium	SAIW Flaps	Interface	Low	100
358	SAIW Rear Spar	Design	Medium	AF Frames	Design	Low	100
359	SAIW Rear Spar	Design	Medium	Fuel SIW Tank 3	Size	Low	100

360	SAIW Rear Spar	Design	Medium	SOW Rear Spar	Design	Low	100
361	SAIW Ribs	Design	Medium	Fuel SIW Tank 3	Design	Low	100
362	SAIW Ribs	Design	Medium	Fuel SW Vent System	Interface	Medium	100
363	SAIW Ribs	Design	Medium	Fuel Transfer System	Interface	Medium	100
364	SAIW Ribs	Design	Medium	HLFC SOW Ducting	Interface	Medium	100
365	SAIW Ribs	Design	Medium	SAIW Front Spar	Design	Low	100
366	SAIW Ribs	Design	High	SAIW Front Spar	Design	Medium	100
367	SAIW Ribs	Design	Medium	SAIW LG Rear Spar	Design	Low	100
368	SAIW Ribs	Design	High	SAIW LG Rear Spar	Design	Medium	100
369	SAIW Ribs	Size	Medium	SAIW Lower Skin_Strgrs	Design	Low	100
370	SAIW Ribs	Size	High	SAIW Lower Skin_Strgrs	Design	Medium	100
371	SAIW Ribs	Design	Medium	SAIW Rear Spar	Design	Low	100
372	SAIW Ribs	Design	High	SAIW Rear Spar	Design	Medium	100
373	SAIW Ribs	Design	Medium	SAIW Upper Skin_Strgrs	Design	Low	100
374	SAIW Ribs	Design	High	SAIW Upper Skin_Strgrs	Design	Medium	100
375	SAIW Ribs	Design	Medium	SFIW LE Front Spar	Design	Low	100
376	SAIW Ribs	Design	High	SFIW LE Front Spar	Design	Medium	100
377	SAIW Ribs	Design	Medium	SFIW LG Front Spar	Design	Low	100
378	SAIW Ribs	Design	High	SFIW LG Front Spar	Design	Medium	100
379	SAIW Upper Skin_Strgrs	Design	Medium	SAIW Ribs	Design	Low	100
380	SAIW Upper Skin_Strgrs	Design	High	SAIW Ribs	Design	Medium	100
381	SAIW Upper Skin_Strgrs	Design	Medium	SAIW Kink Rib	Design	Low	100
382	SAIW Upper Skin_Strgrs	Design	High	SAIW Kink Rib	Design	Medium	100
383	SAIW Upper Skin_Strgrs	Design	Medium	SOW Upper Skin_Strgrs	Design	Medium	100
384	SAIW Upper Skin_Strgrs	Design	High	SOW Upper Skin_Strgrs	Design	High	100
385	SAIW Upper Skin_Strgrs	Design	Medium	SFIW Upper Skin_Strgrs	Design	Medium	100
386	SAIW Upper Skin_Strgrs	Design	High	SFIW Upper Skin_Strgrs	Design	High	100
387	SAIW Upper Skin_Strgrs	Design	Medium	SFIW LG Front Spar	Design	Low	100
388	SAIW Upper Skin_Strgrs	Design	High	SFIW LG Front Spar	Design	Medium	100
389	SAIW Upper Skin_Strgrs	Design	Medium	AF Skin_Strgrs	Design	Low	100
390	SAIW Upper Skin_Strgrs	Design	Medium	SAIW Lower Skin_Strgrs	Design	Medium	100
391	SAIW Upper Skin_Strgrs	Design	High	SAIW Lower Skin_Strgrs	Design	High	100
392	SAIW Upper Skin_Strgrs	Design	Medium	Fuel SIW Tank 3	Design	Low	100
393	SAIW Upper Skin_Strgrs	Design	Medium	SAIW Flaps	Design	Low	100
394	SAIW Upper Skin_Strgrs	Design	High	SAIW Flaps	Design	Medium	100
395	SAIW Upper Skin_Strgrs	Design	Medium	SAIW LG Rear Spar	Design	Low	100
396	SAIW Upper Skin_Strgrs	Design	High	SAIW LG Rear Spar	Design	Medium	100
397	SAIW Upper Skin_Strgrs	Design	Medium	SAIW Rear Spar	Design	Low	100
398	SAIW Upper Skin_Strgrs	Design	High	SAIW Rear Spar	Design	Medium	100
399	SAIW Upper Skin_Strgrs	Design	Low	PAIW Upper Skin_Strgrs	Design	Low	100
400	SAIW Upper Skin_Strgrs	Design	Medium	PAIW Upper Skin_Strgrs	Design	Medium	100
401	SAIW Upper Skin_Strgrs	Design	High	PAIW Upper Skin_Strgrs	Design	High	100
402	SFIW Fwd Spar	Design	Medium	Fuel Transfer System	Interface	Medium	100
403	SFIW LE Front Spar	Design	High	SFIW Fuselage Rib	Design	Medium	100
404	SFIW LE Front Spar	Design	Medium	SFIW Fuel Boundary Panels	Design	Low	100
405	SFIW LE Front Spar	Design	Medium	SFIW Fuselage Rib	Design	Low	100
406	SFIW LE Front Spar	Design	High	SFIW Fuel Boundary Panels	Design	Medium	100
407	SFIW LE Front Spar	Design	Medium	SFIW Fwd Spar	Design	Low	100
408	SFIW LE Front Spar	Design	Medium	Fuel SIW Tank 1	Design	Low	100
409	SFIW LE Front Spar	Design	High	SFIW Fwd Spar	Design	Medium	100
410	SFIW LE Front Spar	Design	Medium	SFIW LE Rear Spar	Design	Medium	100
411	SFIW LE Front Spar	Design	High	SFIW LE Rear Spar	Design	High	100
412	SFIW LE Front Spar	Design	Medium	SFIW Lower Skin_Strgrs	Design	Low	100
413	SFIW LE Front Spar	Design	High	SFIW Lower Skin_Strgrs	Design	Medium	100
414	SFIW LE Front Spar	Design	Medium	SFIW Ribs	Design	Low	100
415	SFIW LE Front Spar	Design	High	SFIW Ribs	Design	Medium	100
416	SFIW LE Front Spar	Design	Medium	SFIW Upper Skin_Strgrs	Design	Low	100
417	SFIW LE Front Spar	Design	High	SFIW Upper Skin_Strgrs	Design	Medium	100
418	SFIW LE Front Spar	Design	High	SFIW Rail Attachments	Design	High	100
419	SFIW Fuel Boundary Panels	Design	Medium	Fuel Transfer System	Interface	Medium	100
420	SFIW LG Front Spar	Design	Medium	AF MLG Walls	Design	Low	100
421	SFIW LG Front Spar	Design	High	AF MLG Walls	Design	Medium	100
422	SFIW LG Front Spar	Design	Medium	CF Rear Bulkhead	Design	Low	100
423	SFIW LG Front Spar	Design	High	CF Rear Bulkhead	Design	Medium	100
424	SFIW LG Front Spar	Design	Medium	Fuel SIW Tank 2	Design	Low	100
425	SFIW LG Front Spar	Design	Medium	HLFC SAIW Ducting	Interface	Medium	100
426	SFIW LG Front Spar	Design	Medium	HLFC SFIW Ducting	Interface	Medium	100
427	SFIW LG Front Spar	Design	Medium	SAIW Kink Rib	Design	Low	100
428	SFIW LG Front Spar	Design	High	SAIW Kink Rib	Design	Medium	100
429	SFIW LG Front Spar	Design	Medium	SAIW Lower Skin_Strgrs	Design	Low	100
430	SFIW LG Front Spar	Design	High	SAIW Lower Skin_Strgrs	Design	Medium	100
431	SFIW LG Front Spar	Design	Medium	SAIW Ribs	Design	Low	100
432	SFIW LG Front Spar	Design	High	SAIW Ribs	Design	Medium	100
433	SFIW LG Front Spar	Design	Medium	SAIW Upper Skin_Strgrs	Design	Low	100
434	SFIW LG Front Spar	Design	High	SAIW Upper Skin_Strgrs	Design	Medium	100
435	SFIW LG Front Spar	Design	Medium	SFIW Fuselage Rib	Design	Low	100
436	SFIW LG Front Spar	Design	High	SFIW Fuselage Rib	Design	Medium	100
437	SFIW LG Front Spar	Design	Medium	SFIW LE Rear Spar	Design	Low	100
438	SFIW LG Front Spar	Design	High	SFIW LE Rear Spar	Design	Medium	100
439	SFIW LG Front Spar	Design	Medium	SFIW Lower Skin_Strgrs	Design	Low	100
440	SFIW LG Front Spar	Design	High	SFIW Lower Skin_Strgrs	Design	Medium	100
441	SFIW LG Front Spar	Design	Medium	SFIW Ribs	Design	Low	100
442	SFIW LG Front Spar	Design	High	SFIW Ribs	Design	Medium	100
443	SFIW LG Front Spar	Design	Medium	SFIW Upper Skin_Strgrs	Design	Low	100
444	SFIW LG Front Spar	Design	High	SFIW Upper Skin_Strgrs	Design	Low	100
445	SFIW Lower Skin_Strgrs	Design	Medium	SFIW LE Rear Spar	Design	Low	100
446	SFIW Lower Skin_Strgrs	Design	High	SFIW LE Rear Spar	Design	Medium	100
447	SFIW Lower Skin_Strgrs	Design	Medium	SAIW Kink Rib	Design	Low	100
448	SFIW Lower Skin_Strgrs	Design	High	SAIW Kink Rib	Design	Medium	100
449	SFIW Lower Skin_Strgrs	Design	Medium	SFIW Upper Skin_Strgrs	Design	Medium	100

450	SFIW Lower Skin_Strgrs	Design	High	SFIW Upper Skin_Strgrs	Design	High	100
451	SFIW Lower Skin_Strgrs	Design	Medium	SFIW Fuselage Rib	Design	Low	100
452	SFIW Lower Skin_Strgrs	Design	High	SFIW Fuselage Rib	Design	Medium	100
453	SFIW Lower Skin_Strgrs	Design	Medium	CF Skin_Strgrs	Design	Low	100
454	SFIW Lower Skin_Strgrs	Design	Medium	SFIW Ribs	Design	Low	100
455	SFIW Lower Skin_Strgrs	Design	High	SFIW Ribs	Design	Medium	100
456	SFIW Lower Skin_Strgrs	Design	Medium	SFIW LG Front Spar	Design	Low	100
457	SFIW Lower Skin_Strgrs	Design	High	SFIW LG Front Spar	Design	Medium	100
458	SFIW Lower Skin_Strgrs	Design	Medium	Fuel SIW Tank 1	Design	Low	100
459	SFIW Lower Skin_Strgrs	Design	Medium	SFIW LE Front Spar	Design	Low	100
460	SFIW Lower Skin_Strgrs	Design	High	SFIW LE Front Spar	Design	Medium	100
461	SFIW Lower Skin_Strgrs	Design	Medium	Fuel SIW Tank 2	Design	Low	100
462	SFIW Lower Skin_Strgrs	Design	Medium	SFIW Fuel Boundary Panels	Design	Low	100
463	SFIW Lower Skin_Strgrs	Design	High	SFIW Fuel Boundary Panels	Design	Medium	100
464	SFIW Lower Skin_Strgrs	Design	Medium	SFIW Fwd Spar	Design	Low	100
465	SFIW Lower Skin_Strgrs	Design	High	SFIW Fwd Spar	Design	Medium	100
466	SFIW Lower Skin_Strgrs	Design	Low	PFIW Lower Skin_Strgrs	Design	Low	100
467	SFIW Lower Skin_Strgrs	Design	Medium	PFIW Lower Skin_Strgrs	Design	Medium	100
468	SFIW Lower Skin_Strgrs	Design	High	PFIW Lower Skin_Strgrs	Design	High	100
469	SFIW LE Rear Spar	Design	Medium	SFIW LE Front Spar	Design	Medium	100
470	SFIW LE Rear Spar	Design	Medium	SOW Front Spar	Design	Low	100
471	SFIW LE Rear Spar	Design	Medium	SAIW Front Spar	Design	Low	100
472	SFIW LE Rear Spar	Design	High	SAIW Front Spar	Design	Low	100
473	SFIW LE Rear Spar	Design	High	SFIW LE Front Spar	Design	High	100
474	SFIW LE Rear Spar	Design	High	SOW Front Spar	Design	Medium	100
475	SFIW LE Rear Spar	Design	Medium	Fuel SIW Tank 2	Design	Low	100
476	SFIW LE Rear Spar	Design	Medium	HLFC SOW Ducting	Interface	Medium	100
477	SFIW LE Rear Spar	Design	Medium	SAIW Kink Rib	Design	Low	100
478	SFIW LE Rear Spar	Design	High	SAIW Kink Rib	Design	Medium	100
479	SFIW LE Rear Spar	Design	Medium	SAIW Lower Skin_Strgrs	Design	Low	100
480	SFIW LE Rear Spar	Design	High	SAIW Lower Skin_Strgrs	Design	Medium	100
481	SFIW LE Rear Spar	Design	Medium	SAIW Ribs	Design	Low	100
482	SFIW LE Rear Spar	Design	High	SAIW Ribs	Design	Medium	100
483	SFIW LE Rear Spar	Design	Medium	SAIW Upper Skin_Strgrs	Design	Low	100
484	SFIW LE Rear Spar	Design	High	SAIW Upper Skin_Strgrs	Design	Medium	100
485	SFIW LE Rear Spar	Design	Medium	SFIW Fwd Spar	Design	Low	100
486	SFIW LE Rear Spar	Design	High	SFIW Fwd Spar	Design	Medium	100
487	SFIW LE Rear Spar	Design	Medium	SFIW Lower Skin_Strgrs	Design	Low	100
488	SFIW LE Rear Spar	Design	High	SFIW Lower Skin_Strgrs	Design	Medium	100
489	SFIW LE Rear Spar	Design	Medium	SFIW Ribs	Design	Low	100
490	SFIW LE Rear Spar	Design	High	SFIW Ribs	Design	Medium	100
491	SFIW LE Rear Spar	Design	Medium	SFIW Upper Skin_Strgrs	Design	Low	100
492	SFIW LE Rear Spar	Design	High	SFIW Upper Skin_Strgrs	Design	Medium	100
493	SFIW LE Rear Spar	Design	Medium	SOW Ribs	Design	Low	100
494	SFIW LE Rear Spar	Design	High	SOW Ribs	Design	Medium	100
495	SFIW Ribs	Design	Medium	Fuel SIW Tank 2	Design	Low	100
496	SFIW Ribs	Design	Medium	Fuel SIW Tank 1	Design	Low	100
497	SFIW Ribs	Design	Medium	Fuel Transfer System	Interface	Medium	100
498	SFIW Ribs	Design	Medium	HLFC SAIW Ducting	Interface	Medium	100
499	SFIW Ribs	Design	Medium	SFIW Fuel Boundary Panels	Design	Low	100
500	SFIW Ribs	Design	High	SFIW Fuel Boundary Panels	Design	Medium	100
501	SFIW Ribs	Design	Medium	SFIW Fwd Spar	Design	Low	100
502	SFIW Ribs	Design	High	SFIW Fwd Spar	Design	Medium	100
503	SFIW Ribs	Design	Medium	SFIW LE Front Spar	Design	Low	100
504	SFIW Ribs	Design	High	SFIW LE Front Spar	Design	Medium	100
505	SFIW Ribs	Design	Medium	SFIW LG Front Spar	Design	Low	100
506	SFIW Ribs	Interface	High	SFIW LG Front Spar	Design	Medium	100
507	SFIW Ribs	Design	Medium	SFIW Lower Skin_Strgrs	Design	Low	100
508	SFIW Ribs	Design	High	SFIW Lower Skin_Strgrs	Design	Medium	100
509	SFIW Ribs	Design	Medium	SFIW Upper Skin_Strgrs	Design	Low	100
510	SFIW Ribs	Design	High	SFIW Upper Skin_Strgrs	Design	Medium	100
511	SFIW Upper Skin_Strgrs	Design	Medium	SFIW Lower Skin_Strgrs	Design	Medium	100
512	SFIW Upper Skin_Strgrs	Design	High	SFIW Lower Skin_Strgrs	Design	High	100
513	SFIW Upper Skin_Strgrs	Design	Medium	SFIW LE Rear Spar	Design	Low	100
514	SFIW Upper Skin_Strgrs	Design	High	SFIW LE Rear Spar	Design	Medium	100
515	SFIW Upper Skin_Strgrs	Design	Medium	SFIW Fuselage Rib	Design	Low	100
516	SFIW Upper Skin_Strgrs	Design	High	SFIW Fuselage Rib	Design	Medium	100
517	SFIW Upper Skin_Strgrs	Design	Medium	CF Skin_Strgrs	Design	Low	100
518	SFIW Upper Skin_Strgrs	Design	Medium	SFIW Ribs	Design	Low	100
519	SFIW Upper Skin_Strgrs	Design	High	SFIW Ribs	Design	Medium	100
520	SFIW Upper Skin_Strgrs	Design	Medium	SFIW LG Front Spar	Design	Low	100
521	SFIW Upper Skin_Strgrs	Design	High	SFIW LG Front Spar	Design	Medium	100
522	SFIW Upper Skin_Strgrs	Design	Medium	SAIW Front Spar	Design	Low	100
523	SFIW Upper Skin_Strgrs	Design	High	SAIW Front Spar	Design	Medium	100
524	SFIW Upper Skin_Strgrs	Design	Medium	Fuel SIW Tank 1	Design	Low	100
525	SFIW Upper Skin_Strgrs	Design	Medium	SAIW Upper Skin_Strgrs	Design	Medium	100
526	SFIW Upper Skin_Strgrs	Design	High	SAIW Upper Skin_Strgrs	Design	High	100
527	SFIW Upper Skin_Strgrs	Design	Medium	SFIW LE Front Spar	Design	Low	100
528	SFIW Upper Skin_Strgrs	Design	High	SFIW LE Front Spar	Design	Medium	100
529	SFIW Upper Skin_Strgrs	Design	Medium	Fuel SIW Tank 2	Design	Low	100
530	SFIW Upper Skin_Strgrs	Design	Medium	SFIW Fuel Boundary Panels	Design	Low	100
531	SFIW Upper Skin_Strgrs	Design	High	SFIW Fuel Boundary Panels	Design	Medium	100
532	SFIW Upper Skin_Strgrs	Design	Medium	SFIW Fwd Spar	Design	Low	100
533	SFIW Upper Skin_Strgrs	Design	High	SFIW Fwd Spar	Design	Medium	100
534	SFIW Upper Skin_Strgrs	Design	Low	PFIW Upper Skin_Strgrs	Design	Low	100
535	SFIW Upper Skin_Strgrs	Design	Medium	PFIW Upper Skin_Strgrs	Design	Medium	100
536	SFIW Upper Skin_Strgrs	Design	High	PFIW Upper Skin_Strgrs	Design	High	100
537	SFIW Fuselage Rib	Design	Medium	CF Frames	Design	Low	100
538	SFIW Fuselage Rib	Design	High	CF Frames	Design	Medium	100
539	SFIW Fuselage Rib	Design	Medium	Fuel SIW Tank 1	Design	Low	100

540	SFIW Fuselage Rib	Design	Medium	Fuel SIW Tank 2	Design	Low	100
541	SFIW Fuselage Rib	Design	Medium	Fuel Transfer System	Interface	Medium	100
542	SFIW Fuselage Rib	Design	Medium	HLFC SAIW Ducting	Interface	Medium	100
543	SFIW Fuselage Rib	Design	Medium	SFIW Fuel Boundary Panels	Design	Low	100
544	SFIW Fuselage Rib	Design	High	SFIW Fuel Boundary Panels	Design	Medium	100
545	SFIW Fuselage Rib	Design	Medium	SFIW Fwd Spar	Design	Low	100
546	SFIW Fuselage Rib	Design	High	SFIW Fwd Spar	Design	Medium	100
547	SFIW Fuselage Rib	Design	Medium	SFIW LE Front Spar	Design	Low	100
548	SFIW Fuselage Rib	Design	High	SFIW LE Front Spar	Design	Medium	100
549	SFIW Fuselage Rib	Design	Medium	SFIW Lower Skin_Strgrs	Design	Low	100
550	SFIW Fuselage Rib	Design	High	SFIW Lower Skin_Strgrs	Design	Medium	100
551	SFIW Fuselage Rib	Design	Medium	SFIW Upper Skin_Strgrs	Design	Low	100
552	SFIW Fuselage Rib	Design	High	SFIW Upper Skin_Strgrs	Design	Medium	100
553	SFIW Fuselage Rib	Design	Medium	SFIW LG Front Spar	Design	Low	100
554	SFIW Fuselage Rib	Design	High	SFIW LG Front Spar	Design	Medium	100
555	SFIW Fuselage Rib	Design	High	SFIW Rail Attachments	Design	High	100
556	SOW Front Spar	Design	Medium	Fuel SW Vent System	Interface	Medium	100
557	SOW Front Spar	Design	Medium	Fuel SOW Tank	Design	Low	100
558	SOW Front Spar	Design	Medium	SOW LE Ribs	Design	Low	100
559	SOW Front Spar	Design	High	SOW LE Ribs	Design	Medium	100
560	SOW Front Spar	Design	Medium	SOW Lower Skin_Strgrs	Design	Low	100
561	SOW Front Spar	Design	High	SOW Lower Skin_Strgrs	Design	Medium	100
562	SOW Front Spar	Design	Medium	SOW Ribs	Design	Low	100
563	SOW Front Spar	Design	High	SOW Ribs	Design	Medium	100
564	SOW Front Spar	Design	Medium	SOW Upper Skin_Strgrs	Design	Low	100
565	SOW Front Spar	Design	High	SOW Upper Skin_Strgrs	Design	Medium	100
566	SOW LE Ribs	Design	High	SOW Front Spar	Design	Medium	100
567	SOW LE Ribs	Design	Medium	Fuel SW Vent System	Interface	Medium	100
568	SOW LE Ribs	Design	Medium	SOW Front Spar	Design	Low	100
569	SOW LE Ribs	Design	Medium	SOW Lower Skin_Strgrs	Design	Low	100
570	SOW LE Ribs	Design	High	SOW Lower Skin_Strgrs	Design	Medium	100
571	SOW LE Ribs	Design	Medium	SOW Upper Skin_Strgrs	Design	Low	100
572	SOW LE Ribs	Design	High	SOW Upper Skin_Strgrs	Design	Medium	100
573	SOW Lower Skin_Strgrs	Design	Medium	SOW LE Ribs	Design	Low	100
574	SOW Lower Skin_Strgrs	Design	High	SOW LE Ribs	Design	Medium	100
575	SOW Lower Skin_Strgrs	Design	Medium	SOW Upper Skin_Strgrs	Design	Medium	100
576	SOW Lower Skin_Strgrs	Design	High	SOW Upper Skin_Strgrs	Design	High	100
577	SOW Lower Skin_Strgrs	Design	Medium	SAIW Lower Skin_Strgrs	Design	Medium	100
578	SOW Lower Skin_Strgrs	Design	High	SAIW Lower Skin_Strgrs	Design	High	100
579	SOW Lower Skin_Strgrs	Design	Medium	SOW Ribs	Design	Low	100
580	SOW Lower Skin_Strgrs	Design	High	SOW Ribs	Design	Medium	100
581	SOW Lower Skin_Strgrs	Design	Medium	Fuel SOW Tank	Design	Low	100
582	SOW Lower Skin_Strgrs	Design	Medium	SOW Wing Tip	Design	Low	100
583	SOW Lower Skin_Strgrs	Design	High	SOW Wing Tip	Design	Medium	100
584	SOW Lower Skin_Strgrs	Design	Medium	SOW Outboard Aileron	Design	Low	100
585	SOW Lower Skin_Strgrs	Design	High	SOW Outboard Aileron	Design	Medium	100
586	SOW Lower Skin_Strgrs	Design	Medium	SOW Inboard Aileron	Design	Low	100
587	SOW Lower Skin_Strgrs	Design	High	SOW Inboard Aileron	Design	Medium	100
588	SOW Lower Skin_Strgrs	Design	Medium	SOW Rear Spar	Design	Low	100
589	SOW Lower Skin_Strgrs	Design	High	SOW Rear Spar	Design	Medium	100
590	SOW Lower Skin_Strgrs	Design	Low	POW Lower Skin_Strgrs	Design	Low	100
591	SOW Lower Skin_Strgrs	Design	Medium	POW Lower Skin_Strgrs	Design	Medium	100
592	SOW Lower Skin_Strgrs	Design	High	POW Lower Skin_Strgrs	Design	High	100
593	SOW Rear Spar	Design	Medium	SOW Inboard Aileron	Design	Medium	100
594	SOW Rear Spar	Design	Medium	SOW Outboard Aileron	Design	Medium	100
595	SOW Ribs	Design	Medium	Fuel Transfer System	Interface	Medium	100
596	SOW Ribs	Design	High	SOW Wing Tip	Design	Medium	100
597	SOW Ribs	Design	High	Fuel SOW Tank	Design	High	100
598	SOW Upper Skin_Strgrs	Design	High	SOW Lower Skin_Strgrs	Design	High	100
599	SOW Upper Skin_Strgrs	Design	Medium	SOW Lower Skin_Strgrs	Design	Medium	100
600	SOW Upper Skin_Strgrs	Design	Medium	SOW LE Ribs	Design	Low	100
601	SOW Upper Skin_Strgrs	Design	High	SOW LE Ribs	Design	Medium	100
602	SOW Upper Skin_Strgrs	Design	Medium	SAIW Upper Skin_Strgrs	Design	Low	100
603	SOW Upper Skin_Strgrs	Design	High	SAIW Upper Skin_Strgrs	Design	Medium	100
604	SOW Upper Skin_Strgrs	Design	Medium	SOW Ribs	Design	Low	100
605	SOW Upper Skin_Strgrs	Design	High	SOW Ribs	Design	Medium	100
606	SOW Upper Skin_Strgrs	Design	Medium	Fuel SOW Tank	Design	Low	100
607	SOW Upper Skin_Strgrs	Design	Medium	SOW Wing Tip	Design	Low	100
608	SOW Upper Skin_Strgrs	Design	High	SOW Wing Tip	Design	Medium	100
609	SOW Upper Skin_Strgrs	Design	Medium	SOW Outboard Aileron	Design	Low	100
610	SOW Upper Skin_Strgrs	Design	High	SOW Outboard Aileron	Design	Medium	100
611	SOW Upper Skin_Strgrs	Design	Medium	SOW Inboard Aileron	Design	Low	100
612	SOW Upper Skin_Strgrs	Design	High	SOW Inboard Aileron	Design	Medium	100
613	SOW Upper Skin_Strgrs	Design	High	SOW Rear Spar	Design	Medium	100
614	SOW Upper Skin_Strgrs	Design	Medium	SOW Rear Spar	Design	Low	100
615	SOW Upper Skin_Strgrs	Design	Low	POW Upper Skin_Strgrs	Design	Low	100
616	SOW Upper Skin_Strgrs	Design	Medium	POW Upper Skin_Strgrs	Design	Medium	100
617	SOW Upper Skin_Strgrs	Design	High	POW Upper Skin_Strgrs	Design	High	100
618	Av HLFC Computer	Power	High	Av Doppler Radar	Power	High	100
619	Av HLFC Computer	Power	High	Av GPS	Power	High	100
620	Av HLFC Computer	Power	High	Av Radar	Power	High	100
621	Av HLFC Computer	Power	High	Av Static Probe	Power	Medium	100
622	Av HLFC Computer	Power	High	Av TCAS n ADS-B	Power	High	100
623	Av HLFC Computer	Positioning	Low	Cockpit Front Wall	Interface	Low	100
624	Cabin Interior	Design	High	Cabin Baggage Floor	Design	Medium	100
625	Cabin Interior	Design	High	Cabin Emergency Door	Design	High	100
626	Cabin Interior	Design	High	Cabin Entry Floor	Design	High	100
627	Cabin Interior	Design	High	Cabin Galley	Design	High	100
628	Cabin Interior	Design	High	Cabin Partitions	Design	High	100
629	Cabin Interior	Design	High	Cabin Slide	Design	High	100

630	Cabin Interior	Design	High	Cabin Toilet	Design	High	100
631	Cabin Interior	Design	High	Cabin Wardrobe	Design	High	100
632	EC Compressor 1	Positioning	High	Cabin Interior	Design	High	100
633	EC Compressor 1	Design	High	Fuel Transfer System	Design	High	100
634	EC Compressor 1	Positioning	High	HLFC SAIW Ducting	Positioning	High	100
635	EC Compressor 1	Positioning	High	HLFC SFIW Ducting	Positioning	High	100
636	EC Compressor 2	Positioning	High	Cabin Interior	Design	Medium	100
637	EC Compressor 2	Positioning	High	Fuel Transfer System	Positioning	High	100
638	EC Compressor 2	Positioning	High	HLFC PAIW Ducting	Positioning	High	100
639	EC Compressor 2	Positioning	High	HLFC PFIW Ducting	Positioning	High	100
640	Fuel Aft Trim Tank 1	Design	Low	Fuel PW Vent System	Interface	Medium	100
641	Fuel Aft Trim Tank 1	Design	Low	Fuel Transfer System	Interface	Medium	100
642	Fuel Aft Trim Tank 1	Design	Low	HLFC Exhaust Ducting	Interface	Low	100
643	Fuel Aft Trim Tank 1	Design	High	AF Frames	Design	High	100
644	Fuel Aft Trim Tank 1	Design	High	AF Skin_Strgrs	Design	High	100
645	Fuel Aft Trim Tank 1	Design	High	HLFC Fin Ducting	Positioning	High	100
646	Fuel Aft Trim Tank 2	Design	Low	Fuel PW Vent System	Interface	Medium	100
647	Fuel Aft Trim Tank 2	Design	Low	Fuel Transfer System	Interface	Medium	100
648	Fuel Aft Trim Tank 2	Design	Low	HLFC Exhaust Ducting	Interface	Low	100
649	Fuel Aft Trim Tank 2	Design	High	Fuel Aft Trim Tank 1	Design	High	100
650	Fuel Aft Trim Tank 2	Design	High	AF Frames	Design	High	100
651	Fuel Aft Trim Tank 2	Design	High	AF Skin_Strgrs	Design	High	100
652	Fuel Aft Trim Tank 2	Design	High	HLFC Fin Ducting	Positioning	Medium	100
653	Fuel Fwd Trim Tank 1	Design	High	Fuel Fwd Trim Tank 2	Design	High	100
654	Fuel Fwd Trim Tank 1	Design	High	FF Frames	Design	High	100
655	Fuel Fwd Trim Tank 1	Design	High	FF Skin_Strgrs	Design	High	100
656	Fuel Fwd Trim Tank 1	Design	High	Fuel SW Vent System	Positioning	Medium	100
657	Fuel Fwd Trim Tank 1	Design	High	LG Nose	Positioning	Medium	100
658	Fuel Fwd Trim Tank 2	Design	High	Fuel Fwd Trim Tank 1	Design	High	100
659	Fuel Fwd Trim Tank 2	Design	High	FF Frames	Design	High	100
660	Fuel Fwd Trim Tank 2	Design	High	Canard S Actuators	Design	High	100
661	Fuel Fwd Trim Tank 2	Design	High	Canard P Actuators	Design	High	100
662	Fuel Fwd Trim Tank 2	Design	High	Fuel SW Vent System	Design	High	100
663	Fuel Fwd Trim Tank 2	Design	High	CF Fwd Bulkhead	Design	Medium	100
664	Fuel PIW Tank 2	Design	High	Fuel Feed System	Positioning	Medium	100
665	Fuel SIW Tank 2	Design	High	Fuel Feed System	Positioning	Medium	100
666	Fuel Transfer System	Size	Medium	Fuel Jettison System	Size	Medium	100
667	HLFC Fin Ducting	Size	Medium	HLFC Fin Plenum Chambers	Size	Medium	100
668	HLFC Fin Ducting	Size	Medium	Fin Structure	Design	Low	66
669	HLFC Fin Ducting	Size	Low	Fuel Aft Trim Tank 1	Interface	Medium	100
670	HLFC Fin Ducting	Size	Low	Fuel Aft Trim Tank 2	Interface	Medium	100
671	HLFC Fin Ducting	Size	High	Fin Structure	Design	Medium	66
672	HLFC Fin Ducting	Size	High	Fin Skin_Strgrs	Design	High	100
673	HLFC Fin Ducting	Size	High	HLFC Fin Plenum Chambers	Size	High	100
674	HLFC Fin Motor	Power	High	SP Generator 1	Power	Low	100
675	HLFC Fin Motor	Power	High	SP Generator 2	Power	Low	100
676	HLFC Fin Motor	Power	Low	HLFC Fin Motor	Size	Low	100
677	HLFC Fin Motor	Power	Medium	HLFC Fin Motor	Size	Medium	100
678	HLFC Fin Motor	Power	High	HLFC Fin Motor	Size	High	100
679	HLFC Fin Plenum Chambers	Size	Low	Fin Skin_Strgrs	Design	Low	66
680	HLFC Fin Plenum Chambers	Size	High	Fin Skin_Strgrs	Design	Medium	66
681	HLFC Fin Plenum Chambers	Size	High	Fin Structure	Design	Medium	100
682	HLFC Fin Pump	Power	Medium	HLFC Fin Ducting	Size	Medium	100
683	HLFC Fin Pump	Power	Medium	HLFC Fin Motor	Power	Medium	100
684	HLFC Fin Pump	Power	Medium	HLFC Fin Flow Control Valve	Size	Medium	66
685	HLFC Fin Pump	Power	Medium	HLFC Fin Pump	Size	Medium	100
686	HLFC Fin Pump	Power	Medium	HLFC Exhaust Ducting	Size	Low	66
687	HLFC Fin Pump	Size	Low	AF MLG Walls	Interface	Low	100
688	HLFC Fin Pump	Power	Low	HLFC Fin Motor	Power	Low	100
689	HLFC Fin Pump	Power	Low	HLFC Fin Pump	Size	Low	100
690	HLFC Fin Pump	Power	High	HLFC Fin Pump	Size	High	100
691	HLFC Fin Pump	Power	High	HLFC Fin Motor	Power	High	100
692	HLFC Fin Pump	Power	High	HLFC Fin Flow Control Valve	Size	High	66
693	HLFC Fin Pump	Power	High	HLFC Fin Ducting	Size	High	100
694	HLFC Fin Pump	Power	High	HLFC Exhaust Ducting	Size	Medium	66
695	HLFC PAIW Ducting	Size	Medium	HLFC PIW Plenum Chambers	Size	Medium	100
696	HLFC PAIW Ducting	Size	High	PFIW LE Front Spar	Design	Medium	100
697	HLFC PAIW Ducting	Size	High	PFIW LE Rear Spar	Design	Medium	100
698	HLFC PAIW Ducting	Size	Medium	PFIW Ribs	Design	Low	100
699	HLFC PAIW Ducting	Size	Medium	PFIW Fuselage Rib	Design	Low	100
700	HLFC PAIW Ducting	Size	Low	CF Rear Bulkhead	Interface	Medium	100
701	HLFC PAIW Ducting	Size	Low	CF Skin_Strgrs	Interface	Medium	100
702	HLFC PAIW Ducting	Size	Medium	PFIW LG Front Spar	Design	Low	100
703	HLFC PAIW Ducting	Size	Medium	Cabin Interior	Design	Low	100
704	HLFC PAIW Ducting	Size	Low	Fuel PIW Tank 1	Interface	Medium	100
705	HLFC PAIW Ducting	Size	High	PFIW Lower Skin_Strgrs	Design	Medium	100
706	HLFC PAIW Ducting	Size	High	EC Cold Air Unit 2	Positioning	Low	100
707	HLFC PAIW Ducting	Size	High	EC Compressor 2	Positioning	Low	100
708	HLFC PAIW Ducting	Size	High	LG P Main	Design	Medium	100
709	HLFC PAIW Ducting	Size	High	HLFC PIW Plenum Chambers	Size	High	100
710	HLFC PAIW Ducting	Size	High	PFIW Fuselage Rib	Design	Medium	100
711	HLFC PAIW Ducting	Size	High	PFIW LG Front Spar	Design	Medium	100
712	HLFC PAIW Ducting	Size	Medium	PFIW Lower Skin_Strgrs	Design	Low	100
713	HLFC PAIW Ducting	Size	High	PFIW Ribs	Design	Medium	100
714	HLFC PAIW Ducting	Size	High	Fuel Transfer System	Positioning	Low	100
715	HLFC PAIW Ducting	Size	Medium	PFIW LE Front Spar	Design	Low	100
716	HLFC PAIW Ducting	Size	Medium	HLFC PAIW Pump	Size	Low	100
717	HLFC PAIW Motor	Power	High	SP Generator 2	Power	Low	100
718	HLFC PAIW Motor	Power	High	SP Generator 1	Power	Low	100
719	HLFC PAIW Motor	Power	Low	HLFC PAIW Motor	Size	Low	100

720	HLFC PAIW Motor	Power	Medium	HLFC PAIW Motor	Size	Medium	100
721	HLFC PAIW Motor	Power	High	HLFC PAIW Motor	Size	High	100
722	HLFC PIW Plenum Chambers	Size	Low	PFIW Upper Skin_Strgrs	Design	Low	66
723	HLFC PIW Plenum Chambers	Size	High	PFIW Upper Skin_Strgrs	Design	Medium	66
724	HLFC PIW Plenum Chambers	Size	High	PFIW LE Front Spar	Design	Medium	100
725	HLFC PIW Plenum Chambers	Size	High	PFIW LE Rear Spar	Design	Medium	100
726	HLFC PIW Plenum Chambers	Size	Low	PAIW Upper Skin_Strgrs	Design	Low	66
727	HLFC PIW Plenum Chambers	Size	High	PAIW Upper Skin_Strgrs	Design	Medium	66
728	HLFC PIW Plenum Chambers	Size	Medium	PFIW LE Front Spar	Design	Low	100
729	HLFC PIW Plenum Chambers	Size	Medium	PFIW LE Rear Spar	Design	Low	100
730	HLFC PAIW Pump	Power	Medium	HLFC PAIW Ducting	Size	Medium	100
731	HLFC PAIW Pump	Power	Medium	HLFC PAIW Flow Control Valve	Size	Medium	66
732	HLFC PAIW Pump	Power	Medium	HLFC PAIW Motor	Power	Medium	100
733	HLFC PAIW Pump	Power	Medium	HLFC PAIW Pump	Size	Medium	100
734	HLFC PAIW Pump	Size	Low	CF Frames	Interface	Low	100
735	HLFC PAIW Pump	Power	Low	HLFC PAIW Pump	Size	Low	100
736	HLFC PAIW Pump	Power	Low	HLFC PAIW Motor	Power	Low	100
737	HLFC PAIW Pump	Power	High	HLFC PAIW Pump	Size	High	100
738	HLFC PAIW Pump	Power	High	HLFC PAIW Motor	Power	High	100
739	HLFC PAIW Pump	Power	Medium	HLFC Exhaust Ducting	Size	Low	66
740	HLFC PAIW Pump	Power	High	HLFC PAIW Flow Control Valve	Size	High	66
741	HLFC PAIW Pump	Power	High	HLFC PAIW Ducting	Size	High	100
742	HLFC PAIW Pump	Power	High	HLFC Exhaust Ducting	Size	Medium	66
743	HLFC PAIW Pump	Size	Medium	Fuel Transfer System	Positioning	Low	100
744	HLFC PAIW Pump	Power	Low	HLFC SAIW Pump	Power	Low	100
745	HLFC PAIW Pump	Power	Medium	HLFC SAIW Pump	Power	Medium	100
746	HLFC PAIW Pump	Power	High	HLFC SAIW Pump	Power	High	100
747	HLFC PFIW Ducting	Size	High	PFIW LE Front Spar	Design	Medium	33
748	HLFC PFIW Ducting	Size	Low	CF Fwd Bulkhead	Interface	Medium	100
749	HLFC PFIW Ducting	Size	Low	CF Rear Bulkhead	Interface	Medium	100
750	HLFC PFIW Ducting	Size	Low	FF Skin_Strgrs	Interface	Medium	100
751	HLFC PFIW Ducting	Size	Medium	PFIW LG Front Spar	Design	Low	100
752	HLFC PFIW Ducting	Size	High	Fuel Fwd Trim Tank 2	Design	Low	66
753	HLFC PFIW Ducting	Size	Medium	Cockpit Front Wall	Design	Low	100
754	HLFC PFIW Ducting	Size	High	PFIW Lower Skin_Strgrs	Design	Medium	33
755	HLFC PFIW Ducting	Size	High	LG P Main	Design	Medium	33
756	HLFC PFIW Ducting	Size	High	EC Cold Air Unit 2	Positioning	Low	100
757	HLFC PFIW Ducting	Size	High	EC Compressor 2	Positioning	Low	100
758	HLFC PFIW Ducting	Size	High	Canard P Actuators	Design	Low	100
759	HLFC PFIW Ducting	Size	High	PFIW Fuselage Rib	Design	Low	33
760	HLFC PFIW Ducting	Size	Medium	HLFC PIW Plenum Chambers	Size	Medium	100
761	HLFC PFIW Ducting	Size	High	HLFC PIW Plenum Chambers	Size	High	100
762	HLFC PFIW Ducting	Size	High	PFIW LG Front Spar	Design	Medium	33
763	HLFC PFIW Ducting	Size	Medium	PFIW Lower Skin_Strgrs	Design	Low	33
764	HLFC PFIW Ducting	Size	High	Fuel Transfer System	Positioning	Low	100
765	HLFC PFIW Ducting	Size	Medium	HLFC PFIW Pump	Size	Low	100
766	HLFC PFIW Motor	Power	High	SP Generator 1	Power	Low	66
767	HLFC PFIW Motor	Power	High	SP Generator 2	Power	Low	66
768	HLFC PFIW Motor	Power	Low	HLFC PFIW Motor	Size	Low	100
769	HLFC PFIW Motor	Power	Medium	HLFC PFIW Motor	Size	Medium	100
770	HLFC PFIW Motor	Power	High	HLFC PFIW Motor	Size	High	100
771	HLFC PFIW Motor	Size	High	Fuel Fwd Trim Tank 2	Design	Low	33
772	HLFC PFIW Pump	Power	Medium	HLFC Exhaust Ducting	Size	Low	66
773	HLFC PFIW Pump	Power	Medium	HLFC PFIW Ducting	Size	Medium	100
774	HLFC PFIW Pump	Power	Medium	HLFC PFIW Motor	Power	Medium	100
775	HLFC PFIW Pump	Power	Medium	HLFC PFIW Flow Control Valve	Size	Medium	66
776	HLFC PFIW Pump	Power	Medium	HLFC PFIW Pump	Size	Medium	100
777	HLFC PFIW Pump	Size	Medium	Fuel Fwd Trim Tank 2	Design	Low	33
778	HLFC PFIW Pump	Size	Medium	Fuel Transfer System	Positioning	Low	100
779	HLFC PFIW Pump	Power	Low	HLFC PFIW Pump	Size	Low	100
780	HLFC PFIW Pump	Power	High	HLFC PFIW Pump	Size	High	100
781	HLFC PFIW Pump	Power	Low	HLFC PFIW Motor	Power	Low	100
782	HLFC PFIW Pump	Power	High	HLFC PFIW Motor	Power	High	100
783	HLFC PFIW Pump	Power	High	HLFC Exhaust Ducting	Size	Medium	66
784	HLFC PFIW Pump	Power	High	HLFC PFIW Flow Control Valve	Size	High	66
785	HLFC PFIW Pump	Power	High	HLFC PFIW Ducting	Size	High	100
786	HLFC PFIW Pump	Power	Low	HLFC SFIW Pump	Power	Low	100
787	HLFC PFIW Pump	Power	Medium	HLFC SFIW Pump	Power	Medium	100
788	HLFC PFIW Pump	Power	High	HLFC SFIW Pump	Power	High	100
789	HLFC PFIW Pump	Size	Low	FF Frames	Interface	Low	100
790	HLFC POW Ducting	Size	Medium	HLFC POW Plenum Chambers	Size	Medium	100
791	HLFC POW Ducting	Size	Medium	POW LE Ribs	Design	Low	100
792	HLFC POW Ducting	Size	High	PFIW LE Rear Spar	Design	Medium	100
793	HLFC POW Ducting	Size	Medium	PAIW Ribs	Design	Low	100
794	HLFC POW Ducting	Size	Medium	PAIW Kink Rib	Design	Low	100
795	HLFC POW Ducting	Size	Low	AF MLG Walls	Interface	Low	33
796	HLFC POW Ducting	Size	Medium	Fuel PW Vent System	Positioning	Low	100
797	HLFC POW Ducting	Size	High	HLFC POW Plenum Chambers	Size	High	100
798	HLFC POW Ducting	Size	High	PAIW Kink Rib	Design	Medium	100
799	HLFC POW Ducting	Size	High	PAIW Ribs	Design	Medium	100
800	HLFC POW Ducting	Size	Medium	PFIW LE Rear Spar	Design	Low	100
801	HLFC POW Ducting	Size	High	POW LE Ribs	Design	Medium	100
802	HLFC POW Ducting	Size	High	POW Front Spar	Design	Medium	100
803	HLFC POW Ducting	Size	Medium	POW Lower Skin_Strgrs	Design	Low	100
804	HLFC POW Ducting	Size	High	POW Lower Skin_Strgrs	Design	Medium	100
805	HLFC POW Ducting	Size	Medium	HLFC POW Pump	Size	Low	100
806	HLFC POW Motor	Power	High	SP Generator 1	Power	Low	100
807	HLFC POW Motor	Power	High	SP Generator 2	Power	Low	100
808	HLFC POW Motor	Power	Low	HLFC POW Motor	Size	Low	100
809	HLFC POW Motor	Power	Medium	HLFC POW Motor	Size	Medium	100

810	HLFC POW Motor	Power	High	HLFC POW Motor	Size	High	100
811	HLFC POW Motor	Size	Low	AF MLG Walls	Interface	Low	66
812	HLFC POW Plenum Chambers	Size	Medium	POW LE Ribs	Design	Low	100
813	HLFC POW Plenum Chambers	Size	High	POW LE Ribs	Design	Medium	100
814	HLFC POW Plenum Chambers	Size	Medium	POW Front Spar	Design	Low	100
815	HLFC POW Plenum Chambers	Size	Low	POW Upper Skin_Strgrs	Design	Low	100
816	HLFC POW Plenum Chambers	Size	High	POW Upper Skin_Strgrs	Design	Medium	100
817	HLFC POW Plenum Chambers	Size	High	POW Front Spar	Design	Medium	100
818	HLFC POW Pump	Power	Medium	HLFC POW Ducting	Size	Medium	100
819	HLFC POW Pump	Power	Medium	HLFC POW Flow Control Valve	Size	Medium	66
820	HLFC POW Pump	Power	Medium	HLFC POW Motor	Power	Medium	100
821	HLFC POW Pump	Power	Medium	HLFC Exhaust Ducting	Size	Low	66
822	HLFC POW Pump	Power	Low	HLFC POW Pump	Size	Low	100
823	HLFC POW Pump	Power	Medium	HLFC POW Pump	Size	Medium	100
824	HLFC POW Pump	Power	High	HLFC POW Pump	Size	High	100
825	HLFC POW Pump	Power	Low	HLFC POW Motor	Power	Low	100
826	HLFC POW Pump	Power	High	HLFC POW Motor	Power	High	100
827	HLFC POW Pump	Power	High	HLFC POW Flow Control Valve	Size	High	66
828	HLFC POW Pump	Power	High	HLFC Exhaust Ducting	Size	Medium	66
829	HLFC POW Pump	Power	High	HLFC POW Ducting	Size	High	100
830	HLFC POW Pump	Size	Low	AF MLG Walls	Interface	Low	100
831	HLFC POW Pump	Power	Low	HLFC SOW Pump	Power	Low	100
832	HLFC POW Pump	Power	Medium	HLFC SOW Pump	Power	Medium	100
833	HLFC POW Pump	Power	High	HLFC SOW Pump	Power	High	100
834	HLFC SAIW Ducting	Size	Medium	HLFC SIW Plenum Chambers	Size	Medium	100
835	HLFC SAIW Ducting	Size	High	SFIW LE Front Spar	Design	Medium	100
836	HLFC SAIW Ducting	Size	High	SFIW LE Rear Spar	Design	Medium	100
837	HLFC SAIW Ducting	Size	Medium	SFIW Ribs	Design	Low	100
838	HLFC SAIW Ducting	Size	Medium	SFIW Fuselage Rib	Design	Low	100
839	HLFC SAIW Ducting	Size	Low	CF Rear Bulkhead	Interface	Medium	100
840	HLFC SAIW Ducting	Size	Low	CF Skin_Strgrs	Interface	Medium	100
841	HLFC SAIW Ducting	Size	Medium	SFIW LG Front Spar	Design	Low	100
842	HLFC SAIW Ducting	Size	Low	Fuel SIW Tank 1	Interface	Medium	100
843	HLFC SAIW Ducting	Size	High	SFIW Lower Skin_Strgrs	Design	Medium	100
844	HLFC SAIW Ducting	Size	High	Cabin Toilet	Design	Low	100
845	HLFC SAIW Ducting	Size	High	LG S Main	Design	Medium	100
846	HLFC SAIW Ducting	Size	High	EC Cold Air Unit 1	Positioning	Low	100
847	HLFC SAIW Ducting	Size	High	EC Compressor 1	Positioning	Low	100
848	HLFC SAIW Ducting	Size	High	HLFC SIW Plenum Chambers	Size	High	100
849	HLFC SAIW Ducting	Size	High	Fuel Transfer System	Positioning	Low	100
850	HLFC SAIW Ducting	Size	High	SFIW LG Front Spar	Design	Medium	100
851	HLFC SAIW Ducting	Size	High	SFIW Ribs	Design	Medium	100
852	HLFC SAIW Ducting	Size	High	SFIW Fuselage Rib	Design	Medium	100
853	HLFC SAIW Ducting	Size	Medium	SFIW Lower Skin_Strgrs	Design	Low	100
854	HLFC SAIW Ducting	Size	Medium	Cabin Interior	Design	Low	100
855	HLFC SAIW Ducting	Size	Medium	SFIW LE Front Spar	Design	Low	100
856	HLFC SAIW Ducting	Size	Medium	HLFC SAIW Pump	Size	Low	100
857	HLFC SAIW Motor	Power	High	SP Generator 1	Power	Low	100
858	HLFC SAIW Motor	Power	High	SP Generator 2	Power	Low	100
859	HLFC SAIW Motor	Power	Low	HLFC SAIW Motor	Size	Low	100
860	HLFC SAIW Motor	Power	Medium	HLFC SAIW Motor	Size	Medium	100
861	HLFC SAIW Motor	Power	High	HLFC SAIW Motor	Size	High	100
862	HLFC SIW Plenum Chambers	Size	High	SFIW Upper Skin_Strgrs	Design	Medium	33
863	HLFC SIW Plenum Chambers	Size	Low	SFIW Upper Skin_Strgrs	Design	Low	33
864	HLFC SIW Plenum Chambers	Size	High	SFIW LE Front Spar	Design	Medium	66
865	HLFC SIW Plenum Chambers	Size	High	SFIW LE Rear Spar	Design	Medium	66
866	HLFC SIW Plenum Chambers	Size	Medium	SFIW LE Front Spar	Design	Low	66
867	HLFC SIW Plenum Chambers	Size	Medium	SFIW LE Rear Spar	Design	Low	66
868	HLFC SIW Plenum Chambers	Size	Low	SAIW Upper Skin_Strgrs	Design	Low	33
869	HLFC SIW Plenum Chambers	Size	High	SAIW Upper Skin_Strgrs	Design	Medium	33
870	HLFC SAIW Pump	Power	Medium	HLFC SAIW Ducting	Size	Medium	100
871	HLFC SAIW Pump	Power	Medium	HLFC SAIW Flow Control Valve	Size	Medium	66
872	HLFC SAIW Pump	Power	Medium	HLFC SAIW Motor	Power	Medium	100
873	HLFC SAIW Pump	Power	Medium	HLFC SAIW Pump	Size	Medium	100
874	HLFC SAIW Pump	Size	Low	CF Frames	Interface	Low	100
875	HLFC SAIW Pump	Power	Low	HLFC SAIW Pump	Size	Low	100
876	HLFC SAIW Pump	Power	Low	HLFC SAIW Motor	Power	Low	100
877	HLFC SAIW Pump	Power	High	HLFC SAIW Pump	Size	High	100
878	HLFC SAIW Pump	Power	High	HLFC SAIW Motor	Power	High	100
879	HLFC SAIW Pump	Power	Medium	HLFC Exhaust Ducting	Size	Low	66
880	HLFC SAIW Pump	Power	High	HLFC Exhaust Ducting	Size	Medium	66
881	HLFC SAIW Pump	Power	High	HLFC SAIW Ducting	Size	High	100
882	HLFC SAIW Pump	Power	High	HLFC SAIW Flow Control Valve	Size	High	66
883	HLFC SAIW Pump	Size	Medium	Fuel Transfer System	Positioning	Low	100
884	HLFC SAIW Pump	Power	Low	HLFC PAIW Pump	Power	Low	100
885	HLFC SAIW Pump	Power	Medium	HLFC PAIW Pump	Power	Medium	100
886	HLFC SAIW Pump	Power	High	HLFC PAIW Pump	Power	High	100
887	HLFC SFIW Ducting	Size	High	SFIW LE Front Spar	Design	Medium	33
888	HLFC SFIW Ducting	Size	Low	CF Fwd Bulkhead	Interface	Medium	100
889	HLFC SFIW Ducting	Size	Low	CF Rear Bulkhead	Interface	Medium	100
890	HLFC SFIW Ducting	Size	Low	FF Skin_Strgrs	Interface	Medium	33
891	HLFC SFIW Ducting	Size	Medium	SFIW LG Front Spar	Design	Low	66
892	HLFC SFIW Ducting	Size	High	Fuel Fwd Trim Tank 2	Design	Medium	66
893	HLFC SFIW Ducting	Size	Medium	Cockpit Front Wall	Design	Low	100
894	HLFC SFIW Ducting	Size	High	SFIW Lower Skin_Strgrs	Design	Medium	33
895	HLFC SFIW Ducting	Size	High	Cabin Toilet	Design	Medium	100
896	HLFC SFIW Ducting	Size	High	LG S Main	Design	Medium	33
897	HLFC SFIW Ducting	Size	High	EC Cold Air Unit 1	Positioning	Low	100
898	HLFC SFIW Ducting	Size	High	EC Compressor 1	Positioning	Low	100
899	HLFC SFIW Ducting	Size	High	Canard S Actuators	Design	Low	100

900	HLFC SFIW Ducting	Size	High	SFIW Fuselage Rib	Design	Low	33
901	HLFC SFIW Ducting	Size	High	Fuel Transfer System	Positioning	Low	100
902	HLFC SFIW Ducting	Size	Medium	HLFC SIW Plenum Chambers	Size	Medium	100
903	HLFC SFIW Ducting	Size	High	HLFC SIW Plenum Chambers	Size	High	100
904	HLFC SFIW Ducting	Size	High	SFIW LG Front Spar	Design	Medium	33
905	HLFC SFIW Ducting	Size	Medium	SFIW Lower Skin_Strgrs	Design	Low	33
906	HLFC SFIW Ducting	Size	Medium	HLFC SFIW Pump	Size	Low	100
907	HLFC SFIW Motor	Power	High	SP Generator 1	Power	Low	66
908	HLFC SFIW Motor	Power	High	SP Generator 2	Power	Low	66
909	HLFC SFIW Motor	Power	Low	HLFC SFIW Motor	Size	Low	100
910	HLFC SFIW Motor	Power	Medium	HLFC SFIW Motor	Size	Medium	100
911	HLFC SFIW Motor	Power	High	HLFC SFIW Motor	Size	High	100
912	HLFC SFIW Motor	Size	High	Fuel Fwd Trim Tank 2	Design	Low	33
913	HLFC SFIW Pump	Power	Medium	HLFC Exhaust Ducting	Size	Low	66
914	HLFC SFIW Pump	Power	Medium	HLFC SFIW Ducting	Size	Medium	100
915	HLFC SFIW Pump	Power	Medium	HLFC SFIW Flow Control Valve	Size	Medium	66
916	HLFC SFIW Pump	Power	Medium	HLFC SFIW Motor	Power	Medium	100
917	HLFC SFIW Pump	Power	Low	HLFC SFIW Pump	Size	Low	100
918	HLFC SFIW Pump	Size	Medium	Fuel Fwd Trim Tank 2	Design	Low	33
919	HLFC SFIW Pump	Power	Medium	HLFC SFIW Pump	Size	Medium	100
920	HLFC SFIW Pump	Power	High	HLFC SFIW Pump	Size	High	100
921	HLFC SFIW Pump	Power	Low	HLFC SFIW Motor	Power	Low	100
922	HLFC SFIW Pump	Power	High	HLFC SFIW Motor	Power	High	100
923	HLFC SFIW Pump	Power	High	HLFC SFIW Ducting	Size	High	100
924	HLFC SFIW Pump	Power	High	HLFC Exhaust Ducting	Size	Medium	66
925	HLFC SFIW Pump	Power	High	HLFC SFIW Flow Control Valve	Size	High	66
926	HLFC SFIW Pump	Power	Low	HLFC PFIW Pump	Power	Low	100
927	HLFC SFIW Pump	Power	Medium	HLFC PFIW Pump	Power	Medium	100
928	HLFC SFIW Pump	Power	High	HLFC PFIW Pump	Power	High	100
929	HLFC SFIW Pump	Size	Low	FF Frames	Interface	Low	100
930	HLFC SOW Ducting	Size	Medium	HLFC SOW Plenum Chambers	Size	Medium	100
931	HLFC SOW Ducting	Size	Medium	SOW LE Ribs	Design	Low	100
932	HLFC SOW Ducting	Size	Medium	SFIW LE Rear Spar	Design	Low	100
933	HLFC SOW Ducting	Size	Medium	SAIW Ribs	Design	Low	100
934	HLFC SOW Ducting	Size	Medium	SAIW Kink Rib	Design	Low	100
935	HLFC SOW Ducting	Size	Low	AF MLG Walls	Interface	Low	33
936	HLFC SOW Ducting	Size	High	SOW Lower Skin_Strgrs	Design	Medium	100
937	HLFC SOW Ducting	Size	High	HLFC SOW Plenum Chambers	Size	High	100
938	HLFC SOW Ducting	Size	High	SAIW Kink Rib	Design	Medium	100
939	HLFC SOW Ducting	Size	High	SAIW Ribs	Design	Medium	100
940	HLFC SOW Ducting	Size	High	SFIW LE Rear Spar	Design	Medium	100
941	HLFC SOW Ducting	Size	High	SOW LE Ribs	Design	Medium	100
942	HLFC SOW Ducting	Size	Medium	SOW Lower Skin_Strgrs	Design	Low	100
943	HLFC SOW Ducting	Size	High	SOW Front Spar	Design	Medium	100
944	HLFC SOW Ducting	Size	Medium	HLFC SOW Pump	Size	Low	100
945	HLFC SOW Motor	Power	High	SP Generator 1	Power	Low	100
946	HLFC SOW Motor	Power	High	SP Generator 2	Power	Low	100
947	HLFC SOW Motor	Power	Low	HLFC SOW Motor	Size	Low	100
948	HLFC SOW Motor	Power	Medium	HLFC SOW Motor	Size	Medium	100
949	HLFC SOW Motor	Power	High	HLFC SOW Motor	Size	High	100
950	HLFC SOW Motor	Size	Low	AF MLG Walls	Interface	Low	66
951	HLFC SOW Plenum Chambers	Size	Medium	SOW LE Ribs	Design	Low	100
952	HLFC SOW Plenum Chambers	Size	Low	SOW Upper Skin_Strgrs	Design	Low	100
953	HLFC SOW Plenum Chambers	Size	High	SOW Upper Skin_Strgrs	Design	Medium	100
954	HLFC SOW Plenum Chambers	Size	High	SOW LE Ribs	Design	Medium	100
955	HLFC SOW Plenum Chambers	Size	Medium	SOW Front Spar	Design	Low	100
956	HLFC SOW Plenum Chambers	Size	High	SOW Front Spar	Design	Medium	100
957	HLFC SOW Pump	Power	Medium	HLFC SOW Ducting	Size	Medium	100
958	HLFC SOW Pump	Power	Medium	HLFC SOW Flow Control Valve	Size	Medium	66
959	HLFC SOW Pump	Power	Medium	HLFC SOW Motor	Power	Medium	100
960	HLFC SOW Pump	Power	Low	HLFC SOW Pump	Size	Low	100
961	HLFC SOW Pump	Power	Medium	HLFC Exhaust Ducting	Size	Low	66
962	HLFC SOW Pump	Power	Medium	HLFC SOW Pump	Size	Medium	100
963	HLFC SOW Pump	Power	High	HLFC SOW Pump	Size	High	100
964	HLFC SOW Pump	Power	Low	HLFC SOW Motor	Power	Low	100
965	HLFC SOW Pump	Power	High	HLFC SOW Motor	Power	High	100
966	HLFC SOW Pump	Size	Low	AF MLG Walls	Interface	Low	100
967	HLFC SOW Pump	Power	High	HLFC Exhaust Ducting	Size	Medium	66
968	HLFC SOW Pump	Power	High	HLFC SOW Ducting	Size	High	100
969	HLFC SOW Pump	Power	High	HLFC SOW Flow Control Valve	Size	High	66
970	HLFC SOW Pump	Power	Low	HLFC POW Pump	Power	Low	100
971	HLFC SOW Pump	Power	Medium	HLFC POW Pump	Power	Medium	100
972	HLFC SOW Pump	Power	High	HLFC POW Pump	Power	High	100
973	Prop P Engine	Size	Medium	PAIW Ribs	Design	Medium	100
974	Prop P Engine	Power	High	SP Generator 2	Power	Low	100
975	Prop P Engine	Power	Medium	Prop P Engine	Size	Medium	100
976	Prop P Engine	Power	High	Prop P Engine	Size	High	100
977	Prop P Engine	Power	Medium	Prop S Engine	Power	Medium	100
978	Prop P Engine	Power	High	Prop S Engine	Power	High	100
979	Prop P Engine	Size	Medium	Prop P Nacelle	Design	Low	100
980	Prop P Engine	Size	High	Prop P Nacelle	Design	Medium	100
981	Prop P Engine	Size	High	PAIW Rear Spar	Design	Medium	100
982	Prop P Engine	Size	High	POW Ribs	Design	Medium	100
983	Prop P Engine	Size	High	POW Rear Spar	Design	Medium	100
984	Prop P Nacelle	Design	Medium	PAIW Front Spar	Design	Low	100
985	Prop P Nacelle	Design	Medium	PAIW Rear Spar	Design	Low	100
986	Prop P Nacelle	Design	Medium	PAIW Ribs	Design	Low	100
987	Prop P Nacelle	Design	Medium	PAIW Lower Skin_Strgrs	Design	Medium	100
988	Prop P Nacelle	Design	Medium	POW Lower Skin_Strgrs	Design	Medium	100
989	Prop P Nacelle	Design	Medium	POW Ribs	Design	Low	100

990	Prop P Nacelle	Design	Medium	POW Rear Spar	Design	Low	100
991	Prop S Engine	Size	Medium	SAIW Ribs	Design	Medium	100
992	Prop S Engine	Power	High	SP Generator 1	Power	Low	100
993	Prop S Engine	Power	Medium	Prop S Engine	Size	Medium	100
994	Prop S Engine	Power	High	Prop S Engine	Size	High	100
995	Prop S Engine	Power	Medium	Prop P Engine	Power	Medium	100
996	Prop S Engine	Power	High	Prop P Engine	Power	High	100
997	Prop S Engine	Size	Medium	Prop S Nacelle	Design	Low	100
998	Prop S Engine	Size	High	Prop S Nacelle	Design	Medium	100
999	Prop S Engine	Size	High	SAIW Rear Spar	Design	Medium	100
1000	Prop S Engine	Size	High	SOW Ribs	Design	Medium	100
1001	Prop S Engine	Size	High	SOW Rear Spar	Design	Medium	100
1002	Prop S Nacelle	Design	Medium	SAIW Rear Spar	Design	Low	100
1003	Prop S Nacelle	Design	Medium	SAIW Ribs	Design	Low	100
1004	Prop S Nacelle	Design	Medium	SAIW Front Spar	Design	Low	100
1005	Prop S Nacelle	Design	Medium	SAIW Lower Skin_Strgrs	Design	Medium	100
1006	Prop S Nacelle	Design	Medium	SOW Lower Skin_Strgrs	Design	Medium	100
1007	Prop S Nacelle	Design	Medium	SOW Ribs	Design	Low	100
1008	Prop S Nacelle	Design	Medium	SOW Rear Spar	Design	Low	100
1009	HLFC Fin Flow Control Valve	Size	Medium	Av HLFC Computer	Software	Low	33
1010	HLFC Fin Flow Control Valve	Size	High	Av HLFC Computer	Interface	Low	33
1011	HLFC PAIW Flow Control Valve	Size	Medium	Av HLFC Computer	Software	Low	100
1012	HLFC PAIW Flow Control Valve	Size	High	Av HLFC Computer	Interface	Low	100
1013	HLFC PAIW Flow Control Valve	Size	High	Fuel Transfer System	Positioning	Low	100
1014	HLFC PFIW Flow Control Valve	Size	Medium	Av HLFC Computer	Software	Low	33
1015	HLFC PFIW Flow Control Valve	Size	High	Av HLFC Computer	Interface	Low	100
1016	HLFC PFIW Flow Control Valve	Size	High	Fuel Fwd Trim Tank 2	Design	Low	100
1017	HLFC POW Flow Control Valve	Size	Medium	Av HLFC Computer	Software	Low	100
1018	HLFC POW Flow Control Valve	Size	High	Av HLFC Computer	Interface	Low	100
1019	HLFC SAIW Flow Control Valve	Size	Medium	Av HLFC Computer	Software	Low	100
1020	HLFC SAIW Flow Control Valve	Size	High	Fuel Transfer System	Positioning	Low	100
1021	HLFC SAIW Flow Control Valve	Size	High	Av HLFC Computer	Interface	Low	100
1022	HLFC SFIW Flow Control Valve	Size	Medium	Av HLFC Computer	Software	Low	33
1023	HLFC SFIW Flow Control Valve	Size	High	Av HLFC Computer	Interface	Low	100
1024	HLFC SFIW Flow Control Valve	Size	High	Fuel Fwd Trim Tank 2	Design	Low	100
1025	HLFC SOW Flow Control Valve	Size	Medium	Av HLFC Computer	Software	Low	100
1026	HLFC SOW Flow Control Valve	Size	High	Av HLFC Computer	Interface	Low	100
1027	HLFC Exhaust Ducting	Size	Low	AF Skin_Strgrs	Interface	Low	100
1028	HLFC Exhaust Ducting	Size	Low	Fuel Aft Trim Tank 1	Interface	Medium	100
1029	HLFC Exhaust Ducting	Size	Low	Fuel Aft Trim Tank 2	Interface	Medium	100
1030	SP Generator 1	Size	High	SAIW Ribs	Design	Medium	66
1031	SP Generator 1	Size	High	SAIW Rear Spar	Design	Medium	100
1032	SP Generator 1	Size	Medium	Prop S Nacelle	Design	Low	100
1033	SP Generator 1	Power	High	SP Generator 1	Size	High	100
1034	SP Generator 1	Size	High	Prop S Nacelle	Design	Medium	100
1035	SP Generator 1	Power	High	SP Gearbox 1	Power	High	100
1036	SP Generator 1	Power	Medium	SP Gearbox 1	Power	Medium	100
1037	SP Generator 1	Power	High	SP Generator 2	Power	High	100
1038	SP Generator 1	Power	Medium	SP Generator 2	Power	Medium	100
1039	SP Generator 1	Power	Low	SP Generator 2	Power	Low	100
1040	SP Generator 1	Power	Medium	SP Generator 1	Size	Medium	100
1041	SP Generator 1	Power	Medium	Prop S Engine	Power	Low	33
1042	SP Generator 2	Size	High	PAIW Ribs	Design	Medium	66
1043	SP Generator 2	Size	High	PAIW Rear Spar	Design	Medium	100
1044	SP Generator 2	Power	High	SP Generator 2	Size	High	100
1045	SP Generator 2	Power	Medium	Prop P Engine	Power	Low	33
1046	SP Generator 2	Power	Low	SP Generator 1	Power	Low	100
1047	SP Generator 2	Power	Medium	SP Gearbox 2	Power	Medium	100
1048	SP Generator 2	Power	High	SP Gearbox 2	Power	High	100
1049	SP Generator 2	Size	Medium	Prop P Nacelle	Design	Low	100
1050	SP Generator 2	Size	High	Prop P Nacelle	Design	Medium	100
1051	SP Generator 2	Power	Medium	SP Generator 2	Size	Medium	100
1052	SP Generator 2	Power	Medium	SP Generator 1	Power	Medium	100
1053	SP Generator 2	Power	High	SP Generator 1	Power	High	100
1054	SP Gearbox 1	Size	High	SAIW Ribs	Design	Medium	66
1055	SP Gearbox 1	Power	Medium	SP Gearbox 1	Size	Medium	100
1056	SP Gearbox 1	Size	High	Prop S Nacelle	Design	Medium	100
1057	SP Gearbox 1	Power	High	SP Gearbox 1	Size	High	100
1058	SP Gearbox 1	Size	Medium	Prop S Nacelle	Design	Low	100
1059	SP Gearbox 2	Size	High	PAIW Ribs	Design	Medium	66
1060	SP Gearbox 2	Size	Medium	Prop P Nacelle	Design	Low	100
1061	SP Gearbox 2	Power	High	SP Gearbox 2	Size	High	100
1062	SP Gearbox 2	Size	High	Prop P Nacelle	Design	Medium	100
1063	SP Gearbox 2	Power	Medium	SP Gearbox 2	Size	Medium	100
1064	Cockpit Front Wall	Design	High	Cockpit Floor	Design	Medium	100
1065	Cockpit Front Wall	Design	High	Cockpit Interior Shell	Design	Medium	100
1066	Cockpit Front Wall	Design	High	Cockpit Upper Control Panel	Design	Medium	100
1067	Cockpit Front Wall	Design	High	Cockpit Lower Control Panel	Design	High	100
1068	Cockpit Lower Control Panel	Design	High	Cockpit P Sidestick Panel	Design	High	100
1069	Cockpit Lower Control Panel	Design	High	Cockpit S Sidestick Panel	Design	High	100
1070	Cockpit Lower Control Panel	Design	High	Cockpit Throttle Panel	Design	High	100
1071	Cockpit P Sidestick Panel	Design	High	Cockpit Pilot Seat	Positioning	Medium	100
1072	Cockpit S Sidestick Panel	Design	High	Cockpit Co-pilot Seat	Positioning	Medium	100

4. E-5 combinatorial dependencies in PA domain

The first table lists the target impacts for the combinatorial dependencies that have been modelled. The second table lists the initiating change combinations. In this list, rows with the same 'Tar_comb' value are part of the same combination and this value corresponds to the target impact number (No) in the first table.

No	T-Item	T-ToC	T-LoC	S-MS	E-MS	Pr
1	SP Generator 1	Power	Medium	1	13	66
2	SP Generator 1	Power	Medium	1	13	66
3	SP Generator 1	Power	Medium	1	13	66
4	SP Generator 1	Power	Medium	1	13	66
5	SP Generator 1	Power	Medium	1	13	66
6	SP Generator 1	Power	Medium	1	13	66
7	SP Generator 1	Power	Medium	1	13	66
8	SP Generator 1	Power	Medium	1	13	66
9	SP Generator 1	Power	Medium	1	13	66
10	SP Generator 1	Power	Medium	1	13	66
11	SP Generator 1	Power	Medium	1	13	66
12	SP Generator 1	Power	Medium	1	13	66
13	SP Generator 1	Power	Medium	1	13	66
14	SP Generator 1	Power	Medium	1	13	66
15	SP Generator 1	Power	Medium	1	13	66
16	SP Generator 1	Power	Medium	1	13	66
17	SP Generator 1	Power	Medium	1	13	66
18	SP Generator 1	Power	Medium	1	13	66
19	SP Generator 1	Power	Medium	1	13	66
20	SP Generator 1	Power	Medium	1	13	66
21	SP Generator 1	Power	Medium	1	13	66
22	SP Generator 2	Power	Medium	1	13	66
23	SP Generator 2	Power	Medium	1	13	66
24	SP Generator 2	Power	Medium	1	13	66
25	SP Generator 2	Power	Medium	1	13	66
26	SP Generator 2	Power	Medium	1	13	66
27	SP Generator 2	Power	Medium	1	13	66
28	SP Generator 2	Power	Medium	1	13	66
29	SP Generator 2	Power	Medium	1	13	66
30	SP Generator 2	Power	Medium	1	13	66
31	SP Generator 2	Power	Medium	1	13	66
32	SP Generator 2	Power	Medium	1	13	66
33	SP Generator 2	Power	Medium	1	13	66
34	SP Generator 2	Power	Medium	1	13	66
35	SP Generator 2	Power	Medium	1	13	66
36	SP Generator 2	Power	Medium	1	13	66
37	SP Generator 2	Power	Medium	1	13	66
38	SP Generator 2	Power	Medium	1	13	66
39	SP Generator 2	Power	Medium	1	13	66
40	SP Generator 2	Power	Medium	1	13	66
41	SP Generator 2	Power	Medium	1	13	66
42	SP Generator 2	Power	Medium	1	13	66

T-Item	T-ToC	T-LoC	Tar_comb
HLFC Fin Motor	Power	High	1
HLFC SFIW Motor	Power	High	1
HLFC Fin Motor	Power	High	2
HLFC SAIW Motor	Power	High	2
HLFC Fin Motor	Power	High	3
HLFC SOW Motor	Power	High	3
HLFC Fin Motor	Power	High	4
HLFC PFIW Motor	Power	High	4
HLFC Fin Motor	Power	High	5
HLFC PAIW Motor	Power	High	5
HLFC Fin Motor	Power	High	6
HLFC POW Motor	Power	High	6
HLFC SFIW Motor	Power	High	7
HLFC SAIW Motor	Power	High	7
HLFC SFIW Motor	Power	High	8
HLFC SOW Motor	Power	High	8
HLFC SFIW Motor	Power	High	9
HLFC PFIW Motor	Power	High	9
HLFC SFIW Motor	Power	High	10
HLFC PAIW Motor	Power	High	10
HLFC SFIW Motor	Power	High	11
HLFC POW Motor	Power	High	11
HLFC SAIW Motor	Power	High	12
HLFC SOW Motor	Power	High	12
HLFC SAIW Motor	Power	High	13
HLFC PFIW Motor	Power	High	13
HLFC SAIW Motor	Power	High	14
HLFC PAIW Motor	Power	High	14
HLFC SAIW Motor	Power	High	15
HLFC POW Motor	Power	High	15
HLFC SOW Motor	Power	High	16
HLFC PFIW Motor	Power	High	16
HLFC SOW Motor	Power	High	17
HLFC PAIW Motor	Power	High	17
HLFC SOW Motor	Power	High	18
HLFC POW Motor	Power	High	18
HLFC PFIW Motor	Power	High	19
HLFC PAIW Motor	Power	High	19
HLFC PFIW Motor	Power	High	20
HLFC POW Motor	Power	High	20
HLFC PAIW Motor	Power	High	21
HLFC POW Motor	Power	High	21
HLFC Fin Motor	Power	High	22
HLFC SFIW Motor	Power	High	22
HLFC Fin Motor	Power	High	23
HLFC SAIW Motor	Power	High	23
HLFC Fin Motor	Power	High	24
HLFC SOW Motor	Power	High	24
HLFC Fin Motor	Power	High	25
HLFC PFIW Motor	Power	High	25
HLFC Fin Motor	Power	High	26
HLFC PAIW Motor	Power	High	26
HLFC Fin Motor	Power	High	27
HLFC POW Motor	Power	High	27
HLFC SFIW Motor	Power	High	28
HLFC SAIW Motor	Power	High	28
HLFC SFIW Motor	Power	High	29
HLFC SOW Motor	Power	High	29
HLFC SFIW Motor	Power	High	30
HLFC PFIW Motor	Power	High	30
HLFC SFIW Motor	Power	High	31
HLFC PAIW Motor	Power	High	31
HLFC SFIW Motor	Power	High	32
HLFC POW Motor	Power	High	32
HLFC SAIW Motor	Power	High	33
HLFC SOW Motor	Power	High	33
HLFC SAIW Motor	Power	High	34
HLFC PFIW Motor	Power	High	34
HLFC SAIW Motor	Power	High	35
HLFC PAIW Motor	Power	High	35
HLFC SAIW Motor	Power	High	36
HLFC POW Motor	Power	High	36
HLFC SOW Motor	Power	High	37
HLFC PFIW Motor	Power	High	37
HLFC SOW Motor	Power	High	38
HLFC PAIW Motor	Power	High	38
HLFC SOW Motor	Power	High	39
HLFC POW Motor	Power	High	39
HLFC PFIW Motor	Power	High	40
HLFC PAIW Motor	Power	High	40
HLFC PFIW Motor	Power	High	41
HLFC POW Motor	Power	High	41
HLFC PAIW Motor	Power	High	42
HLFC POW Motor	Power	High	42

5. E-5 Dependencies from PA domain to DT domain

This table lists all the dependencies from the components in the Physical Architecture to the people in the Design Team. The validity range of all dependencies is set from M1 to M13.

No	Initiating Item	Initiating ToC	Initiating LoC	Target Item	Target ToC	Target LoC	Pr
1	Fin Rudder	Any	Any	Claire Gini	N/A	N/A	100
2	Fin Skin_Strgrs	Any	Any	Andrew Klewer	N/A	N/A	100
3	Fin Structure	Any	Any	Andrew Klewer	N/A	N/A	100
4	AF Frames	Any	Any	Robert Morency	N/A	N/A	100
5	AF MLG Walls	Any	Any	Robert Morency	N/A	N/A	100
6	AF Rudder Bracket	Any	Any	Robert Morency	N/A	N/A	100
7	AF Skin_Strgrs	Any	Any	Robert Morency	N/A	N/A	100
8	Canard P Actuators	Any	Any	Dale Ferrier	N/A	N/A	100
9	Canard P Foreplane	Any	Any	Dale Ferrier	N/A	N/A	100
10	Canard S Actuators	Any	Any	Dale Ferrier	N/A	N/A	100
11	Canard S Foreplane	Any	Any	Dale Ferrier	N/A	N/A	100
12	CF Fwd Bulkhead	Any	Any	Edouard Menard	N/A	N/A	100
13	CF Rear Bulkhead	Any	Any	Edouard Menard	N/A	N/A	100
14	CF Skin_Strgrs	Any	Any	Edouard Menard	N/A	N/A	100
15	CF Frames	Any	Any	Edouard Menard	N/A	N/A	100
16	FF Skin_Strgrs	Any	Any	Gerardo Rojas	N/A	N/A	100
17	FF Frames	Any	Any	Gerardo Rojas	N/A	N/A	100
18	PAIW Flaps	Any	Any	Cedric Godard	N/A	N/A	100
19	PAIW Front Spar	Any	Any	Florian Eggenspieler	N/A	N/A	100
20	PAIW Kink Rib	Any	Any	Florian Eggenspieler	N/A	N/A	100
21	PAIW LG Rear Spar	Any	Any	Florian Eggenspieler	N/A	N/A	100
22	PAIW Lower Skin_Strgrs	Any	Any	Florian Eggenspieler	N/A	N/A	100
23	PAIW Rear Spar	Any	Any	Florian Eggenspieler	N/A	N/A	100
24	PAIW Ribs	Any	Any	Florian Eggenspieler	N/A	N/A	100
25	PAIW Upper Skin_Strgrs	Any	Any	Florian Eggenspieler	N/A	N/A	100
26	PFIW LE Front Spar	Any	Any	Vincent Loubiere	N/A	N/A	100
27	PFIW Fuel Boundary Panels	Any	Any	Vincent Loubiere	N/A	N/A	100
28	PFIW Fuselage Rib	Any	Any	Vincent Loubiere	N/A	N/A	100
29	PFIW Fwd Spar	Any	Any	Vincent Loubiere	N/A	N/A	100
30	PFIW LG Front Spar	Any	Any	Vincent Loubiere	N/A	N/A	100
31	PFIW Lower Skin_Strgrs	Any	Any	Vincent Loubiere	N/A	N/A	100
32	PFIW Rail Attachments	Any	Any	Vincent Loubiere	N/A	N/A	100
33	PFIW LE Rear Spar	Any	Any	Vincent Loubiere	N/A	N/A	100
34	PFIW Ribs	Any	Any	Vincent Loubiere	N/A	N/A	100
35	PFIW Upper Skin_Strgrs	Any	Any	Vincent Loubiere	N/A	N/A	100
36	POW Front Spar	Any	Any	Blong Siong	N/A	N/A	100
37	POW Inboard Aileron	Any	Any	Nicolas Bataille	N/A	N/A	100
38	POW LE Ribs	Any	Any	Blong Siong	N/A	N/A	100
39	POW Lower Skin_Strgrs	Any	Any	Blong Siong	N/A	N/A	100
40	POW Outboard Aileron	Any	Any	Vinay Madhavan	N/A	N/A	100
41	POW Rear Spar	Any	Any	Blong Siong	N/A	N/A	100
42	POW Ribs	Any	Any	Blong Siong	N/A	N/A	100
43	POW Upper Skin_Strgrs	Any	Any	Blong Siong	N/A	N/A	100
44	POW Wing Tip	Any	Any	Blong Siong	N/A	N/A	100
45	SAIW Flaps	Any	Any	Cedric Godard	N/A	N/A	100
46	SAIW Front Spar	Any	Any	Florian Eggenspieler	N/A	N/A	100
47	SAIW Kink Rib	Any	Any	Florian Eggenspieler	N/A	N/A	100
48	SAIW LG Rear Spar	Any	Any	Florian Eggenspieler	N/A	N/A	100
49	SAIW Lower Skin_Strgrs	Any	Any	Florian Eggenspieler	N/A	N/A	100
50	SAIW Rear Spar	Any	Any	Florian Eggenspieler	N/A	N/A	100
51	SAIW Ribs	Any	Any	Florian Eggenspieler	N/A	N/A	100
52	SAIW Upper Skin_Strgrs	Any	Any	Florian Eggenspieler	N/A	N/A	100
53	SFIW Fwd Spar	Any	Any	Vincent Loubiere	N/A	N/A	100
54	SFIW LE Front Spar	Any	Any	Vincent Loubiere	N/A	N/A	100
55	SFIW Fuel Boundary Panels	Any	Any	Vincent Loubiere	N/A	N/A	100
56	SFIW LG Front Spar	Any	Any	Vincent Loubiere	N/A	N/A	100
57	SFIW Lower Skin_Strgrs	Any	Any	Vincent Loubiere	N/A	N/A	100
58	SFIW Rail Attachments	Any	Any	Vincent Loubiere	N/A	N/A	100
59	SFIW LE Rear Spar	Any	Any	Vincent Loubiere	N/A	N/A	100
60	SFIW Ribs	Any	Any	Vincent Loubiere	N/A	N/A	100
61	SFIW Upper Skin_Strgrs	Any	Any	Vincent Loubiere	N/A	N/A	100
62	SFIW Fuselage Rib	Any	Any	Vincent Loubiere	N/A	N/A	100
63	SOW Front Spar	Any	Any	Blong Siong	N/A	N/A	100
64	SOW Inboard Aileron	Any	Any	Nicolas Bataille	N/A	N/A	100
65	SOW LE Ribs	Any	Any	Blong Siong	N/A	N/A	100
66	SOW Lower Skin_Strgrs	Any	Any	Blong Siong	N/A	N/A	100
67	SOW Outboard Aileron	Any	Any	Vinay Madhavan	N/A	N/A	100
68	SOW Rear Spar	Any	Any	Blong Siong	N/A	N/A	100
69	SOW Ribs	Any	Any	Blong Siong	N/A	N/A	100
70	SOW Upper Skin_Strgrs	Any	Any	Blong Siong	N/A	N/A	100
71	SOW Wing Tip	Any	Any	Blong Siong	N/A	N/A	100
72	Av Doppler Radar	Any	Any	Ian White	N/A	N/A	100
73	Av GPS	Any	Any	Ian White	N/A	N/A	100
74	Av Radar	Any	Any	Ian White	N/A	N/A	100
75	Av Static Probe	Any	Any	Ian White	N/A	N/A	100
76	Av TCAS n ADS-B	Any	Any	Ian White	N/A	N/A	100
77	Av HLFC Computer	Any	Any	Ian White	N/A	N/A	100
78	Av HLFC Computer	Any	Any	Jonathan Pearson	N/A	N/A	100
79	Cabin Baggage Floor	Any	Any	Benedicte Gillot	N/A	N/A	100
80	Cabin Emergency Door	Any	Any	Benedicte Gillot	N/A	N/A	100
81	Cabin Entry Floor	Any	Any	Benedicte Gillot	N/A	N/A	100
82	Cabin Galley	Any	Any	Benedicte Gillot	N/A	N/A	100

83	Cabin Interior	Any	Any	Benedicte Gillot	N/A	N/A	100
84	Cabin Partitions	Any	Any	Benedicte Gillot	N/A	N/A	100
85	Cabin Slide	Any	Any	Benedicte Gillot	N/A	N/A	100
86	Cabin Toilet	Any	Any	Benedicte Gillot	N/A	N/A	100
87	Cabin Wardrobe	Any	Any	Benedicte Gillot	N/A	N/A	100
88	Cockpit Floor	Any	Any	Guillaume Raud	N/A	N/A	100
89	Cockpit Pilot Seat	Any	Any	Guillaume Raud	N/A	N/A	100
90	Cockpit Co-pilot Seat	Any	Any	Guillaume Raud	N/A	N/A	100
91	EC Cold Air Unit 1	Any	Any	Imran Akhtar	N/A	N/A	100
92	EC Cold Air Unit 2	Any	Any	Imran Akhtar	N/A	N/A	100
93	EC Compressor 1	Any	Any	Imran Akhtar	N/A	N/A	100
94	EC Compressor 2	Any	Any	Imran Akhtar	N/A	N/A	100
95	Fuel Aft Trim Tank 1	Any	Any	Mathieu Schwartz	N/A	N/A	100
96	Fuel Aft Trim Tank 2	Any	Any	Mathieu Schwartz	N/A	N/A	100
97	Fuel Feed System	Any	Any	Mathieu Schwartz	N/A	N/A	100
98	Fuel Fwd Trim Tank 1	Any	Any	Mathieu Schwartz	N/A	N/A	100
99	Fuel Fwd Trim Tank 2	Any	Any	Mathieu Schwartz	N/A	N/A	100
100	Fuel Jettison System	Any	Any	Mathieu Schwartz	N/A	N/A	100
101	Fuel PIW Tank 1	Any	Any	Mathieu Schwartz	N/A	N/A	100
102	Fuel PIW Tank 2	Any	Any	Mathieu Schwartz	N/A	N/A	100
103	Fuel PIW Tank 3	Any	Any	Mathieu Schwartz	N/A	N/A	100
104	Fuel POW Tank	Any	Any	Mathieu Schwartz	N/A	N/A	100
105	Fuel PW Vent System	Any	Any	Mathieu Schwartz	N/A	N/A	100
106	Fuel SIW Tank 1	Any	Any	Mathieu Schwartz	N/A	N/A	100
107	Fuel SIW Tank 2	Any	Any	Mathieu Schwartz	N/A	N/A	100
108	Fuel SIW Tank 3	Any	Any	Mathieu Schwartz	N/A	N/A	100
109	Fuel SOW Tank	Any	Any	Mathieu Schwartz	N/A	N/A	100
110	Fuel SW Vent System	Any	Any	Mathieu Schwartz	N/A	N/A	100
111	Fuel Transfer System	Any	Any	Mathieu Schwartz	N/A	N/A	100
112	HLFC Fin Ducting	Any	Any	Jonathan Pearson	N/A	N/A	100
113	HLFC Fin Motor	Any	Any	Jonathan Pearson	N/A	N/A	100
114	HLFC Fin Plenum Chambers	Any	Any	Jonathan Pearson	N/A	N/A	100
115	HLFC Fin Pump	Any	Any	Jonathan Pearson	N/A	N/A	100
116	HLFC PAIW Ducting	Any	Any	Jonathan Pearson	N/A	N/A	100
117	HLFC PAIW Motor	Any	Any	Jonathan Pearson	N/A	N/A	100
118	HLFC PIW Plenum Chambers	Any	Any	Jonathan Pearson	N/A	N/A	100
119	HLFC PAIW Pump	Any	Any	Jonathan Pearson	N/A	N/A	100
120	HLFC PFIW Ducting	Any	Any	Jonathan Pearson	N/A	N/A	100
121	HLFC PFIW Motor	Any	Any	Jonathan Pearson	N/A	N/A	100
122	HLFC PFIW Pump	Any	Any	Jonathan Pearson	N/A	N/A	100
123	HLFC POW Ducting	Any	Any	Jonathan Pearson	N/A	N/A	100
124	HLFC POW Motor	Any	Any	Jonathan Pearson	N/A	N/A	100
125	HLFC POW Plenum Chambers	Any	Any	Jonathan Pearson	N/A	N/A	100
126	HLFC POW Pump	Any	Any	Jonathan Pearson	N/A	N/A	100
127	HLFC SAIW Ducting	Any	Any	Jonathan Pearson	N/A	N/A	100
128	HLFC SAIW Motor	Any	Any	Jonathan Pearson	N/A	N/A	100
129	HLFC SIW Plenum Chambers	Any	Any	Jonathan Pearson	N/A	N/A	100
130	HLFC SAIW Pump	Any	Any	Jonathan Pearson	N/A	N/A	100
131	HLFC SFIW Ducting	Any	Any	Jonathan Pearson	N/A	N/A	100
132	HLFC SFIW Motor	Any	Any	Jonathan Pearson	N/A	N/A	100
133	HLFC SFIW Pump	Any	Any	Jonathan Pearson	N/A	N/A	100
134	HLFC SOW Ducting	Any	Any	Jonathan Pearson	N/A	N/A	100
135	HLFC SOW Motor	Any	Any	Jonathan Pearson	N/A	N/A	100
136	HLFC SOW Plenum Chambers	Any	Any	Jonathan Pearson	N/A	N/A	100
137	HLFC SOW Pump	Any	Any	Jonathan Pearson	N/A	N/A	100
138	LG Nose	Any	Any	Phillip Romelt	N/A	N/A	100
139	LG S Main	Any	Any	Salih Hamdi	N/A	N/A	100
140	LG P Main	Any	Any	Salih Hamdi	N/A	N/A	100
141	Prop P Engine	Any	Any	Tohid Roozfararh	N/A	N/A	100
142	Prop P Nacelle	Any	Any	Tohid Roozfararh	N/A	N/A	100
143	Prop S Engine	Any	Any	Tohid Roozfararh	N/A	N/A	100
144	Prop S Nacelle	Any	Any	Tohid Roozfararh	N/A	N/A	100
145	HLFC Fin Flow Control Valve	Any	Any	Jonathan Pearson	N/A	N/A	100
146	HLFC PAIW Flow Control Valve	Any	Any	Jonathan Pearson	N/A	N/A	100
147	HLFC PFIW Flow Control Valve	Any	Any	Jonathan Pearson	N/A	N/A	100
148	HLFC POW Flow Control Valve	Any	Any	Jonathan Pearson	N/A	N/A	100
149	HLFC SAIW Flow Control Valve	Any	Any	Jonathan Pearson	N/A	N/A	100
150	HLFC SFIW Flow Control Valve	Any	Any	Jonathan Pearson	N/A	N/A	100
151	HLFC SOW Flow Control Valve	Any	Any	Jonathan Pearson	N/A	N/A	100
152	HLFC Exhaust Ducting	Any	Any	Jonathan Pearson	N/A	N/A	100
153	SP Generator 1	Any	Any	Imran Akhtar	N/A	N/A	100
154	SP Generator 2	Any	Any	Imran Akhtar	N/A	N/A	100
155	SP Gearbox 1	Any	Any	Imran Akhtar	N/A	N/A	100
156	SP Gearbox 2	Any	Any	Imran Akhtar	N/A	N/A	100
157	SP APU	Any	Any	Imran Akhtar	N/A	N/A	100
158	Cockpit Front Wall	Any	Any	Guillaume Raud	N/A	N/A	100
159	Cockpit Interior Shell	Any	Any	Guillaume Raud	N/A	N/A	100
160	Cockpit Lower Control Panel	Any	Any	Guillaume Raud	N/A	N/A	100
161	Cockpit P Sidestick Panel	Any	Any	Guillaume Raud	N/A	N/A	100
162	Cockpit S Sidestick Panel	Any	Any	Guillaume Raud	N/A	N/A	100
163	Cockpit Throttle Panel	Any	Any	Guillaume Raud	N/A	N/A	100
164	Cockpit Upper Control Panel	Any	Any	Guillaume Raud	N/A	N/A	100

6. E-5 Dependencies between DA, DCh and Req domains

This table lists all the dependencies between the items in the Design Activity, Design Characteristics and Requirements domains. The validity range of all dependencies is set from M1 to M13.

No	Initiating Item	Initiating ToC	Initiating LoC	Target Item	Target ToC	Target LoC	Pr
1	Aerofoil Design	Output	N/A	Aerofoil Design	Input	N/A	100
2	Aerofoil Design	Input	N/A	Aerofoil Design	Output	N/A	100
3	Panel Porosity Definition	Output	N/A	Panel Porosity Definition	Input	N/A	100
4	Panel Porosity Definition	Input	N/A	Panel Porosity Definition	Output	N/A	100
5	Pump Sizing	Output	N/A	Pump Sizing	Input	N/A	100
6	Pump Sizing	Input	N/A	Pump Sizing	Output	N/A	100
7	BL Stability Analysis	Output	N/A	BL Stability Analysis	Input	N/A	100
8	BL Stability Analysis	Input	N/A	BL Stability Analysis	Output	N/A	100
9	Internal Flow Analysis	Input	N/A	Internal Flow Analysis	Output	N/A	100
10	Internal Flow Analysis	Output	N/A	Internal Flow Analysis	Input	N/A	100
11	Suction Systems Design	Output	N/A	Suction Systems Design	Input	N/A	100
12	Suction Systems Design	Input	N/A	Suction Systems Design	Output	N/A	100
13	Performance Analysis	Output	N/A	Performance Analysis	Input	N/A	100
14	Performance Analysis	Input	N/A	Performance Analysis	Output	N/A	100
15	Aerofoil Design	Output	N/A	Fin Flow	N/A	N/A	100
16	Aerofoil Design	Output	N/A	Wing Flow	N/A	N/A	100
17	Panel Porosity Definition	Output	N/A	Chamber Pressure Distribution	N/A	N/A	100
18	Pump Sizing	Output	N/A	HLFC Pump Pressure	N/A	N/A	100
19	Pump Sizing	Output	N/A	SFC	N/A	N/A	100
20	BL Stability Analysis	Output	N/A	Drag	N/A	N/A	100
21	BL Stability Analysis	Input	N/A	Fin Flow	N/A	N/A	100
22	BL Stability Analysis	Input	N/A	Panel Hole Velocities	N/A	N/A	100
23	BL Stability Analysis	Input	N/A	Wing Flow	N/A	N/A	100
24	Internal Flow Analysis	Input	N/A	Chamber Pressure Distribution	N/A	N/A	100
25	Internal Flow Analysis	Input	N/A	Ducting Pressure Distribution	N/A	N/A	100
26	Internal Flow Analysis	Output	N/A	Panel Hole Velocities	N/A	N/A	100
27	Suction Systems Design	Output	N/A	Ducting Pressure Distribution	N/A	N/A	100
28	Suction Systems Design	Input	N/A	HLFC Pump Pressure	N/A	N/A	100
29	Suction Systems Design	Output	N/A	HLFC System Weight	N/A	N/A	100
30	Performance Analysis	Output	N/A	Range	N/A	N/A	100
31	Drag	N/A	N/A	Performance Analysis	Input	N/A	100
32	Wing Flow	N/A	N/A	Aerofoil Design	Output	N/A	100
33	Wing Flow	N/A	N/A	BL Stability Analysis	Input	N/A	66
34	Fin Flow	N/A	N/A	Aerofoil Design	Output	N/A	66
35	Fin Flow	N/A	N/A	BL Stability Analysis	Input	N/A	66
36	SFC	N/A	N/A	Performance Analysis	Input	N/A	100
37	HLFC System Weight	N/A	N/A	Performance Analysis	Input	N/A	100
38	Chamber Pressure Distribution	N/A	N/A	Panel Porosity Definition	Output	N/A	100
39	Chamber Pressure Distribution	N/A	N/A	Internal Flow Analysis	Input	N/A	66
40	Panel Hole Velocities	N/A	N/A	BL Stability Analysis	Input	N/A	66
41	Panel Hole Velocities	N/A	N/A	Internal Flow Analysis	Output	N/A	100
42	HLFC Pump Pressure	N/A	N/A	Pump Sizing	Output	N/A	100
43	HLFC Pump Pressure	N/A	N/A	Suction Systems Design	Input	N/A	66
44	Ducting Pressure Distribution	N/A	N/A	Internal Flow Analysis	Input	N/A	66
45	Ducting Pressure Distribution	N/A	N/A	Suction Systems Design	Output	N/A	100
46	Range	N/A	N/A	Pump Sizing	Input	N/A	100
47	Range	N/A	N/A	Aerofoil Design	Input	N/A	100
48	Range	N/A	N/A	Panel Porosity Definition	Input	N/A	100

7. E-5 Dependencies from DCh domain to PA domain

This table lists all dependencies from the Design Characteristics to the components in the Physical Architecture. The validity range of all dependencies is set from M1 to M13.

Initiating Item	Initiating ToC	Initiating LoC	Target Item	Target ToC	Target LoC	Pr
Drag	Any	Any	Fin Rudder	Any	Any	100
Drag	Any	Any	Fin Skin_Strgrs	Any	Any	100
Drag	Any	Any	AF Skin_Strgrs	Any	Any	100
Drag	Any	Any	Canard P Foreplane	Any	Any	100
Drag	Any	Any	Canard S Foreplane	Any	Any	100
Drag	Any	Any	CF Skin_Strgrs	Any	Any	100
Drag	Any	Any	FF Skin_Strgrs	Any	Any	100
Drag	Any	Any	PAIW Flaps	Any	Any	100
Drag	Any	Any	PAIW Lower Skin_Strgrs	Any	Any	100
Drag	Any	Any	PAIW Upper Skin_Strgrs	Any	Any	100
Drag	Any	Any	PFIW Lower Skin_Strgrs	Any	Any	100
Drag	Any	Any	PFIW Upper Skin_Strgrs	Any	Any	100
Drag	Any	Any	POW Inboard Aileron	Any	Any	100
Drag	Any	Any	POW Lower Skin_Strgrs	Any	Any	100
Drag	Any	Any	POW Outboard Aileron	Any	Any	100
Drag	Any	Any	POW Upper Skin_Strgrs	Any	Any	100
Drag	Any	Any	POW Wing Tip	Any	Any	100
Drag	Any	Any	SAIW Flaps	Any	Any	100
Drag	Any	Any	SAIW Lower Skin_Strgrs	Any	Any	100
Drag	Any	Any	SAIW Upper Skin_Strgrs	Any	Any	100
Drag	Any	Any	SFIW Lower Skin_Strgrs	Any	Any	100
Drag	Any	Any	SFIW Upper Skin_Strgrs	Any	Any	100
Drag	Any	Any	SOW Inboard Aileron	Any	Any	100
Drag	Any	Any	SOW Lower Skin_Strgrs	Any	Any	100
Drag	Any	Any	SOW Outboard Aileron	Any	Any	100
Drag	Any	Any	SOW Upper Skin_Strgrs	Any	Any	100
Drag	Any	Any	SOW Wing Tip	Any	Any	100
Wing Flow	Any	Any	PAIW Flaps	Any	Any	100
Wing Flow	Any	Any	PAIW Lower Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	PAIW Upper Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	PFIW Lower Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	PFIW Upper Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	POW Inboard Aileron	Any	Any	100
Wing Flow	Any	Any	POW Lower Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	POW Outboard Aileron	Any	Any	100
Wing Flow	Any	Any	POW Upper Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	POW Wing Tip	Any	Any	100
Wing Flow	Any	Any	SAIW Flaps	Any	Any	100
Wing Flow	Any	Any	SAIW Lower Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	SAIW Upper Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	SFIW Lower Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	SFIW Upper Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	SOW Inboard Aileron	Any	Any	100
Wing Flow	Any	Any	SOW Lower Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	SOW Outboard Aileron	Any	Any	100
Wing Flow	Any	Any	SOW Upper Skin_Strgrs	Any	Any	100
Wing Flow	Any	Any	SOW Wing Tip	Any	Any	100
Fin Flow	Any	Any	Fin Rudder	Any	Any	100
Fin Flow	Any	Any	Fin Skin_Strgrs	Any	Any	100
SFC	Any	Any	Prop P Engine	Any	Any	100
SFC	Any	Any	Prop S Engine	Any	Any	100
HLFC System Weight	Any	Any	HLFC Fin Ducting	Any	Any	100
HLFC System Weight	Any	Any	HLFC Fin Flow Control Valve	Any	Any	100
HLFC System Weight	Any	Any	HLFC Fin Motor	Any	Any	100
HLFC System Weight	Any	Any	HLFC Fin Plenum Chambers	Any	Any	100
HLFC System Weight	Any	Any	HLFC Fin Pump	Any	Any	100
HLFC System Weight	Any	Any	HLFC PAIW Ducting	Any	Any	100
HLFC System Weight	Any	Any	HLFC PAIW Flow Control Valve	Any	Any	100
HLFC System Weight	Any	Any	HLFC PAIW Motor	Any	Any	100
HLFC System Weight	Any	Any	HLFC PIW Plenum Chambers	Any	Any	100
HLFC System Weight	Any	Any	HLFC PAIW Pump	Any	Any	100
HLFC System Weight	Any	Any	HLFC PFIW Ducting	Any	Any	100
HLFC System Weight	Any	Any	HLFC PFIW Flow Control Valve	Any	Any	100
HLFC System Weight	Any	Any	HLFC PFIW Motor	Any	Any	100
HLFC System Weight	Any	Any	HLFC PFIW Pump	Any	Any	100
HLFC System Weight	Any	Any	HLFC POW Ducting	Any	Any	100
HLFC System Weight	Any	Any	HLFC POW Flow Control Valve	Any	Any	100
HLFC System Weight	Any	Any	HLFC POW Motor	Any	Any	100

HLFC System Weight	Any	Any	HLFC POW Plenum Chambers	Any	Any	100
HLFC System Weight	Any	Any	HLFC POW Pump	Any	Any	100
HLFC System Weight	Any	Any	HLFC SAIW Ducting	Any	Any	100
HLFC System Weight	Any	Any	HLFC SAIW Flow Control Valve	Any	Any	100
HLFC System Weight	Any	Any	HLFC SAIW Motor	Any	Any	100
HLFC System Weight	Any	Any	HLFC SIW Plenum Chambers	Any	Any	100
HLFC System Weight	Any	Any	HLFC SAIW Pump	Any	Any	100
HLFC System Weight	Any	Any	HLFC SFIW Ducting	Any	Any	100
HLFC System Weight	Any	Any	HLFC SFIW Flow Control Valve	Any	Any	100
HLFC System Weight	Any	Any	HLFC SFIW Motor	Any	Any	100
HLFC System Weight	Any	Any	HLFC SFIW Pump	Any	Any	100
HLFC System Weight	Any	Any	HLFC SOW Ducting	Any	Any	100
HLFC System Weight	Any	Any	HLFC SOW Flow Control Valve	Any	Any	100
HLFC System Weight	Any	Any	HLFC SOW Motor	Any	Any	100
HLFC System Weight	Any	Any	HLFC SOW Plenum Chambers	Any	Any	100
HLFC System Weight	Any	Any	HLFC SOW Pump	Any	Any	100
Chamber Pressure Distribution	Any	Any	HLFC Fin Plenum Chambers	Any	Any	100
Chamber Pressure Distribution	Any	Any	HLFC PIW Plenum Chambers	Any	Any	100
Chamber Pressure Distribution	Any	Any	HLFC POW Plenum Chambers	Any	Any	100
Chamber Pressure Distribution	Any	Any	HLFC SIW Plenum Chambers	Any	Any	100
Chamber Pressure Distribution	Any	Any	HLFC SOW Plenum Chambers	Any	Any	100
Panel Hole Velocities	Any	Any	HLFC Fin Plenum Chambers	Any	Any	100
Panel Hole Velocities	Any	Any	HLFC PIW Plenum Chambers	Any	Any	100
Panel Hole Velocities	Any	Any	HLFC POW Plenum Chambers	Any	Any	100
Panel Hole Velocities	Any	Any	HLFC SIW Plenum Chambers	Any	Any	100
Panel Hole Velocities	Any	Any	HLFC SOW Plenum Chambers	Any	Any	100
HLFC Pump Pressure	N/A	Any	HLFC Fin Pump	Power	Low	66
HLFC Pump Pressure	N/A	Any	HLFC PAIW Pump	Power	Low	66
HLFC Pump Pressure	N/A	Any	HLFC PFIW Pump	Power	Low	66
HLFC Pump Pressure	N/A	Any	HLFC POW Pump	Power	Low	66
HLFC Pump Pressure	N/A	Any	HLFC SAIW Pump	Power	Low	66
HLFC Pump Pressure	N/A	Any	HLFC SFIW Pump	Power	Low	66
HLFC Pump Pressure	N/A	Any	HLFC SOW Pump	Power	Low	66
Ducting Pressure Distribution	Any	Any	HLFC Fin Ducting	Any	Any	100
Ducting Pressure Distribution	Any	Any	HLFC PAIW Ducting	Any	Any	100
Ducting Pressure Distribution	Any	Any	HLFC PFIW Ducting	Any	Any	100
Ducting Pressure Distribution	Any	Any	HLFC POW Ducting	Any	Any	100
Ducting Pressure Distribution	Any	Any	HLFC SAIW Ducting	Any	Any	100
Ducting Pressure Distribution	Any	Any	HLFC SFIW Ducting	Any	Any	100
Ducting Pressure Distribution	Any	Any	HLFC SOW Ducting	Any	Any	100