INSTITUTO SUPERIOR TÉCNICO

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A FRAMEWORK TO ANALYSE AND IMPROVE ENGINEERING PROCESSES

Carla Marisa Valente Salsinha Pepe

Supervisor: Doctor Elsa Maria Pires Henriques

Thesis approved in public session to obtain the PhD degree in Leaders for Technical Industries

Jury final classification: Pass With Merit

Jury

Chairperson: Chairman of the IST Scientific Board

Members of the committee:

Doctor António Augusto Fernandes

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Doctor Michael Andrew Moss, Corporate Specialist, Knowledge Management, Design Process Automation, Rolls-Royce plc., as specialist in the thesis research topic

FCT Fundação para a Ciência e a Tecnologia
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2012

— To my Mum and to Andreas —

Title: A Framework to Analyse and Improve Engineering Processes

Abstract

Many engineering companies recognise the importance of efficient engineering processes to develop competitive products. However, the intricacy of designing complex products leads to enormous challenges in understanding where the inefficiencies of engineering processes lie. In opposition to manufacturing, where the value stream can easily be visualised, engineering processes are characterised by iterative information flows where waste is often indiscernible. Engineering processes require the involvement of different teams and engineering functions which creates a complex interaction of activities. Due to uncertainty of duration of these activities, it is extremely challenging to identify where improvements would have the highest impact.

In order to overcome these problems, a framework has been developed from a theoretical basis and then validated in an industrial environment. The framework involves the application of Value Stream Mapping to identify sources of waste in the engineering processes and of the Design Structure Matrix to analyse and optimise process iterations. Moreover, simulation is used to prototype improvements, taking into account the variation of activities durations and to define a robust design process.

The framework has made a valuable contribution for improving engineering processes in two case studies within the aerospace industry, achieving a significant reduction of engineering processes lead time.

Key Words: Engineering Process, Product Development, Process Map, Value Stream Map, Waste, Design Structure Matrix, Process Simulation, Design of Experiments

Título: Desenvolvimento de uma Metodologia para Melhorar Processos de Desenvolvimento de Produto

Nome: Carla Marisa Valente Salsinha Pepe
Doutoramento em: Líderes para Indústrias Tecnológicas
Orientadora: Professora Elsa Maria Pires Henriques

Resumo

É reconhecida a importância da eficiência dos processos de desenvolvimento de produto (PDP) para a capacidade competitiva das empresas. No entanto, a análise e a melhoria de processos de engenharia de produtos complexos reveste-se dos desafios inerentes à dificuldade em perceber as ineficiências desses processos. Em oposição aos processos de fabrico, onde a cadeia de valor pode ser visualizada, os PDP são caracterizados por diferentes fluxos de informação de natureza iterativa. Os PDP requerem o envolvimento de diversas equipas e áreas de engenharia o que gera incerteza e interações complexas. O desperdício torna-se indiscernível, sendo difícil identificar o que melhorar no processo, onde e como, de forma a tingir o maior benefício.

Esta tese apresenta uma metodologia de análise dos PDP complexos, propondo-se contribuir para facilitar os desenhos e os planos de melhoria desses processos. A metodologia envolve a aplicação do mapeamento da cadeia de valor, para identificar as fontes de desperdício no PDP. A aplicação da Design Structure Matrix para analisar e melhorar o processo de iterações e o uso de simulação para prototipar o efeito dos melhoramentos no processo tendo em conta a variabilidade na duração das atividades.

A contribuição desta metodologia foi reconhecida com a sua aplicação em dois casos de estudo na indústria aeronáutica.

Palavras Chave: Processos de Engenharia, Desenvolvimento de Produto, Mapa do Processo, Value Stream Map, Desperdício, Design Structure Matrix, Simulação do Processo, Desenho de Experiências

Acknowledgments

Several times during the last couple of years, I questioned if I would manage to complete this work while having a full time job at the same time. I have to say that many people have helped me to overcome this lack of confidence and gave me support and strength to accomplish my goal.

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To conclude, I have to thank God for providing me energy and motivation to start and conclude this work, and for putting all the above people in my life.

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Chapter 1

Introduction

1.1. Research Motivation

Many engineering companies recognise the importance of efficient engineering processes to develop competitive products. However, the intricacy of designing complex products leads to enormous challenges in understanding where the main inefficiencies of engineering processes lie. In opposition to manufacturing processes, where the value stream can easily be visualised and waste identified, engineering processes are characterised by iterative information flows where waste is often indiscernible. Many engineering processes require the involvement of different teams and engineering functions which creates a complex interaction of engineering activities. Due to uncertainty of duration of these activities, it can be extremely challenging to identify where improvements would have the highest impact on process lead time.

In order to overcome the mentioned problems, a framework has been developed from a theoretical basis and then validated in an industrial environment. The framework aims to address the lean pillars such as waste reduction, value maximisation through an efficient value stream and striving to achieve perfection. In practice it involves the application of Value Stream Mapping (VSM) to identify sources of waste in the engineering processes. The Design Structure Matrix (DSM) is used to analyse and reduce process iterations. Moreover, simulation is used to prototype improvements, taking into account the variation of activities durations and to define a robust design process.

The increase in product development complexity and the importance of improving product development processes has changed and increased the focus on design research (Blessing, 2009). Considering that the aim of design research is to improve design, the research should have an impact in practice (Blessing, 2009). Many guidelines, methods and tools have weak foundations: empirical data are hardly used to inform and drive support development; evaluation is poor, and implementation

issues are rarely addressed (Blessing, 2009). One of the goals of this thesis is to overcome these problems, developing an approach to improve product development processes but validating the use of results in practice.

The adaptation of VSM for product development environment has been studied by McManus and Millard (2001) and reported in a VSM Manual for Product Development (McManus, 2005). However, there is a lack of practical evidence in the manual and companies still question the applicability of VSM for improving complex environments such as product development. In the manual, McManus recommends the use of DSM to overcome the problems caused by the product development complexity, but it is however not clear how both tools can be applied in the real industrial world. The complexity of real product development processes complicates the use of VSM to calculate process lead time and the potential effect of waste reduction. Rather than simple duration calculations as applied in manufacturing, more sophisticated tools, such as process simulation, are required to analyse complex and high uncertain processes.

The main contributions of this thesis are an Engineering Processes Improvement (EPI) framework that combines these existing methods for improving product development processes and the results of its exploitation in the industrial world. Each step of the framework utilisation is described with practical guidance that was developed through the framework validation in the industrial environment.

This EPI framework recognises the differences between manufacturing and product development processes such as the non-visible information flow, the higher uncertainty or the long lead times and provides recommendations and guidelines to use a robust analysis of improvements.

The framework has made a valuable contribution for improving engineering processes in two case studies within the aerospace industry. The first case study aimed to improve the detailed design of the High Pressure Turbine Blade, one of the most complex components of a Jet Engine. This case study was completed in a seven-month period in one of the major Jet Engine manufacturers, Rolls-Royce. The second case study was focused on reducing the preliminary design lead time of the High Pressure Turbine Disc Architecture, which includes the disc and the surrounding environment. The framework application in these two case studies aimed at identifying non-value added activities such as manual data handling and re-work activities.

1.2. Research Questions

As described in the previous section, product development processes are complex and different from manufacturing processes. However, this thesis argues that product development processes can also be improved using lean principles and lean tools. Having this in mind, the main goal of this thesis is to understand:

Can tools such as Value Stream Map, Design Structure Matrix and Process Simulation be used

together to improve complex product development processes? Do they need adaptation to be used in a complementary way in this particular environment?

How can these methods be applied successfully to improve real product development processes?

This research has been designed to contribute to both the academic knowledge and the industrial practice of improving product development processes. Therefore a success criteria for this research needs to analyse if the results contribute to both perspectives.

1.3. Research Approach

The research of this thesis followed a structured approach which can be compared with the methodological framework defined by Blessing (2009), see Figure 1-1.

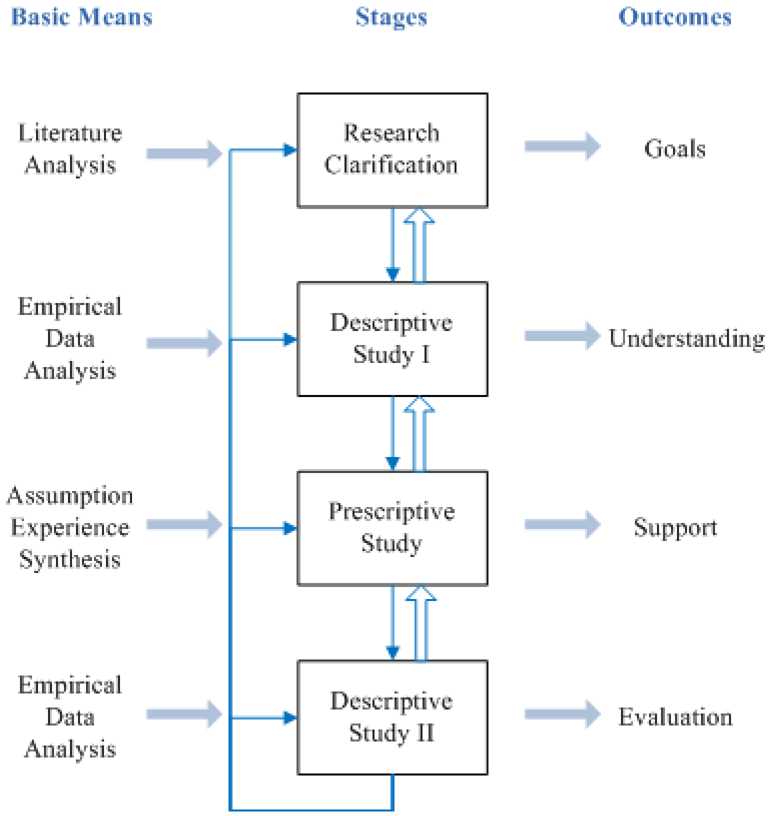


Figure 1-1: Methodological Framework to Conduct Design Research (Blessing, 2009)

Blessing (2009) states that the "Research Clarification" phase is constituted by the capture of the evidence to support the researchers assumptions in order to formulate the research goal. Moreover it is in this first phase in which the researchers define the success criteria to evaluate their research results. Blessing defines the second phase, "Descriptive Study I", as the stage of detailed understanding of the existing situation and the influencing factors. This second phase is constituted by detailed literature review and by first analysis of empirical data. The third phase, "Prescriptive Study", is defined as the phase to increase the understanding of the existing situation and correcting their initial assumptions.

The fourth phase is when the usefulness of the research results is investigated and validated. In a similar way, this research was conducted in four phases that are detailed below.

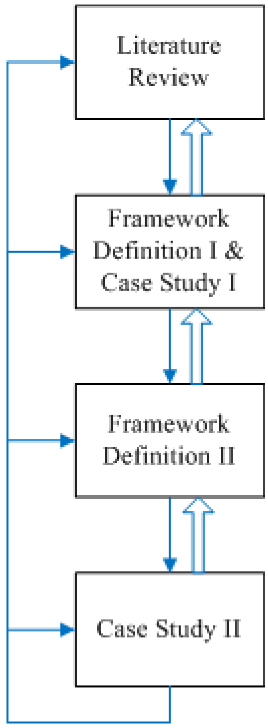


Figure 1-2: Research Approach

The first phase of this research was focused on understanding the problem and the literature gaps. Moreover, the literature review helped to define the success measures of this research. This literature review was focused on understanding the product development complexity and challenges as well as the current methods to address these issues. As the lean approach has been identified as a way forward for companies' success (Holman, 2003), this literature review was also focused on understanding how lean principles have been applied in product development. The output of this phase was a literature review report and a research proposal for discussion with the research supervisors. This research proposal was very useful when discussing the potential case studies with industrial partners and to get adequate support from academic and industrial sponsors.

The second phase occurred in the industrial environment, in the sponsoring company, Rolls-Royce plc. The aim of this phase was to understand the real problems and to define this research's response to these problems. A seven-month on-site case study was therefore undertaken to ensure the research was addressing real problems. Building on an understanding of the Rolls-Royce product development process gained during this first case study, the EPI (Engineering Processes Improvement) framework was developed with the aim to analyse and improve this product development. This case study involved observation, interviews and workshops with direct feedback from the process users. The results of this phase were two reports, one describing the framework and another describing the

process improvement carried out in this first case study. This phase also resulted in an international conference paper (Pepe et al., 2010).

The aim of the third phase was to re-adjust the framework based on the inputs and results from the first case study.

The fourth phase was constituted by a second case study in which the re-defined framework was applied to a different product development process within the same sponsoring company. This second case study was essential to validate the results of this research. As in the first case study, it involved process understanding through observation, discussion with the users, interviews and workshops. This work resulted in a second international conference paper (Pepe et al., 2011). This research and the results of the second case study have been highly appreciated within Rolls-Royce and are now part of the process improvement best practices.

This research took place during four years. The author had the opportunity to work within Rolls-Royce for two and a half years. This fact allowed the author to further investigate and exploit the results achieved as explained in the following chapters.

1.4. Thesis Structure

This thesis has the following structure:

Chapter 1: In this chapter the reader can find the thesis' context and motivation. It also presents the research questions and the approach followed to answer these questions.

Chapter 2: The second chapter presents the literature review which includes not only the specific methods used in the EPI framework but also other tools that could be used to achieve the same objectives. The difficulties of improving product development are addressed as well as the application of lean principles in this area. A comparison between lean product development and lean manufacturing is captured and summarised. Finally the few available lean product development industrial cases studies are summarized to support this research.

Chapter 3: The EPI framework is detailed in this chapter. For a better explanation of the framework a fictitious example is used to illustrate the framework's application to product development.

Chapter 4: The case studies are presented in this chapter as well as the industrial context and the company where the case studies were performed. The chapter is divided in three sections as follows: description of the industrial environment in Rolls-Royce, High Pressure Turbine Blade case study and High Pressure Turbine Disc Architecture case study.

Chapter 5: The research questions are discussed in this chapter. The results and research contributions are reviewed and opportunities for future work are proposed.

Chapter 2

Literature Review

2.1. Overview

The organisation and rationale of this chapter is represented in Figure 2-1. This literature review starting point is the basic question "why should companies improve product development processes". Once this point is clarified the difficulty and complexity to improve product development is investigated. After understanding the challenges companies face improving their way of developing products, various methods which are being used to improve and support product development are introduced. The literature review finds a consensus that product development should be improved using a Lean philosophy, hence a deep review on the Lean Product development literature, including industrial implementation examples, is conducted. From this review, the author identified the main gaps in the literature that led to the development of a framework to improve product development processes (see Chapter3). To support the framework development the author investigated the state-of-art of specific tools and methods that are part of the framework.

2.2. Why should companies improve product development processes?

Every day companies face the demanding challenge of bringing better products to the market more quickly. This associated with a trend to a customisation market makes the companies' life very difficult. Morgan and Liker (2006) asserted that to successfully face a micro-segmented market, companies need to reduce their development costs. These authors also defended that in today's market, excellence in product development is becoming more of a strategic differentiator than manufacturing capability. Holman et al. (2003) claimed that in order to react better to change in customers' requirements, market dynamics and suppliers capabilities, companies should develop products in a more agile and flexible way. The rigorous and disciplined traditional way of developing

products, following linear processes, defining firm time lines, conducting design review gates for decision making, and using cross-functional development teams that lead to significant improvements in the past are not sufficient anymore.

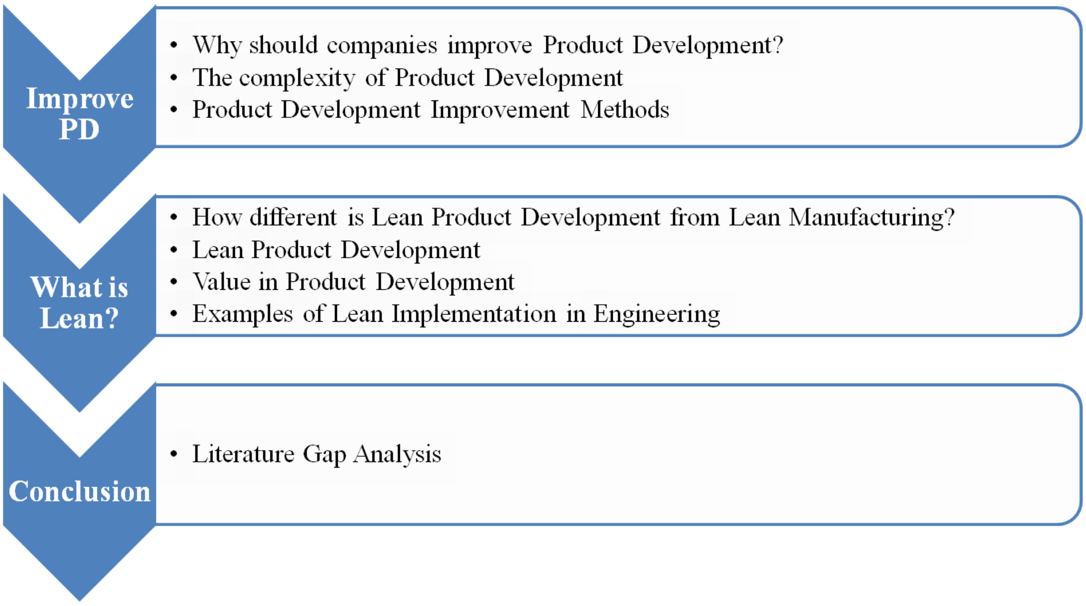


Figure 2-1: Chapter description

Morgan and Liker (2011) asserted that there are two main reasons to justify product development improvement. Firstly to allow a better level of manufacturing, for example designing for manufacturing can eliminate barriers such as lack of manufacturing capability, lack of modularity and lack of parts standardisation. Secondly enhancing product development performance can improve market responsiveness, reduce costs, improve quality and shorten lead times.

Browning and Ramasesh (2007) noted that product development can be a major competitive lever for a company. Clark and Fujimoto (1991) stated that improving product development companies can significantly change their market position. They presented the example of how General Electric gained market share from Pratt & Whitney in the nineties and attributed this success to an efficient product development, with modular features that dramatically shortened the duration and cost of their engines' development.

Clark and Fujimoto claimed that early decisions have the largest impact on the efficiency and effectiveness of product development (Clark and Fujimoto, 1991). It is during product development that commitments with the customer are made, suppliers are selected, materials and tests are defined. Considering these aspects, Morgan and Liker (2006) stated that the ability to impact customer-defined value, as well as to influence product cost, is much higher in product development than in manufacturing. Whitney (1988) stated that companies in the 1980s were already aware of the importance and power of improving product development. He gave the example of General Motors stating that 70% of the cost of manufacturing was determined in the design phase as well as Rolls-Royce revealing that design determines 80% of the final production cost of 2000 components

(Corbett, 1986). In 2001, Barton et al. challenged this 70-80% improvement-on-cost figure, however recognising the benefits of upstream evaluation. The authors suggested that this figure can be seen as unverifiable but showed that Design for Existing Environment produces higher cash flows, profit and ROE (Return on Equity) values when compared with a traditional approach with sequential processes in which manufacturing or service constraints are not considering during the design phase.

2.3. The complexity of Product Development

Ulrich and Eppinger (2000) defined product development as the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of the product. The product development activities can be represented by Figure 2-2.

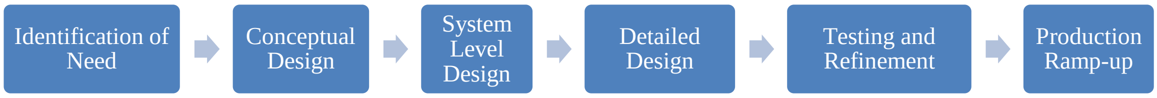


Figure 2-2 Product development typical activities (adapted from Ulrich and Eppinger, 2000)

This definition is extensively used in research and industry. Although not represented as product development phases other product life cycle phases, such as service or end-of-life phases, have a significant impact on the product development. Bearing in mind that the service support constitutes a significant of part of companies' business, the service phase should be taken into account in the design phase. Considering product end-of-life, companies have to think about all related aspects of their product development and avoid penalties and high costs for end-of-life disposal.

For many companies, as for example aerospace Original Equipment Manufacturers, product development continues in the form of improvements after the product has been delivered to the customer. On the other hand, it is during the first service period that potential issues are identified, which may launch re-design activities.

Product development by definition requires the interaction and collaboration of multi-disciplinary teams which increases the process complexity (Womack and Jones 1990, Ulrich and Eppinger 2000, Clarkson and Eckert 2005). The involvement of different teams can vary along the design process depending on the project phase, for example the marketing team is expected to have a higher involvement in the early phases of the product development which is then reduced.

Adding to product development complexity, Clarkson and Eckert (2005) stated that product development can be constrained by several factors, divided in three categories: project, company and external constraints. Project constraints include development cost, time and product nature; company constraints consist of product strategy, manufacturing capabilities, resources, skills, safety and quality; finally external constraints may be related with customers, suppliers, markets or legislation. Even if all these constraints affect product development processes, different companies, depending on their market strategies or of their products, choose different factors as the dominant design drivers.

Examples of different strategies may be an aerospace company driving their products' design on safety certification requirements and time to market and a computer company driving their products' design in terms of cost and time to market. Browning et al. (1999) states that product development process is to produce a "recipe" that satisfies requirements. However, requirements are not independent and often companies need to make compromises between the different design drivers, for example the reliability of an aircraft engine can be increased sacrificing the cost of the product or the time to market. Therefore, product development can be seen as a multi-objective optimisation process in which a solution is sought that can satisfy all constraints as well as is possible (Clarkson and Eckert, 2005). If not balanced at the right time critical drivers can promote unplanned and unnecessary process iterations. An example of a waste iteration can be caused by not considering the manufacturing capability when optimising the product quality; if the manufacturing problems are only identified on the production line the re-work cost can be enormous. The design optimisation or by other words the balance of the critical design drivers is essential to reduce re-work and achieve high performing products (Galbraith, 1974).

An additional challenge in product development is to provide the required information at the right point in time to the teams. During the product development process teams have to cope with uncertainty which can be defined as the difference between of information required to perform a task and the information available at a specific point in time (Galbraith, 1974).

Morgan and Liker (2011) noted that another key challenge for large complex development is properly specifying interfaces of the various subsystems. As described above, product development teams can be composed by people from different functional areas, with different backgrounds and mindsets, located in different places (which may cause communication problems) and with different goals. All of these aspects contribute to product development complexity.

Considering the importance of improving product development and supporting product development activities as well as its complexity, numerous tools and methods have been developed. A selection of the most relevant for this study is briefly described in the next section.

2.4. Product Development Improvement Methods

As described in the previous section, improving product development processes is a challenging task. There are many approaches to improve product development discussed in literature. Some of these theories are currently applied in industrial environments, but as Blessing (2009) states it is still a big step to bring engineering design research to the real world. To structure these methods, Browning and Ramasesh (2007) defined four groups of product development process models according to their purpose: process visualisation, process planning, execution and control and process development. From the point of view of this research the latter group is the most relevant. This category includes

process modelling for continuous improvement, organisational learning and knowledge management, training and compliance.

Vergidis et al. (2008) divided the process analysis in three groups: business process languages, mathematic models and diagrammatic models. Several diagrammatical methods are described below. These methods use graphical representations to describe the processes; most were initially developed for software development. Some of the methods are criticised for being based on graphical notation and lacking the necessary semantics to support more complex and standardised constructions. The main advantage of these methods is that no technical expertise is required to read and understand the models.

The next paragraphs describe some of the most well-known approaches and methods for product development improvement or to support product development.

2.4.1.Precedence Diagramming Method (PDM)

Process evaluation and review technique (PERT) and critical-path method (CPM) are two well-known examples of Precedence Diagramming Method (PDM). On both of these methods, activities are represented by boxes or nodes on a network and the flow of information or material from one activity to the other is represented by arrows. PERT charts represent both the dependencies and duration of a set of activities (Ulrich and Eppinger, 2000). CPM can be developed from the PERT chart analysing the activities sequence as well as dependencies and analysing the longest duration sequence of activities involved in the process (Clarkson and Eckert, 2005). Both of these techniques use simple graphical notation which make them easy to communicate. PDM methods are very useful when the process activities are predictable but are less effective in terms of representing the information flows and representing the iterative behaviour of product development. Some attempts to include the iteration analysis have been made developing GERT (Graphical Evaluation and Review Technique) and Q-GERT (Taylor and Moore, 1980).

2.4.2.Gantt Charts

Gantt charts are possibly the most well-known tool of project management; where the activities' duration is represented by horizontal bars along a time scale axis (Ulrich and Eppinger, 2000). In a Gantt chart the project manager can also represent the activity progression partially filling the activity bar. The task dependency is limited to representing the activities that must be completed before starting subsequent ones. For complex product development, project managers tend to use Gantt charts at a very high level, losing in terms of controlling what happens at lower levels and gaining in terms of communication aspect.

All of the above described tools are often used in product development mainly for planning and analysis but they are not suitable for improving product development. Ward (2007) even argues that

some of these techniques create inefficiencies in product development. The main reason for this is because these tools were mainly developed to support sequential product development processes but their use is still adopted by companies developing products concurrently (León and Farris, 2011).

2.4.3.IDEF

IDEF or Integration DEFinition is a family of modelling structures (IDEF0 to IDEF14) started to develop in the beginning of the 1980s in a US Air Force programme for business process analysis. IDEF0 and IDEF3 are the models of this family more relevant for the purpose of this thesis. IDEF0 aims to model the functional behaviour of engineering systems and it is already widely used, including in design activities, as for example by Airbus development (Clarkson and Eckert, 2005). When applied to design systems, IDEF0 captures the flows of information and resources. The model captures activities' precedence, but not the activity duration. On the other side, IDEF3 captures the process dynamics; it includes both time and activities' precedence and it may be used for analysis of iterations. The main disadvantage of IDEF is the complexity and the amount of understanding required to successfully use it.

2.4.4.Role Activity Diagram (RAD)

Role Activity Diagram (RAD) is often used for Business Process Analysis. It is useful for modelling both the current and the future (or desired) processes. In a RAD, one can find the roles that are part of the process, their actions and interactions with other roles. A specific graphical notation is used to produce RAD as shown in Figure 2-3.

In RAD, activities are represented by rectangular boxes placed in vertical swimlanes which represent different roles. Interactions between different roles are represented by horizontal lines between activities. Different options or decisions are represented by circles; triangles mean that the subsequent activities can be done in any order.

Even if the communication and understanding of the map is not too complicated, it is not self explanatory either, as is the case for other diagram techniques. RAD has been developed for business improvement and several challenges may be identified when applying RAD to product development, such as to model the iterative behaviour of product development. Capturing this behaviour make the diagram very complex eliminating the benefit of being a simple graphical tool. On another side, the use of RAD for product development improvement may also be a challenge because the diagram is not specifically developed to analyse waste and inefficiencies.

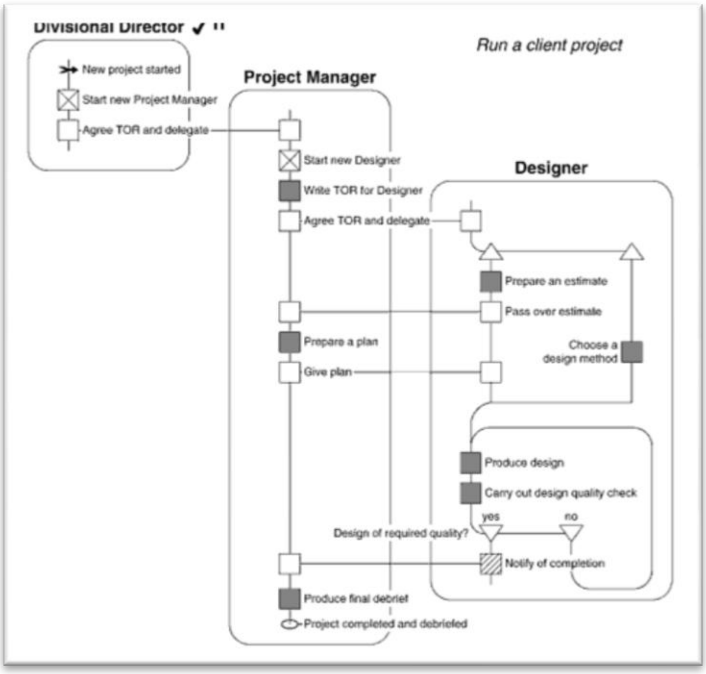


Figure 2-3: Simple RAD diagram (Ould, 1995)

2.4.5.Signposting

Signposting, developed in the Cambridge Engineering Design Centre, is an activity-based model of the design process which represents activities in terms of their information input/ output characteristics (Clarkson and Eckert, 2005). This method was developed to overcome the issue that product development engineers with specialized competencies often lack an understanding of the overall design process. The signposting model was extended to include probabilistic data, resource limitation, activity concurrency, learning/experience curve effects and the impact of trading off design quality/design risk against process duration and cost. A simulation-based approach was adopted to support analysis of process duration. Signposting has been developed to assess "what-if" scenarios, based on the simulation algorithms (Clarkson and Eckert, 2005). This most recent capability was identified as very useful to prototype design processes before investing in improvements, allowing companies to preview the improvement project impact before investing. Simulation can provide the necessary means to analyse processes and determine where the bottlenecks are, providing a solid basis for an improvement project business case.

2.4.6.Design Structure Matrix (DSM)

This methodology was developed to represent and analyse the activities' dependency and iterative loops of engineering processes which are difficult to represent with other methods (Pepe et al, 2011). The DSM was originally created by Steward (1981) but it was extensively developed by MIT researchers (Eppinger et al., 1994). The DSM is a square matrix with the activities sequence ordered identically in both rows and columns. The activities' dependencies are represented by marks on the

matrix as represented in Figure 2-4. Having a mark under the diagonal means that activity B depends on activity A. However having a mark on the upper part of the matrix main diagonal means that an upstream activity depends on inputs created in a downstream activity, for example activity A depends on activity D. A mark in the upper part of the matrix main diagonal therefore means that the information used to do activity A will need to be revisited after finishing activity D, which depending on the change required can impact the plan and cost of a project. To reduce the probability of facing these cases, the columns and rows of the matrix can be rearranged. This order change is called sequencing or partitioning of the DSM. Sometimes the marks cannot be brought to the lower part of the matrix but can be brought closer to the diagonal which means a reduction on the iteration loop and may be translated in a time reduction in the design process. More sophisticated DSM representations have been developed to support complex product development (Yassine et al., 2000; Yassine et al., 2001; Sharman and Yassine, 2003; Browning, 2001; Guivarch and Whitney, 2004).

	Activity A	Activity B	Activity C	Activity D	Activity E	Activity F	Activity G
Activity A	■			•			
Activity B	•	■					
Activity C		•	■	•			
Activity D		•		■			
Activity E				•	■		
Activity F			•		•	■	
Activity G						•	■

Figure 2-4: Design Structure Matrix example

2.4.7.Value Stream Map (VSM)

Value Stream Map (VSM) appears as one of the main tools of Lean Manufacturing. VSM was originally applied in operations environments, where it was used as a graphical representation of the materials and information flow. It was mainly used as a visual analysis tool to facilitate the understanding of the whole manufacturing process, with the purpose of identification of waste. In this context, waste is defined as any activity that consumes resources but is not valuable to the customer, in other words the customer would not pay for it. Nowadays the Lean philosophy has been extended to other areas outside of the manufacturing environment. McManus (2005) developed a manual for using VSM for improving product development processes.

On the value stream map, the design activities are represented as well as several time metrics such as “elapsed time”, “processing time” and “value-added time” (Pepe et al., 2011). The first purpose of the VSM is to capture the “as-is” design process, followed by identifying the process inefficiencies and finally developing a more efficient “to-be” state. VSM is a tool to allow cross-functional teams to identify waste in the current process and identify the enablers to improve the next design cycle

(Morgan and Liker, 2011). The main difficulties faced when using VSM for engineering improvement is the data collection phase and the representation of the iterative behaviour of product development.

2.4.8. Summary

As described in the previous sections, there are in literature many methods to improve product development processes. As discussed, the complexity of using each method changes as well as their objectives. Some methods are focused on reducing process waste, others on improving the product development interactions and others on reducing the complexity of process iterations. All of these methods have particular benefits, but none of them is self-sufficient to improve product development as a whole.

2.5. What is Lean?

Instead of focusing in the tools, Holman et al. (2003) stated that the improvements required for product development should be based on Lean manufacturing principles. Eight years passed since this article was published and there is still a lack of good examples and lessons learnt from applying lean to engineering processes in literature. A very recent example of lean engineering application is the work published by Morgan and Liker (2011) reporting the implementation of lean in Ford. Holman's et al. (2003) noted that a successful product development needs to be more flexible, efficient, minimising the waste at each step of the process, focused on the customer satisfaction and driven by world class leadership. These authors suggested that product development should change from the traditional process-based (phase-gate) approach to a more flexible and efficient information-based approach.

Lean practice started in Toyota in the 1950s as an attempt to overcome the Japanese crisis that followed World War II, even if lean is not part of the Toyota jargon. Lean was the denomination created by Womack et al. (1990) to define the Toyota philosophy. In the 1950s the industrial world, and specifically the automotive industry, was following the American mass production model. Due to the lack of human and material resources, as well as the reduced size of their market, the Japanese could not follow the mass production model, which basically takes full advantage of the economies of scale to strengthen the cost reduction potential. Following a push approach, producing enough buffers that allow decoupling production steps from each other and even from demand, mass production could assure a continuous flow but at the cost of large amounts of work in progress which the Japanese couldn't afford in their weak condition. Therefore the solution found by Toyota was to do more with the available resources increasing the efficiency by eliminating any type of waste from the processes or by other words making their processes lean.

It was only in the 1980s that the Western industries became aware of this lean paradigm. Based on the International Motor Vehicle Program work comparing the Japanese and American industries,

Womack et al. published in 1990 “The Machine That Change the World” with an insight on the Toyota managerial system of lean production (Womack et al., 1990). Although the authors describe more than the Toyota production processes, companies around the world improved their production processes following the Toyota Production System model, seeking to increase efficiency. Lean manufacturing is only one chapter of the book; other chapters focus for example on product development, supplier and customer relationships. The product development chapter, the most relevant for this research, was based on Clark and Fujimoto (1991) work in which they compared American and Japanese auto companies, concluding that the main differences were related with flow of information, push/ pull concept of development and leadership.

If the Toyota way is much more than lean production, why were companies primarily interested in adopting lean production techniques? The author of this thesis believes that lean product development is a much bigger challenge than lean manufacturing which is one of the main reasons why companies started to implement lean manufacturing. The lean principles were quickly substantiated in methods and tools to improve manufacturing processes which quickly generated visible improvements. However, the innovative and complex product development processes, with their contingent behaviour, presented a much higher challenge and consequently less successful results are present in literature.

2.5.1.How different is Lean Product Development from Lean Manufacturing?

The way to apply lean product develop and lean manufacturing may vary in application terms but both are valuable and bring benefits to companies. According to some authors (Reinertsen, 2005; Baines et al., 2006; Morgan and Liker, 2011) the application of lean in product development can even be more beneficial than in manufacturing.

Morgan and Liker (2011) stated that there are two main competitive advantages of implementing lean in product development. Firstly it makes lean manufacturing easier to implement and more efficient, reducing for example the manufacturing or assembling problems. Secondly it improves the performance of the product development process itself. This can improve the market responsiveness, reduce costs of the product and costs of the development process, improve design quality and dramatically reduce lead times. For example reducing waste from the process reduces lead time, which may allow front-loading the process, thereby reducing the risk of later and expensive iterations which can be directly reflected in the product unit cost.

When applying lean to product development a major difficulty is identifying the flow of both value and waste. In the manufacturing environment, the flow of material and information can be easily identified and followed. The same cannot be seen in product development because most of the flow is constituted by information which may be transmitted formally or informally, via documents as well as verbally or electronically. It is even more difficult to identify waste in product development processes.

In manufacturing any re-work activity is waste; the same judgement cannot be applied to product development where some iteration is necessary due to the concurrent design approach or needed to optimise the product performance.

Product development is characterised by a highly iterative behaviour. A part of these iterations is essential to optimise product performance and reduce the design risk. However, there are also wasteful iterations caused by incorrect assumptions, mistakes or insufficient consideration of customer requirements. These iterations generally do not add any value to the product or promote any learning and therefore should be considered waste and if possible eliminated. However, to distinguish between required and wasteful iterations may be a challenge. In product development, as well as in manufacturing, waste should be seen as any activity that uses resources, but does not add any value from the customers' point of view. This value can be seen in terms of reducing the risk of failing to meet the customers' requirements. Moreover, another important difference between manufacturing and product development activities is the fact of being humans processing the information flow instead of machines. In manufacturing the information flow exists to support the visible material flow. Changing machine set-up, position or function may be expensive but is straightforward when compared with changing and controlling people's way of working. People tend to resist changes, even if the benefits are obvious. Changing people's way of working, or by other words a company culture is even more challenging and the main topic of organisation psychology research Clegg and Walsh (2004). Finally, in product development processes, each product design may be different from the previous one, either because of different customer requirements or because of a different project environment (time scales, operation environment, etc.).

Womack and Jones (1996) characterized lean thinking in five principles. The first lean principle is about specifying *value*, which is defined as value for the ultimate customer. The second principle is to identify *value stream* which can be done through graphical mapping, such as value stream maps capturing the flow of material and information. The third principle is about continuous *flow* and can be achieved eliminating waste from the value stream. The fourth principle is to *pull* the flow at a request from the customer in opposition to pushing material or information because a future demand is foreseen. The fifth and final principal is *perfection* that implies continuous improvement using the four previous principles.

For manufacturing environments these principles seem to be clear and achievable. Value is seen as anything the customer would pay for, all re-work is therefore a waste. The value stream is captured following the parts on the production line. Flow is achieved by promoting the one-piece-flow and eliminating the non-value added activities from the production process; the pull principle is implemented by using techniques such as just-in-time and perfection is understood as producing "the right thing right first time".

Translating these principles to product development is a challenge that some authors already undertook. For example, Haque and James-Moore (2004) re-defined the five principles for the product development context:

- *Value:* The value should be defined not only from the ultimate customer point of view but also from internal customers and stakeholders point of view. This perspective is also supported by Slack (1999). The internal customers should be understood as the receivers of results of the upstream activities. Making these internal customers' needs and requirements clear along the product development process would eliminate significant amount of waste as can be found in this research. Satisfying the intermediate needs will conduce to a more efficient process and consequently offer benefits for the ultimate customer as well.
- *Identify value stream and eliminate waste:* The new product introduction value stream should be modelled, analysed and non value-added activities eliminated. This includes identifying and mapping the value streams, as well as standardising and measuring in order to achieve customer expectations with a lean process. The authors also recognize the use of simulation tools to identify waste. Several other tools are presented to identify waste in product development such as 5C's, the seven waste sources, visual control and standardisation of processes. The need to define waste for product development is recognised.
- *Make the value flow:* The achievement of this principle is described as making the value flow through value-added steps and controlling the information flow. The authors identify as key characteristics of making the value flow the focus on integration (in opposition to co-ordination), effective programme planning and control, reduction of batching and buffering of information, effective communication and effective technology.
- *Pull:* This principle is achieved through the definition of a plan in which activities deliverables are based on the needs of downstream activities, ensuring that information is made available when it is needed.
- *Perfection:* Is defined through continuously focusing on adding value, reducing waste and through a visible quantitative measurement system.

After describing the main differences between lean manufacturing and lean product development, a more detailed review on lean product development is presented on the following section.

2.5.2. Lean Product Development

After observing the success of Lean Manufacturing and aiming to deliver faster, better and cheaper products, companies are now starting to strive for achieving Lean Product Development. Even if there is not much evidence of the results, Baines et al. (2006) stated that it is clear that lean can be applied beneficially in product development. Lean product development as presented by Womack et al. (1990) is the Toyota culture of developing new products and it is mainly distinct from the Western

companies' product development approach in terms of leadership, teamwork, communication and simultaneous development. Whereas Japanese companies talk of philosophy and culture, Western companies tend to focus on Lean through the application of tools and techniques. Whatever the perspective and approach taken, the elimination of waste and mainly the value enhancement are common and essential for a Lean status achievement (Baines et al., 2006).

McManus et al. (2005) define lean engineering, which is called lean product development here, as doing the right thing right. This means working on the right products, which are the products the customers want, using a lean approach to create value and eliminate product development waste sources. McManus et al. (2005) stated that there is a set of key best practices that emerged from lean product development:

- Focus on understanding customer requirements and expectations
- Hold-up key decisions as far as possible in the design process. Delaying the key decisions will give the opportunity to do the required activities with better information.
- Develop products that can be upgraded, reducing the cost and development time for future programmes.

Companies can develop high performing products but if these products are not aligned with the customer expectations they may be perceived as flawed products. This best practice of focusing on understanding the customers' requirements should also be used for internal customers, as stated by Haque and James-Morgan (2004). For example if a designer is producing geometry to be analysed by a stress engineer, the latter should be considered the internal customer of the geometry. If the designer has the stress engineer's requirements in consideration during his activity the chances of re-work between these two functions may be significantly reduced. Clegg and Walsh (2004) also note that product development contributors should start treating internal customers like the company treats the ultimate customers.

Delaying key decisions in the design process is an advantage from two perspectives. Firstly the requirements often change significantly along the design process. If key decisions have already been taken, a requirements change can have a severe impact on the project plan and cost. After assuming a decision to design and develop the production tools, any geometry change in the product may cause damage on cost and time. Delaying key decisions gives more flexibility to accommodate design changes. Secondly considering that the value of an activity depends on the value of the information it uses and creates (Browning et al. 1999) it is clear that the decision taken in a later phase of the design process is more supported than one taken in early phases of the design. Saying this it is also recognised that delaying key decisions is a challenge in product development. One reason for this is the production tools definition – because of the tools development time, companies have to take key manufacturing decisions in a very early design stage, accepting the risk of these early decisions.

The third best practice, the use of design modularity, is often found in the automobile industry. This practice can also be found in aerospace industry. For example the risk and difficulty of developing aero engines is high and therefore normally reduced through demonstrator projects and evolutionary design which uses modules of validated products. This reduces risk, cost and time in the development process and provides the opportunity to reuse data as well as manufacturing processes and tools.

After a systematic literature review on lean outside of manufacturing environment and mainly focused on product development Baines et al. (2006) identified key aspects of lean product development as well as some associated implementation issues. The authors describe how the focus in waste reduction in manufacturing is being substituted by the focus in value creation in product development environments. The value creation aspect is not only pointed out as critical but also as particularly challenging in product development. As recognised in Section 2.5.3, the concept of value in engineering activities is different and more difficult to identify than in manufacturing. Baines et al. (2006) say that defining value is essential in product development. The authors also acknowledge the importance of adopting a set-based design approach. Set-based design is a key characteristic of Toyota’s product development system. In set-based design, in opposition of point-based design, several design concepts are simultaneously analysed by different design functions in early phases of the design process. This practice requires special technical skills and communication links but it seems to give substantial benefit in terms of learning capability and communication that can be reflected in terms of re-work and time reduction in the later and more expensive parts of product development (Sobek, 1997). Another significant advantage of set-based design is that all the results are captured, both the successful and unsuccessful concepts, giving the opportunity to re-use the knowledge. Baines et al. (2006) also identify the figure of the Chief Engineering as fundamental to coordinate a good lean product development. The Chief Engineer as mentioned in *The Machine* (Womack et al., 1990) needs to be more than a manager, he or she also needs to be a leader that *owns* the project and unifies the team. The Chief Engineer needs to have not only excellent technical and social skills as power to conduct *his* project. The last key finding of Baines et al. (2006) and also supported by other authors (Morgan and Liker, 2006; Murman et al., 2002; Womack and Jones, 1996) is that a lean transformation needs to be done at a company level. In summary, the key issues identified by Baines et al. (2006) are related with knowledge management (the difficulty of capturing, maintaining and reusing knowledge), the value definition and in more general terms the re-definition of product development structure to accommodate these lean changes.

Morgan and Liker (2006) stated that to improve product development, a company needs to improve the integration of technology, processes and people. Even if described in the context of product development, this need should be transversal to all business functions from marketing to manufacturing and service. The sociotechnical theory that became popular in the 1970s and 1980s states that to be successful an organisation must find the appropriate integration between the social

and technical systems that fit the organisational purpose and external environment (Morgan and Liker, 2006). All of this seems to be obvious and common sense; however when faced with the pressure arising in the day-to-day work, caused for example by stretched human resources, inefficient processes or lack of IT capability, it is easy to lose the balance. When taking actions to address the above described problems, companies do not consider the whole picture (people-processes-technology). Brynjolfsson and Hitt (1998) concluded that large IT investments would not have the same impact if not coupled with complementary investments in new strategies, processes and organisation. Clegg et al. (2000) illustrated this scenario swith the case of a company investing in an expensive CAD/CAM system to improve the integration of designers and manufacturing engineers instead of getting the two functions to talk and work in integrated teams. This does not mean that the IT investment was wrong, but that there were other aspects, such as the social perspective, that should also be considered when planning design systems improvement activities. Improving an engineering process should be seen as improving a complex system in which the whole system should be analysed for getting the right improvement, not only a part of it such as the IT capability.

Considering the involvement of an interdependent mix of social and technical sub-systems, design activities can be defined as sociotechnical systems (Clegg, 2000). Cherns (1976) asserted that to better achieve objectives, sociotechnical systems should optimise the integration of technical and social aspects. Almost twenty-five years later, Clegg said that the design and performance of new systems can only work properly if the social and technical systems are analysed together and considered interdependent aspects of the whole system.

Cherns defined in the 1970s, nine sociotechnical principles to support design activities. An interesting aspect is that these principles have a lot of similarity to the nowadays well known lean values. For example the second principle called “minimal critical specification” states that no more should be specified than what is absolutely essential. In a lean context any activity performed in excess of what is needed is waste. This principle as Clegg (2000) described can also be interpreted in terms of users being authorized to solve their own problems, avoiding the waiting time for specialised “problem shooting people” and having decisions taken at the lowest possible level. Another example is the third principle which asserts that all the variances should be eliminated; if this is not possible variances should be closely controlled. Variance is defined as the difference between actual and expected results. Reducing variation is one of the main ideas of lean six sigma theory (George, 2005). Remarkably Cherns’s ideas were developed much earlier than the lean theory in the Western world. Considering the industrial and commercial environments changes, Clegg (2000) revised Cherns’s principles ending with nineteen principles. The revised sociotechnical principles were defined for use by systems managers, designers or social scientists (re-)designing design systems. In 2000, Clegg already made frequent associations between the sociotechnical principles and the lean manufacturing philosophy. Another interesting point from the sociotechnical principles is the focus and importance

given to the concurrent design. Clegg (2000) identifies a key feature of the sociotechnical design which involves bringing together people from different roles and disciplinary backgrounds with different skills. The concurrent engineering or simultaneous development has been identified in *The Machine* (Womack et al., 1990) as one of the key characteristics of Toyota's product development system.

Table 2-1 Sociotechnical Design Principles (Clegg, 2000)

Sociotechnical Design Principles (Clegg, 2000)
1. Design is systemic
2. Values and mindsets are central to design
3. Design involves making choices
4. Design should reflect the needs of the business, its users and their managers
5. Design is an extended social process
6. Design is socially shaped
7. Design is contingent
8. Core processes should be integrated
9. Design entails multiple task allocations between and amongst humans and machines
10. System components should be congruent
11. System should be simple and make problems visible
12. Problems should be controlled at the source
13. The means of undertaking tasks should be flexibly specified
14. Design practice is itself a sociotechnical system
15. System and their design should be owned by their managers and users
16. Evaluation is an essential aspect of design
17. Design involves multidisciplinary education
18. Resources and support are required for design
19. System design involves political processes

Morgan and Liker (2006) showed that the Toyota production system is a sociotechnical system based in three subsystems, as represented in Figure 2-5.

The *People* sub-system is strongly focused on the Chief Engineering role and the importance of his authority to integrate the project with the functional units, to develop the technical excellence in the company, to fully integrate the supply chain in sustainable relationships and support the culture of continuous improvement.

The *Process* sub-system's centre of attention is the customer value and consequently the distinction of waste and value-added activities. It also calls attention to the importance of front-loading the design process, bringing the right resources to the system design before starting the detailed design and levelling the design process flow. Finally it focuses on variability and unpredictability reduction as well as increasing flexibility.

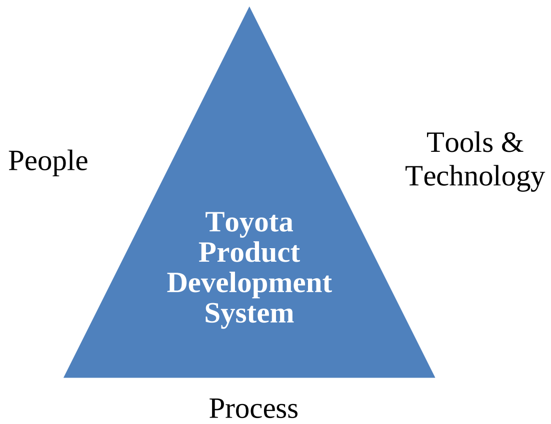


Figure 2-5: Product Development System (Morgan and Liker, 2006)

The *Tools & Technology* sub-system's main point is on adapting the technology to fit processes and people and not the opposite. Surprisingly, the authors include in this sub-system the importance of effective communication and powerful standardisation. One could think that the effective communication being on the technology sub-system would mean high tech communication platforms. However Toyota keeps the communication at the simplest level, for example having "war rooms" in which the walls are covered with project information or circulating results of improvement projects in single-page "A3 reports".

Morgan and Liker (2006) divided these three sub-systems in thirteen Toyota Product Development principles (see Table 2-2). These thirteen principles represent the most comprehensive description of what lean product development should look like. They are described below and often used for sanity checks along this research. The first four principles address issues related with processes, a process being a sequence of tasks required to produce a product from concept to launch of manufacturing.

Principle 1 *Establish customer-defined value to separate value-added activity from waste* notes the importance of the customer in a Lean product development system and the importance of having the voice of the customer clearly shared across all the companies' levels. Normally the voice of the customer is clear among the senior/ medium management. However in a large and complex matrix organisation, it is difficult for engineers with little or no customer contact to see the impact of their

work on the customer's satisfaction. Morgan and Liker also described how important it is to identify customer value. From this research it was concluded that one of the main challenges in engineering improvement is to identify non value added activities. Literally non value added means any activity that consumes resources and does not add value to the customer, but if the voice of the customer is not clearly defined, the identification of the waste is not an easy task.

Principle 2 *Front-load the product development process while there is maximum design space to explore alternative solutions thoroughly* is commonly understood by the design community but very challenging to implement. Companies discuss the best practices to achieve less rework doing more pre-work. To achieve this, companies should invest in resources, human and technology, for the earlier phases of product development. Another important point is to have the right distinct resources supporting preliminary design, such as manufacturing or service engineering.

With Principle 3 *Create a levelled product development process flow*, Morgan and Liker asserted that product development should be treated as a "knowledge work shop" and should be levelled adapting process improvement tools from manufacturing. The aim is to level the process, create *takt* time (or drum beat, which means the time taken to produce one product accomplishing the customer's time scales), minimise queues, synchronise products and reduce re-work. In product development this concept can be seen at activity level, for example levelling the process may include planning the time available to perform activities e.g. a stress analysis. If several activities have to be completed, the plan should define the available time for each activity in order to meet the overall deadline.

Principle 4 is related with standardisation at three different levels: design, process and skills standardisation. Design standardisation is seen as reusing similar architectures, modules and sharing components, as discussed by McManus et al (2005). Following this principle not only helps to reduce the development time, but also avoids re-inventing the wheel, as well as reducing the design risk re-using already validated components, modules or architectures. Morgan and Liker discuss process standardisation focusing on the manufacturing process point of view, but the same principle should be applied to product development processes. Often large companies tend to use different product development processes for different product and different customers. Different processes may even be used to develop identical products in different geographical locations. The lack of standard processes makes it difficult to share knowledge and resources between different projects. Finally the standardisation of engineering skill sets is important to efficiently plan and resource product development.

Principle 5 is focused on the Chief Engineer's role and how he or she should be developed to be responsible for the complete project integration. The Chief Engineer is essential to integrate all the different functions along the product development. Without a powerful Chief Engineer in a matrix structure company project leaders may struggle to get the required resources that are normally allocated to functional areas. The Chief Engineer needs to be an excellent leader but also an excellent

technical expert. According to Morgan and Liker it is the Chief Engineer that holds together the product development system from the start to the end of a project.

Principle 6 is related to the balance of functional expertise and cross functional integration. Mainly large companies develop a matrix structure and create silos of expertise. The challenge is the cross-integration of these silos of expertise. Toyota uses the Chief Engineer to achieve a successful cross-functional integration as well as integrated component development teams and the “obeya” system in which each project has as a “war room”.

Principle 7 is about developing technical excellence which is fundamental for a lean product development. Toyota people respect technical excellence and they are developed on a solid technical background. In western companies, the management ladder is often perceived as the faster career path. In order to develop technical experts, companies need to recognise the technical excellence in the same way they recognise leadership.

Principle 8 is concerned with supplier integration in product development. Morgan and Liker state that companies should treat their suppliers in the same way as they treat internal resources and partners. Moreover, to avoid problems in manufacturing or other development phases, suppliers should be involved in early product development phases.

Principle 9 asserts that continuous improvement activities should be part of the day-to-day work and not considered secondary activities. Toyota considers improvement activities when planning and ensures that everyone is assessed for accomplishing improvement activities. This is important not only to improve the way people work but also to avoid duplication of work.

Principle 10 is related to building a culture to support excellence and relentless improvement. This principle is possibly the most difficult to implement in Western cultures. At Toyota people breathe the company philosophy and principles. Everyone work harmoniously towards the same goals. A company culture cannot be changed from one day to another; it has to be built, as stated in the title of this principle.

Principles to 11 to 13 are related with tools and technology to support the entire system. Principle 11 declares that the technology should be adapted to people and processes and not the other way around. Technology on its own does not make the difference, firstly because it can be replicated by competitors and secondly because the introduction of technology which has not been planned considering people and processes may have a negative impact in performance.

Principle 12 is about tools that support the decomposition of high level goals (customer value) in feasible and achievable tasks and the ability to solve problems through simple approaches and to use visual methods for communicating information. An interesting fact related with this principle is that Toyota encourages engineers to share not only the best practices but also the lessons learnt from problems. According to Baker (2011) this culture of sharing problems instead of hiding them is very difficult to install in the Western culture.

Principle 13 describes the importance of having simple tools to support the knowledge capture in a standard way. Toyota uses very simple tools as for example know-how databases, engineering checklists or quality matrices to capture and maintain knowledge.

Table 2-2: Toyota Lean Product Development Principles (Morgan and Liker, 2006)

Toyota Lean Product Development Principles (Morgan and Liker, 2006)
1. Establish customer-defined value to separate value-added from waste
2. Front-load the product development process to explore toughly alternative solutions while there is maximum design space
3. Create a levelled product development process flow
4. Utilise rigorous standardisation to reduce variation, and create flexibility and predictable outcomes
5. Develop a Chief Engineer system to integrate development from start to finish
6. Organise to balance functional expertise and cross-functional integration
7. Develop towering technical competence in all engineers
8. Fully integrate suppliers into product development system
9. Build in learning and continuous improvement
10. Build a culture to support excellence and relentless improvement
11. Adapt technology to fit your people and process
12. Align your organisation through simple, visual communication
13. Use powerful tools for standardisation and organisational learning

Considering the statement from Morgan and Liker (2006) that the Toyota lean product development system is a sociotechnical system, a comparison between its principles and Clegg's sociotechnical principles has been carried out. Figure 2-6 shows this analysis, where dark-green represents sociotechnical principles represented in the Toyota principles, light-green column shows sociotechnical principles that are intrinsic to the Toyota system but not reflected as a principle and yellow represents a weak link.

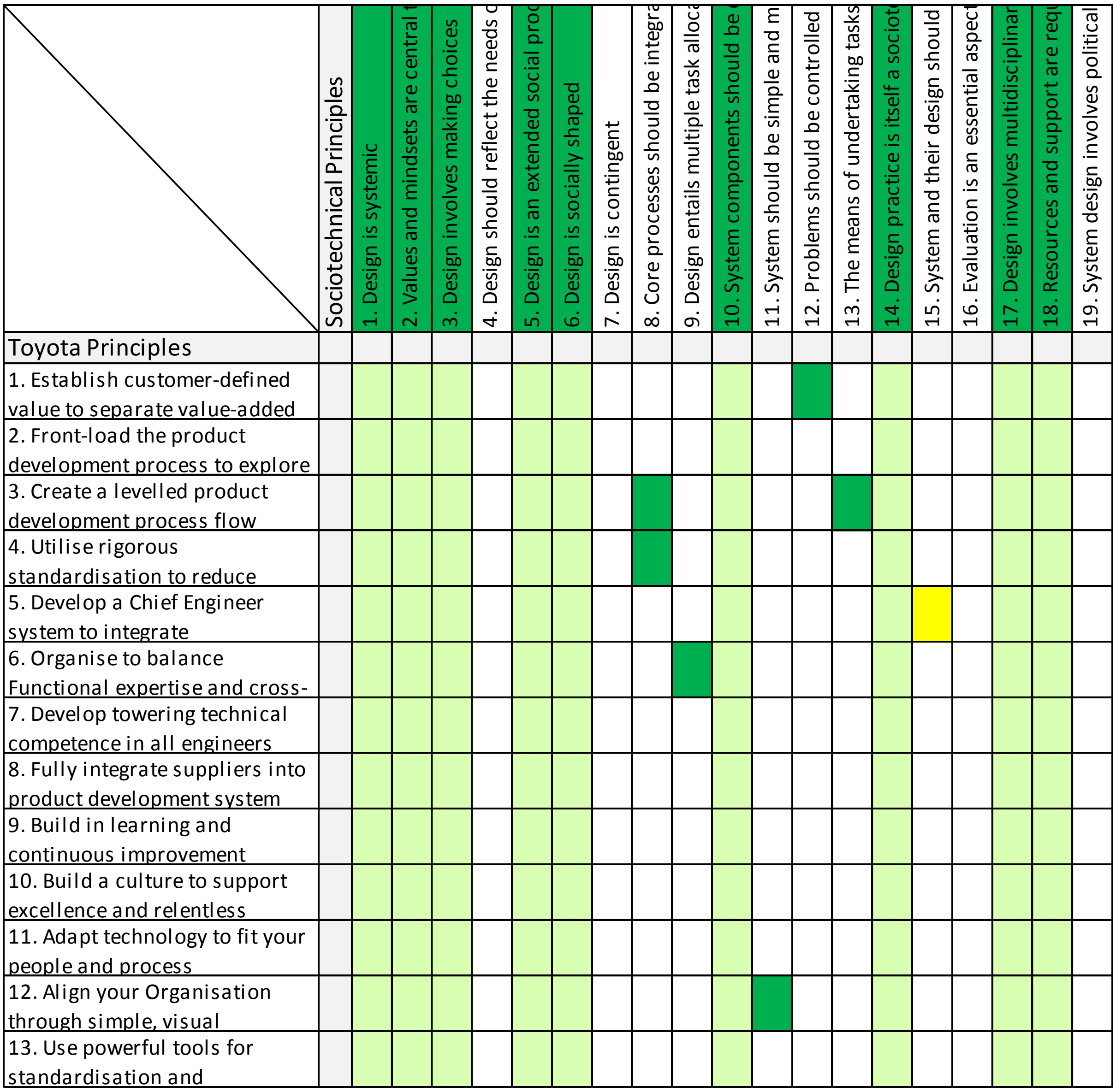


Figure 2-6: Comparison between the Toyota product development and the sociotechnical principles

The first conclusion of this analysis is that there are some sociotechnical principles that are inherent to the Toyota philosophy but are not reflected as Toyota principles. On the other hand, there are some sociotechnical principles there are directly reflected in the Toyota principles. One of them is "core processes should be integrated" that is clearly reflected in the third and forth Toyota principles where Morgan and Liker describe the importance of process synchronization and standardisation. The following principle "design should reflect the needs of the business, its users and their managers" may create some conflict with the lean focus on the customer. However if "customer" is defined by internal and external customer, and the business perspective is included in the definition of value as stated by Slack (1999), this sociotechnical principle is in complete harmony with the lean product development philosophy. The principle "design is contingent" which means that "one size doesn't fit all" is one of the reasons why it is difficult to apply lean to product development. This means that

each time a design process is executed it can turn out differently from previous times because of new circumstances or because the requirements and needs are different.

There are other principles that are not explicitly described on the Toyota principles, but are part of it such as evaluation and measurement of performance. The only sociotechnical principle that does not appear to be related with the Toyota principles is the last one, "system design involves political processes".

Noting that the empirical base for lean product development remains weak, Hoppmann et al. (2011) analysed the existing frameworks for lean product development and combined them into a single and structured framework. The framework developed has eleven components that the authors consider essential for lean product development. After identifying these components, the authors analysed the dependencies between them. They scanned twenty-seven publications searching for quotes describing elements of a lean product development. The authors subsequently checked for common themes and clustered them in the eleven components, listed in Table 2-3.

Table 2-3: Components of Lean Product Development (Hoppmann et al., 2011)

Components of Lean Product Development (Hoppmann et al., 2011)
1. Strong project manager
2. Specialist Career Path
3. Workload levelling
4. Responsibility-based Planning and Control
5. Cross-project Knowledge Transfer
6. Simultaneous Engineering
7. Supplier integration
8. Product Variety Management
9. Rapid prototyping, simulation and testing
10. Process Standardisation
11. Set-based Engineering

The first component *strong project management* is defined in the same way as Morgan and Liker (2006) defined their Principle 5. An additional point is the fact that the Chief Engineer represents the voice of the customer and is responsible to translate this voice into feasible and understandable

activities that will conduct to the development of the product which satisfies the customer expectations.

The second component *specialist career path* is very similar to Morgan and Liker's seventh principle in which the authors acknowledge the importance of technical excellence for a lean product development. Hoppmann et al. (2011) stated that to become specialists engineers have to spend long periods in the same function. To promote this scenario, companies have to make sure engineers feel compensated in their roles and do not feel they have to move jobs to progress in their careers.

The third component *workload levelling* is comparable to the third principle according to Morgan and Liker. An additional point is that Hoppmann et al. (2011) extend the workload balance across different projects. They mentioned a statement made by Ward (2007) in which the author states that to achieve the balance, companies should launch projects in constant intervals. This seems to be hard considering that most of the companies' new product development depends on the market demand and competitors' performance. However, even if this scenario cannot be achieved, companies should try to plan their projects and reduce planning variability.

Component four, *responsibility-based planning and control*, is mainly related with changing from a micro-planning and micro-scheduling performed by the project leader (top-down planning) to a self-planning owned by the engineers (responsibility-based). In this scenario, the engineers are given the overall goal and time-scales which will allow them to define their own planning and schedule. This approach has two main benefits: more realistic planning and more commitment from the engineers once they work to accomplish their own plan. This component is related with two Morgan and Liker principles. Principle twelve in which they recommended the use of simple tools for organisation alignment with the customer expectations and in a more subtle way with principle seven, develop towering technical competence in all engineers, from the point of view of developing the right technical competencies to self-manage their own tasks.

Component five, *cross-project knowledge*, is related with capturing, maintain and applying lessons learnt to avoid work duplication from project to project. Morgan and Liker declared in their thirteen's principle that this should be done using simple and effective tools.

Component six, *simultaneous engineering*, is identified by several authors as a key characteristic of lean product development (Sobek, 1997; Haque and James-Moore, 2004; Ward, 1995). Simultaneous engineering means that the different functional areas work in parallel tasks, significantly reducing the project lead time as well as reducing long iterations caused by problems found later in the project. This component is related with two of Morgan and Liker principles, the second in which they stated that the early phase of design should be front-loaded with all the relevant functions and the sixth where the authors discuss the cross integration of functions.

The seventh component, *supplier integration*, is literally the same as principle eight from Morgan and Liker analysis. Hoppmann et al. (2011) stated that a lean product development is based in a small

number of suppliers with strong and stable relationships with the primary companies and involved in an earlier stage of the design stage as defined by Morgan and Liker.

The eighth component, *product variety management*, aligned with principle four, supports the approach of using modules, platforms or even common architecture to overcome the loss of economies of scale that companies are facing with an increased product variety. It is in fact the mass customisation approach discussed in the first section of this chapter.

The ninth component is related to *rapid prototyping, simulation and testing*. It is a common understanding that good simulation and prototyping tools can cut down time and cost and improve product development performance. As Morgan and Liker, also these authors stated that introducing more simulation and prototyping in early stages of product development can make a difference. The use of these techniques not only reduces the evaluation time but also the evaluation cost. For example using Finite Element models to predict stress failures is far less expensive than testing physical prototypes. On the other side prototypes for testing can use cheaper but representative materials. It is thus cheaper than testing the final product.

Hoppmann et al. described standardisation just in terms of process standardisation, not covering the two other types of standardisation defined by Morgan and Liker (2006), design and engineering skills standardisation. As previously mentioned product design standardisation is covered by component eight. The focus of this component is in identifying and standardising the reoccurring activities of product development to define standard product development processes.

The last component, *set-based engineering*, previously described in this research as different design functions cooperate to design several concepts simultaneously in early phases of the design process, is also described in the second principle of Morgan and Liker as critical for a successful product development.

As represented in Figure 2-7, the lean product development components of Hopmann et al. are covered by the Morgan and Liker Toyota principles. The first authors claim that there is some redundancy in the later authors' principles and try to eliminate it defining the eleven lean product development components. However, there are some critical points missing in these eleven components, such as the focus on customer value or the focus on building on continuous improvement. Figure 2-7 also shows the interactions: green shows a strong relationship and yellow a feeble relationship between components and principles.

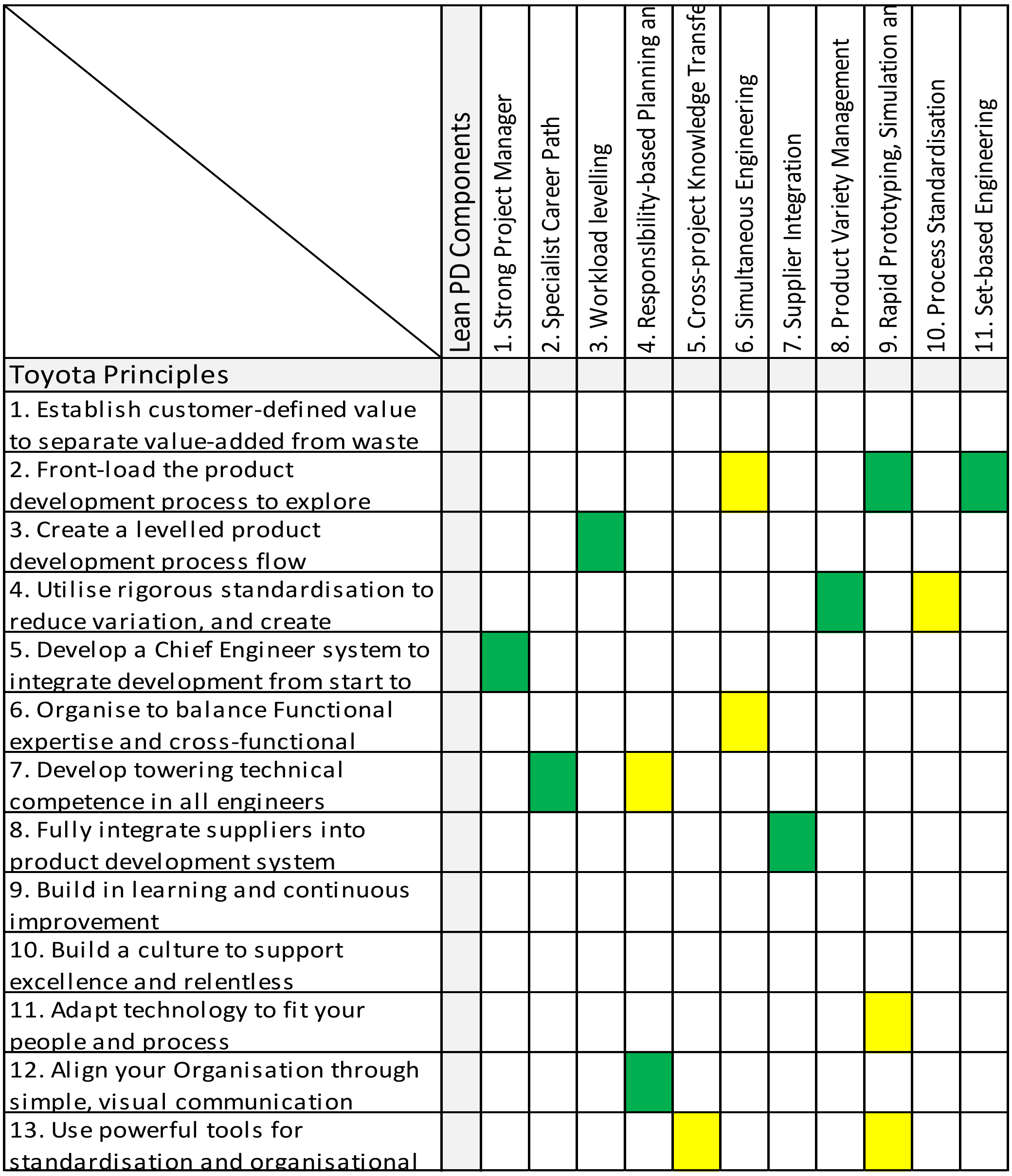


Figure 2-7: Hoppmann et al. components and Morgan & Liker principles comparison

Based on the same eleven components, Hoppmann et al. (2009) conducted a survey to understand how difficult and useful the implementation of lean product development in the industrial environment is and to what extent companies were implementing lean product development aspects. To perform this study the authors collected information from 113 product development stakeholders (such as managers, chief engineers and development engineers) from different companies and different industries.

Figure 2-8 shows the ranking of the most used lean product development components within the 113 companies. This graph shows that the contacted companies are already implementing nine of these components in more than half of their projects. The least used components are set-based engineering and cross-project knowledge transfer. The survey conclusions do not justify this difference. Other

aspects that the authors do not discuss are the impact of implementing these components in the companies' results and the interrelation between the different components.

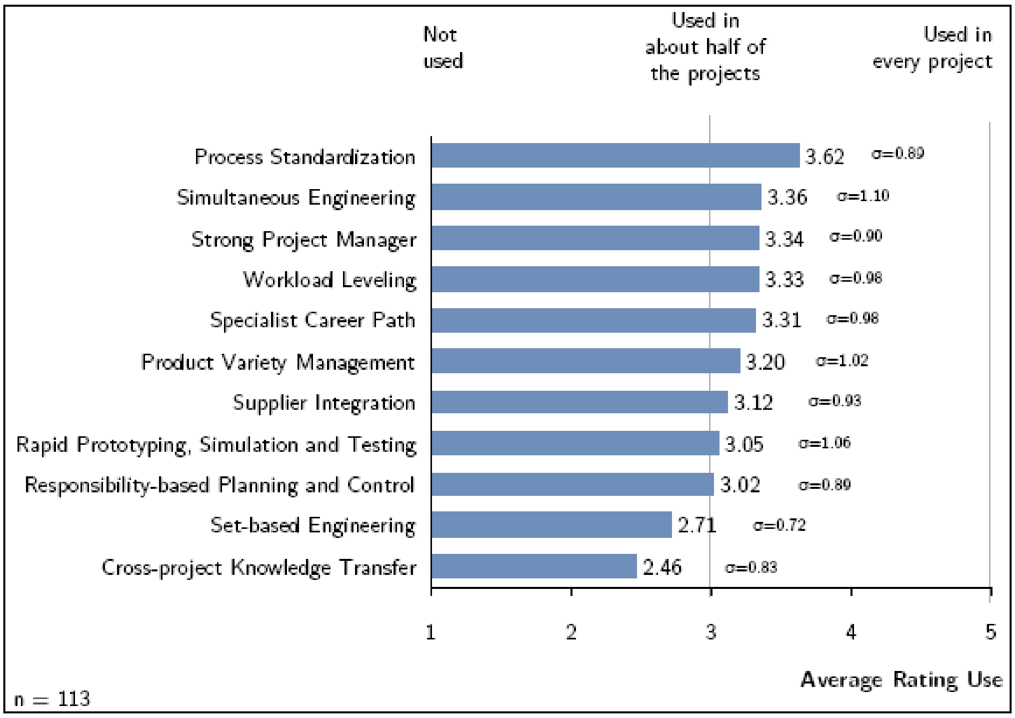


Figure 2-8: Ranking of lean product development components in use by 113 companies (Hoppmann et al., 2009)

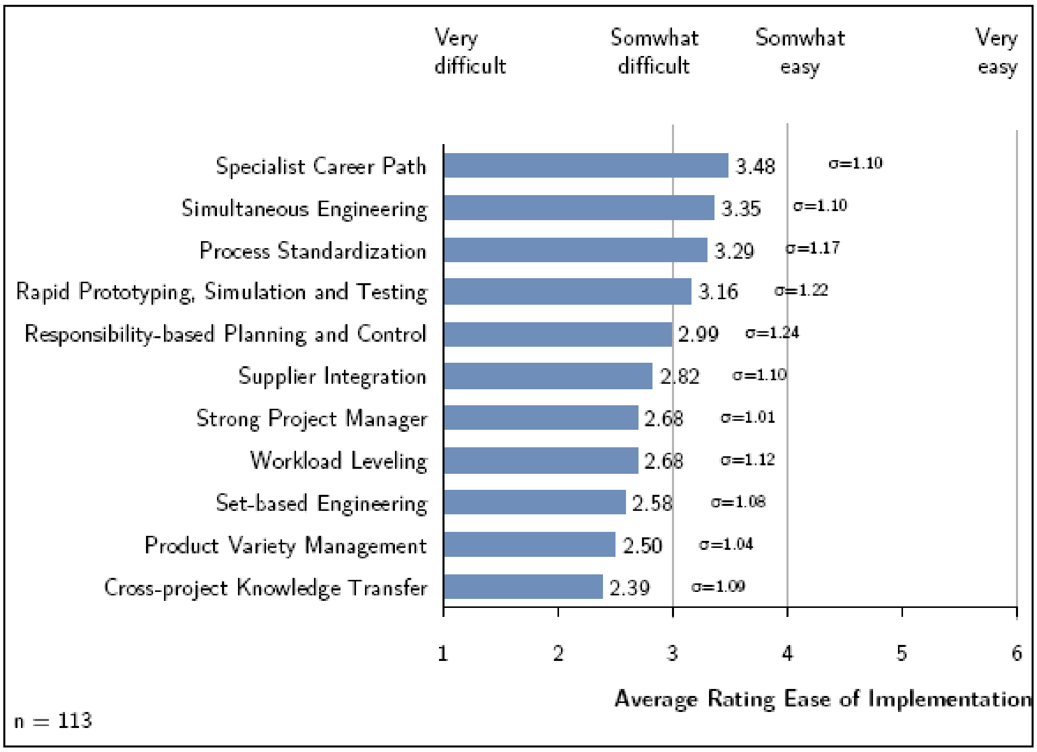


Figure 2-9: Ranking of difficulty to implement each component (Hoppmann et al., 2009)

Figure 2-9 shows the ranking of the components in terms of implementation difficulty. Only four components were identified as between "somewhat difficult"/ "somewhat easy": specialist career

path, simultaneous engineering, process standardisation and rapid prototyping, simulation and testing. All the other seven components are classified from “somewhat difficult” to “very difficult”. Knowledge transfer across projects has been identified as the most difficult to implement which explains why it is the least used. However, set-based engineering is considered less difficult to implement than product variety management but is least used than this later.

Table 2-4 shows a list of problems found by the companies when implementing each lean product development component (Hoppmann et al., 2009).

Table 2-4: Problems identified when implementing each component (Hoppmann et al., 2009)

Main problems identified when implementing each component	
1. Strong project manager	✓ Lack of qualified project managers (52.3%) ✓ Resisting functional organisations (18.2%) ✓ Lack of upper management support (9.1%) ✓ Lack of task prioritisation (9.1%) ✓ Resisting corporate culture (6.8%) ✓ Conflict cross-project standardisation (4.5%)
2. Specialist Career Path	✓ Resisting corporate culture (50%) ✓ Lack of upper management support (18.2%) ✓ Conflict with flat hierarchy (13.6%) ✓ Lack of quality developers (9.1%) ✓ Complexity of human resource management (9.1%)
3. Workload levelling	✓ Changes in schedule (30%) ✓ Lack of cross-project coordination (16.7%) ✓ Lack of supporting tools (13.3%) ✓ Excess number of projects (10%) ✓ Lack of reliable data (10%) ✓ Lack of upper management support (6.7%) ✓ High complexity (3.3%) ✓ Lack of acceptance by developers (3.3%) ✓ Lack of high-capability suppliers (3.3%) ✓ Lack of standard skill sets (3.3%)
4. Responsibility-based Planning and Control	✓ Resisting management culture (25%) ✓ Lack of qualified developers (20%) ✓ Conflict with process standardisation (15%) ✓ Potential loss of holistic project view (10%) ✓ Lack of support by upper management (5%) ✓ Lack of supporting tools (5%) ✓ Lack of time (5%) ✓ Lack of trust (5%) ✓ Lack of acceptance (5%) ✓ Lack of priority setting (5%)
5. Cross-project Knowledge Transfer	✓ Lack of acceptance by developers (34.4%) ✓ Lack of supporting tools (25%) ✓ Lack of time (9.4%) ✓ Large amount of information (9.4%) ✓ Lack of resources (6.3%) ✓ Lack of support by upper management (6.3%) ✓ Large employee turnover (3.1%) ✓ Large product variety (3.1%) ✓ Confidentiality issues (3.1%)
6. Simultaneous Engineering	✓ Lack of acceptance by functional organisation (29.4%) ✓ Lack of resources (23.5%) ✓ Capacity conflicts between manufacturing and ram-up (11.8%) ✓ Geographical distance of functions (11.8%) ✓ Lack of synchronization (11.8%) ✓ Resisting functional organisations (5.9%) ✓ Lack of support by upper management (5.9%)

7. Supplier integration	✓ Risk of intellectual property loss (17.4%) ✓ Risk of dependency on suppliers (13%) ✓ Lack of resources (13%) ✓ Large geographical distance of suppliers (8.7%) ✓ Resisting corporate culture (8.7%) ✓ Lack of supplier base consolidation (8.7%) ✓ Higher costs of supplied parts (8.7%) ✓ High supplier turnover (8.7%) ✓ Lack of support by upper management (4.3%) ✓ Lack of supporting tools (4.3%) ✓ Lack of competence for integration (4.3%)
8. Product Variety Management	✓ Diversity of customer requirements (23.8%) ✓ Lack of acceptance by developers (14.3%) ✓ Lack of cross-project knowledge transfer (14.3%) ✓ Large complexity (14.3%) ✓ Lack of supporting tools (9.5%) ✓ Budget constraints (4.8%) ✓ Lack of consensus on standards (4.8%) ✓ Resisting corporate culture (4.8%) ✓ Uncertain technology roadmap (4.8%) ✓ Fast change of product mix (4.8%)
9. Rapid prototyping, simulation and testing	✓ Budget constraints (30.8%) ✓ High complexity (23.1%) ✓ Lack of qualified developers (7.7%) ✓ Lack of resources (7.7%) ✓ Lack of standardized test procedures (7.7%) ✓ Lack of time (7.7%) ✓ Leads to early choice of solutions (7.7%) ✓ Resisting corporate culture (7.7%)
10. Process Standardisation	✓ Conflict with flexibility requirements (35.3%) ✓ Lack of acceptance by developers (29.4%) ✓ Administrative requirements (8.8%) ✓ Lack of consensus on standards (5.9%) ✓ Lack of documentation (5.9%) ✓ Conflict with low bid supplier philosophy (2.9%) ✓ High product variety (2.9%) ✓ Lack of qualified developers (2.9%) ✓ Lack of resources (2.9%) ✓ Time constraints (2.9%)
11. Set-based Engineering	✓ Lack of acceptance by developers (32%) ✓ Lack of capacity (24%) ✓ Time constraints (16%) ✓ Budget constraints (8%) ✓ High employee turnover (4%) ✓ Lack of upper management support (4%) ✓ Lack of supporting tools (4%) ✓ Lack of training (4%) ✓ Resisting corporate culture (4%)

Analysing the list of problems found in each component it is possible to understand that some are common for different components' implementation. For example resisting to corporate culture is a common problem for seven components. Other common problems are lack of supporting tools, lack of time, lack of resources and lack of acceptance by developers. Figure 2-10 shows the most common problems and illustrates the number of affected components.

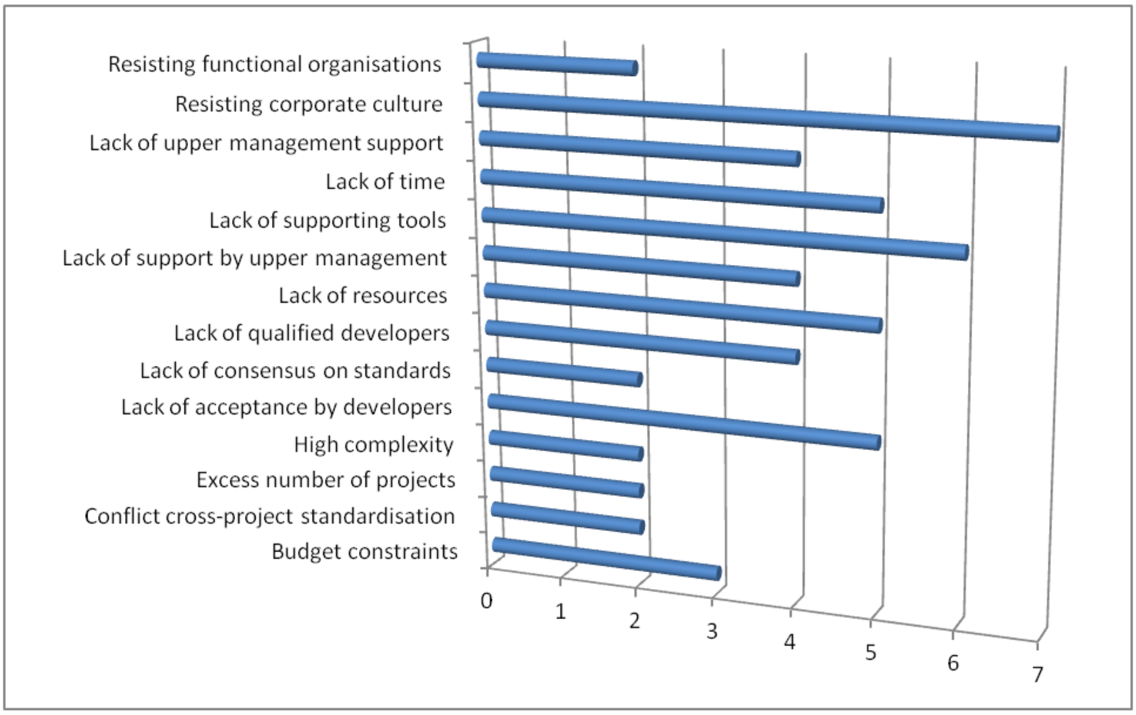


Figure 2-10: Most common problems affecting the implementation of lean product development components

León and Farris (2011) also performed a literature review on lean product publications. This work covers a twenty-one-year period (ending in 2009). From this systematic review the authors concluded that there were seven main areas of knowledge in lean product development research: product development performance, decision analysis, process modelling, company strategy, suppliers and partners relationships, knowledge management and adaptation of lean manufacturing practices. It is important to note that their review included techniques that are not described as part of the lean tools, which however contribute to achieve a lean product development, such as the Design Structure Matrix. They also concluded that most of these publications were done in the academic environment and that further industrial validation is needed. The authors identified twenty principles and concepts listed in Table 2-5.

Table 2-5: Lean Product Development Principles and Concepts (León and Farris, 2011)

Lean Product Development Principles and Concepts (León and Farris, 2011)
1. Manage multiple products
2. Starve for standardisation and re-utilisation
3. Adapt organisation structure
4. Adopt coordination mechanisms between functions and activities
5. Fewer suppliers with long-term relationships
6. Varying supplier involvement and responsibility

7. Encourage supplier learning
8. Rich communication with suppliers
9. Pursue organisational knowledge creation
10. Practice Hansei: responsibility, self-reflection and organisation learning
11. Create effective learning networks
12. Do redundancy (information overlapping)
13. Share knowledge with suppliers
14. Minimise re-invention
15. Maximise knowledge re-use
16. Define value
17. Define value stream and eliminate waste
18. Make the value flow (batch reduction and fast feedback)
19. Let customer pull
20. Pursue perfection

The authors state that the goal of lean product development can be seen as enhancing value and eliminating waste from the product and respective product development before it arrives to the production line, when it is too late and mainly too expensive to implement changes.

2.5.3. Value in Product Development

Because the definition of value is critical for achieving a successful lean product development (as stated in the first lean principle defined by Womack and Jones, 1996), several authors tried to define value within product development context (Slack, 1999; Chase, 2000; Browning et al., 2002; Siyam et al., 2011). In manufacturing value creation is physically visible and therefore easier to identify. According to Womack and Jones (1996), activities can be defined in three types: activities that add value, activities that do not add value but are necessary (type 1 muda) and activities that do not add value and are not necessary (type 2 muda). The lean goal is to maximise the first type of activities, have a controlled number of type 1 activities and eliminate type 2 activities. However how can these activities be identified in product development? In product development several problems arise such as the value creation on iterations, the difficulty of assessing the value of information or the value of communication (formal meetings, informal chats or email communication).

Questioning the application of the five lean principles in product development, very much focused on value, Slack (1999) investigated the meaning of value in both the general and in the lean thinking contexts. Slack disagrees with the Lean Thinking theory (Womack and Jones, 1996) that value should be measured against an ideal, ignoring the market context and that value should only be defined from the customer point of view. Therefore he defines value from the customer, shareholders and employees' perspectives. The customer value being influenced by product quality, price and schedule; the employee value by job quality and compensation and finally the shareholder value influenced by the economic added value. Slack states that these three value perspectives should be considered for achieving a lean product development. Slack also claims that if the analysis of the other perspectives has been completed before implementing changes, focusing on customer perspective is acceptable. The main point lacking in Slack definition of value is the consideration of internal customers. The author of this research believes that to achieve a lean product development, companies need to treat internal customers in a similar way as end customers and that making an effort to understand the internal customers' needs will avoid unnecessary iterations. The other point missing on Slack's research is the definition of value related to tasks as mentioned by Chase (2000).

In 2000, Chase also focused his research on defining value in product development. He stated that to adequately define value for product development one needs to think about the different perspectives of value (customer, end-user, shareholders, employees...), the product development entities (activity, information, product, flow...), the value attributes (performance, risk, schedule, cost...) and quantifiable metrics (seconds, minutes...).

Browning et al. (1999) developed a method – the risk value method – to assess progress and value added in product development, considering the performance level and the performance risk reduction. The authors say that producing useful information reduces the risk of not accomplishing the customer requirements; therefore they propose a method to assess value added considering the risk reduction over time. An interesting point mentioned in this paper (Browning et al, 1999) is the difficulty of measuring the value of an activity immediately. An example of this may be a design activity performed with the maximum efficiency that can only be assessed as successful after the production, tests or even service phases. If on one side Browning et al. (1999) introduced the relation of value-added and time, they lose the focus on perspective introduced by Chase (2000) and Slack (1999) and consequently the importance of customer focus, both the end and the internal customer.

More than ten years later, Siyam et al. (2011) worked on re-conceptualising value in product development. The authors started defining four types of value in product development: product value as the product capability to meet customers' requirements, process value related to the ability of working on efficient processes, learning value related with the ability to innovate, improve and learn and finally financial value that is related with the profit generated from the product delivery. The authors proposed a model for value delivery decomposition into source, transmitter and value

receiver. Even if this is a work in progress, Siyam et al. believe that these definitions will contribute to product development improvement through supporting decision-making and logistics activities. The fact that they are considering the different perspectives of value and the value-activities relationship may become a good asset of this methodology.

Even if some of these conceptualisations for assessing value in product development can be very useful to improve product development, their simplicity and applicability in industrial environments is critical. If the method is too complex or expensive in terms of application time it cannot be easily adopted by companies.

2.5.4. Examples of Lean Implementation in Engineering

One of the key discussions companies face when deciding to implement lean is how to change the company culture, which is one of the main problems identified when implementing lean in product development (see Section 2.5.2). Shook (2010) explains how he experienced a culture change in NUMMI (New United Motor Manufacturing, Inc.) and what was behind this change that conduced to radical improvements in quality and absenteeism reduction from 20% to 2%. Shook concludes that the way to change culture is changing the behaviours, or by other words companies should "start changing what people do than changing what they think". Changing the way people behave will change values and attitudes that ultimately will be reflected in a cultural change. Shook gave an example in which NUMMI's culture changed giving the employees a clear definition of what they were responsible for and providing them the right tools as well as the right training to enable them to perform successfully. The main change identified by several NUMMI employees was the way they face problems. When equipped with the right tools to see and solve the problems as well as simple ways to learn from mistakes, changed the attitude toward problems which was a major step to achieve a lean state.

Charlie Baker, the first American chief engineer for Honda, describes his experience of implementing lean in an American company and the challenges of transferring lean to a Western culture (Baker, 2011). Baker learnt lean development at Honda by applying in his day-to-day work and learning from his own mistakes. After this experience in Honda, Baker started to dream about teaching what he knew to American companies, so he decided to join a traditional American automotive company, the North America Automotive Supplier (NAAS). When he joined the main objectives of this company were to significantly improve cost, quality and lead time to launch new products in the market. After more than three years, Baker stated that lean product development can be implemented in a western company with impressive results. He started his lean transformation focusing on Plan-Do-Check-Adjust (PDCA) cycles, teaching good problem solving techniques, understanding the voice of the customer and introducing some lean tools such as A3 reporting and *obeya* – the war room for multi-disciplinary discussions with the walls displaying the project information. Applying these changes as

well as being involved at the *gemba* – the working level – he managed to reduce waste and rework from the development process. However, Baker knew that applying lean tools would not be enough to create a lean company, but he used this approach to engage people and stabilize the basic engineering processes. Baker divided the transformation plan in two parts, the tactical transformation, aiming to restore the basics and engage people through quick-wins activities, and the strategic transformation, a three year plan aspiring to achieve the lean development status. The main actions completed as part of the tactical transformation were:

- Review of the organisation structure to clarify system integration responsibility, defining a clear ownership of the technical project, similar to the Toyota Chief Engineer, and strong leadership of functional engineering specialists.
- Elimination of bureaucratic waste (from the phase-gate product development process and alignment of processes to achieve customer deliverables), promote team work and perform risk assessment.
- Creation of and training on the basic engineering process, extensive use of PDCA and recording the knowledge in A3 reports.
- Use of future state VSMs to define high level plans and development of cross-functional detailed five-day plans in paper to promote good communication.
- Break-down of requirements to a functional level and review of the status of the requirements in regular review meetings.
- Introduction of best practices in design and project reviews.
- Development of engineering metrics to make flow, waste and value visible.

The next transformation stage, the strategic plan, was characterised by the following actions:

- Establishment of a lean champion executive staff position responsible for all lean initiatives.
- Implementation of lean skills assessment with direct impact on each employee personal development.
- Spreading of lean achievements across the company through newsletters, lean champions, website and training programmes.
- Designation of a technical expert in each group, similar to the Toyota technical mentor figure (Morgan and Liker, 2011), recognising and rewarding technical excellence
- Implementation of the design for cost principle, starting to treat cost as a design variable. Through a joint effort by the design and cost teams, they managed to design for cost and also to do reverse engineering starting with the cost target.

There were points in which Baker had to adapt the lean philosophy to the western culture. For example the Japanese attitude of focusing on improvement needs gave him a reputation of being negative. In order to engage the Western employees, he had to take a more positive approach –

acknowledging people and their success. Moreover changing the culture of hiding problems was a big challenge, as well as the change of the team leaders' attitude when confronted with bad news. The results of this lean product development transformation were seen in terms of cost reduction, quality and customer satisfaction improvement.

A second example of lean product development transformation is the lean revolution in Ford described by Morgan and Liker (2011). After finishing his research focused on the Toyota Product Development System, Morgan joined Ford to apply what he had learnt from the Japanese lean culture in a new socio-technical environment (Morgan and Liker, 2011). After almost going bankrupt in 2006, Ford's turnaround evolved from the integration of people, processes and technology. Examples of the changes was the high integration of the different disciplines involved on the product development; the focus on standardisation for common vehicles architectures; and the fact that the product development was now being facilitated at a global level. In 2005, Morgan was hired to lead Ford Global Product Development System (GPDS). The first thing he did in this job was to divide the product development in a matrix structure composed by functional areas and programme-based teams. The GPDS was the central knowledge repository, the central communication link between the functional teams and it was critical for the continuous learning. The project was discussed in the *obeya*, each improvement project was recorded in A3 reports and displayed in the *obeya*.

The next paragraph describes the product development changes that conduced to many improvements such as 40% reduction on average lead team, 35% improvement on quality and 30% improvement on employee satisfaction/ moral. Morgan and Liker (2011) divided these changes across the three product development subsystems. The main changes on the People subsystem were:

- The company started looking into the mirror and once employees had understood the company's state, the willingness to change was increased.
- Encouraging different teams to work towards the same objective and being responsible for the results made them engaged and proud of their work;
- Focus on technical excellence was emphasised by recruiting engineers with the best skills and training the existing engineers;
- Embedding a culture of communication across the different hierarchic levels with the senior management often participating in team meetings. The leadership ensured effective global level of communication.
- Engagement of the leadership as illustrated by the CEO's participation in technical meetings giving his view of the business.
- Identifying the best supplier, treating them as partners instead of enemies, and working together on cost models and plans.

In terms of Process transformations, the main changes were:

- Comparison of all the current major development steps with the ideal step, helped identify a list of strategic enablers. Value Stream Map events generated ideas for improvement, which were subsequently prioritised. The sessions proved useful for enabling cross-functional dialogue and for identifying waste.
- Moving focus to the front of the development and delaying key decisions until as close as possible to the customer.
- The quality of the data flow was measured at design reviews.
- Cross-functional meetings to discuss problems helped to develop joint agreements on standards to be followed by the different functional groups.
- Meetings with suppliers allowed aligning the different companies processes; purchasing was highly involved in these meetings.
- Global meetings were held to make sure the latest standards were met, lessons learnt were captured and incorporated and test criteria were passed.
- Knowledge was captured along the project when the ideas were still fresh and there was still time to incorporate the knowledge on the project.
- A non-punitive behaviour was necessary to avoid a blame culture and work towards continuous improvement.
- In order to reduce rework, robust design techniques were implemented; each team was optimising their design considering the variation promoted by other functions.

In terms of Technology and Tools changes, Ford had a clear understanding that the right way and the right knowledge to apply technology was even more important than the technology itself.

- Knowledge management was a key challenge not only in terms of knowledge capture but also in updating it. Investment in capturing important information in easy to use databases, check-lists, virtual simulations and embedding it in parametric engineering templates was made.
- Investments in virtual and design tools were made as well, and more importantly, in standardising software and processes.
- Development cost models were created with the suppliers to improve development efficiency and supplier relationships.
- Tools to visualise the work status across the global teams were used to synchronise the development.
- One powerful tool was the *obeya* process. Making problems visible to everyone is critical to solve problems in real time.

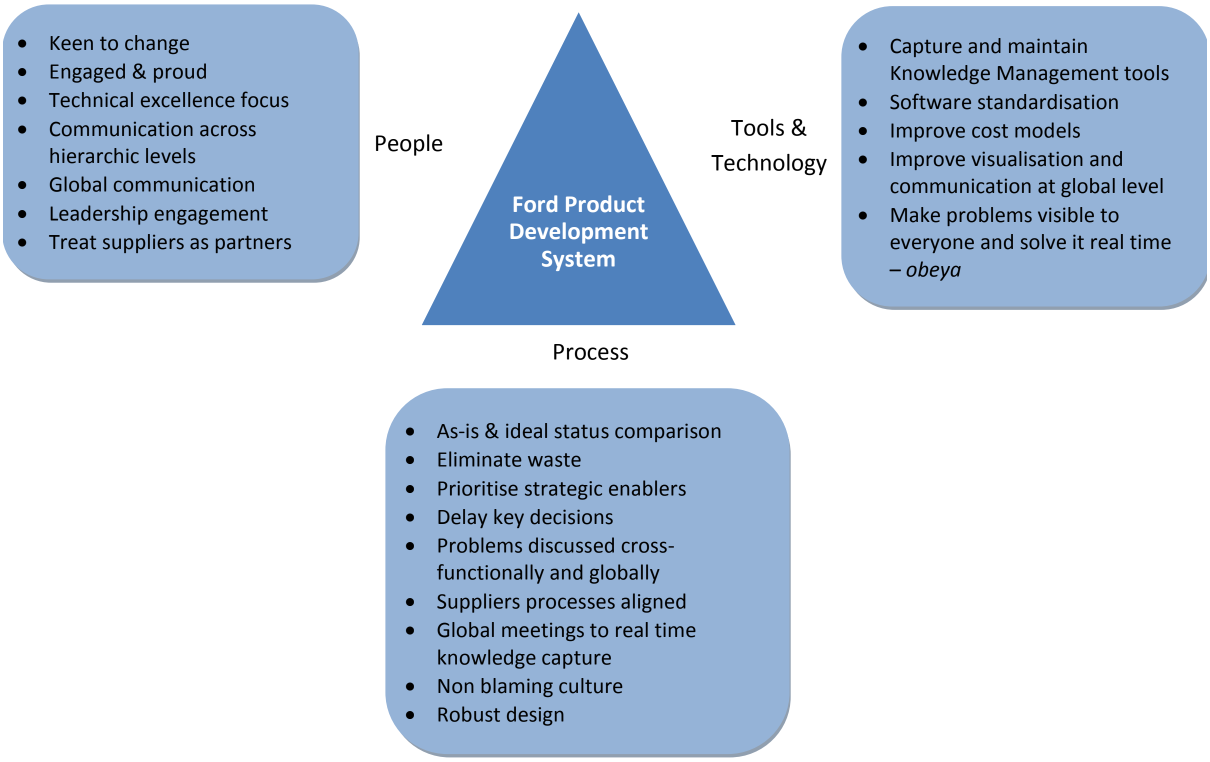


Figure 2-11: Ford Product Development Transformations

The examples above show the application of the principles presented in Section 2.5.2. Several similarities can be seen in these two successful lean product development transformations. One of the most remarkable is that both companies had previously unsuccessfully tried to implement lean in product development. The question whether the experience of failure was essential to the following success and what made the difference between the successful and unsuccessful attempts (perhaps the effort magnitude and persistence driven by the challenging situations the companies were facing) unfortunately remain unanswered.

Another similarity of the two cases is that neither of both companies tried to change the entire company or "boil the ocean". Ford started the lean transformation piloting projects with key individuals that afterwards came back to their departments and spread the lean word. NAAS defined a tactical plan strongly supported on the Plan-Do-Check-Adjust problem solving approach to engage people on lean through quick-wins results communication.

In both examples a strong, almost autocratic leadership was critical to implement lean. Mostly because of the enormous difficulty of changing people's culture and the way people think.

One of the main differences from Ford (Morgan and Liker, 2011) to Toyota (Morgan and Liker, 2006) and NAAS (Baker, 2011) is the focus on the Chief Engineer figure. The importance of leadership in Ford appears as fundamental for a lean product development, but its success is not associated to the Chief Engineer.

2.6. Literature Gap Analysis

Several conclusions can be raised from this literature review. Firstly, companies should improve their product development to maintain their competitive position and face the market challenges. Secondly, lean product development is identified as the way forward to improve product development efficiency. However some gaps in the literature are identified in the implementation of lean product development in industrial environments. The implementation of lean is well explored in manufacturing but the same cannot be said for lean product development. Examples of lean product development implementation in industry are rare and very recent (Morgan and Liker, 2011; Baker, 2011). These examples are also high level, normally at a company or department level. It is difficult to understand how lean was implemented in detail and what the direct results of these actions at this level were. On the other side, even if lean product development starts to be much debated within the academic world, examples of the passage to the industrial environment are still lacking in literature, which has been described by Blessing (2009) as a major challenge for research in engineering design. Considering that lean product development is more than applying the same tools and methods of lean manufacturing to engineering processes and that a large part of lean product development is constrained by the social interactions and behaviours, one arrives at the conclusion that there is no best practice to transform product development. However several good practices can be defined for different companies. There are common goals that should be achieved in lean product development, such as efficient and robust product development. An example of a lean "how to" guide was developed by McManus (2005); it explains the theory on how to develop a Value Stream Map to improve product development at component level. Following this best practice would allow achieving a more efficient product development but the validation of McManus theory in the real industrial world is still lacking.

The iterative behaviour of lean product development process has been studied by McManus (2005) through combination of VSM (to achieve a waste-free process) and DSM (to improve the iterations management). However the application of this approach to the industrial context is still missing in literature.

Another knowledge gap is related with robust product development processes. From literature review it was seen that companies are directing more effort on making their products robust to variability, namely using robust design techniques. However the same cannot be seen for product development processes.

The research gaps can be summarized as described below:

- Lack of best practice in passing from lean product development theory to the real industrial application, including a description of the main lessons captured when improving product development.

- No examples of considering the iterative behaviour of product development processes in the lean implementation in the industrial world
- Lack of methodology to achieve a robust and efficient product development process.

This research is proposing a framework to analyse product development processes, aiming to achieve efficient (eliminating waste and maximizing value) and robust processes (eliminating sources of variability and addressing critical activities in the process). Differently to what is described by Morgan and Liker (2011) and Baker (2011), this framework aims to address a higher level of detail on how to improve product development processes. The aim of this thesis framework is to help companies to achieve leaner product development processes, eliminating waste and understanding where best to target improvements.

Chapter 3

Engineering Process Improvement (EPI) Framework

3.1. Overview

In order to address the gaps identified in the literature review, a framework is developed and presented in this thesis to guide product development improvement activities. This chapter presents this framework basis. The first section presents the overall description and the following sections detail the framework's steps. For a better understanding of the methodology, beside the detailed description an invented example is applied to illustrate the framework utilisation.

3.2. Framework

The literature review identified the need to develop a framework to support improvement activities in product development and to validate this framework in the industrial environment. Therefore a framework was developed aiming on achieving an efficient and robust product development process. An efficient process is defined here as a waste-free process, in which all the resources are efficiently used. The robustness is achieved analysing not only the iterative behaviour of product development but also reducing the variability of critical activities.

In order to achieve these goals several methods have been reviewed as described in Chapter 3. The conclusion of this review was that there is no single method able to perform all the analysis described namely waste/value analysis, process duration and potential improvements impact (considering iterations if necessary) and process robustness analyses. Therefore a combination of methods in a framework appeared as the best option to analyse and improve product development processes. When selecting the framework's methods, the revision was not limited to methods used for improving product development; firstly the analysis was focused on suitable methods that could perform the

required analyses and secondly it was focused on analysing what changes would be needed to address product development issues. An example of this was the choice of VSM to analyse process waste; because VSM was developed to analyse manufacturing processes, some adaptation is needed to use it to improve product development processes. The author of this study acknowledges the fact that different methods could be chosen to integrate the framework if they perform the same type of analyses. Moreover, for future work, other methods can be added to support this analysis if necessary. For more detail please see the Future Work Section.

The framework can be seen as a three phase analysis, in which the current state is captured, analysed and improvements are proposed. Figure 3-2 represents the framework different steps.

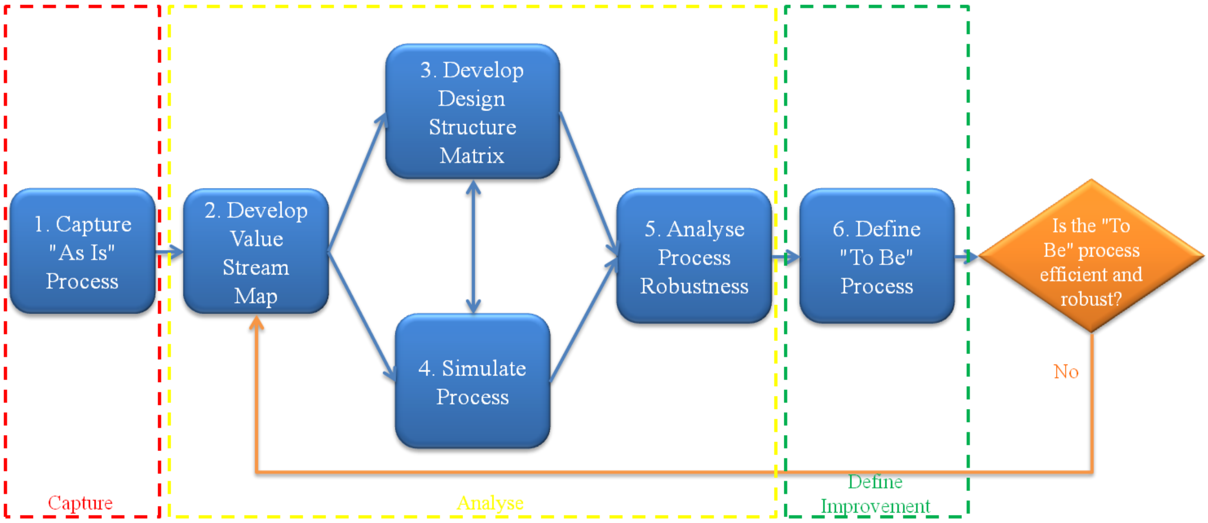


Figure 3-1: Engineering Process Improvement Framework

The first phase is focused on understanding the current problems; the analysis phase is the most complex and comprises several types of studies that will be detailed on the following sections, however the goal is to analyse the problem and look for efficient and robust solutions; and the third phase is focused on simulating the future state as well as comparing the improvement benefit with the effort needed for its implementation.

As represented in Figure 3-2, this approach can be compared with the DMAIC (Define-Measure-Analyse-Improve-Control) six sigma methodology. The DMAIC approach has been developed for improving manufacturing processes, but it has recently been used to address problems in processes outside of the shop-floor (George, 2005). The challenge discussed here, as explained in Chapter 3 is related with the complexity of improving product development processes and the difficulty of applying some of the DMAIC approach tools in the product development context.

The first phase of the Engineering Process Improvement (EPI) framework is equivalent to the Define DMAIC phase, in which the problem is identified and the improvement scope is defined. The second and third EPI framework phases are comparable with the Measure and Analyse phases of the DMAIC approach, where measurements are taken to support the problem analysis and subsequently to define

potential improvements. In the DMAIC approach the improvements are then implemented and sustained in the Improvement and Control phases. Because the EPI framework focuses on the problem and solution identification, the implementation and control are not part of framework. The author anticipates that the common tools and methods, such as implementation plan, piloting small scale improvements and control plan, used in the two latter DMAIC phases can be applied to product development processes.

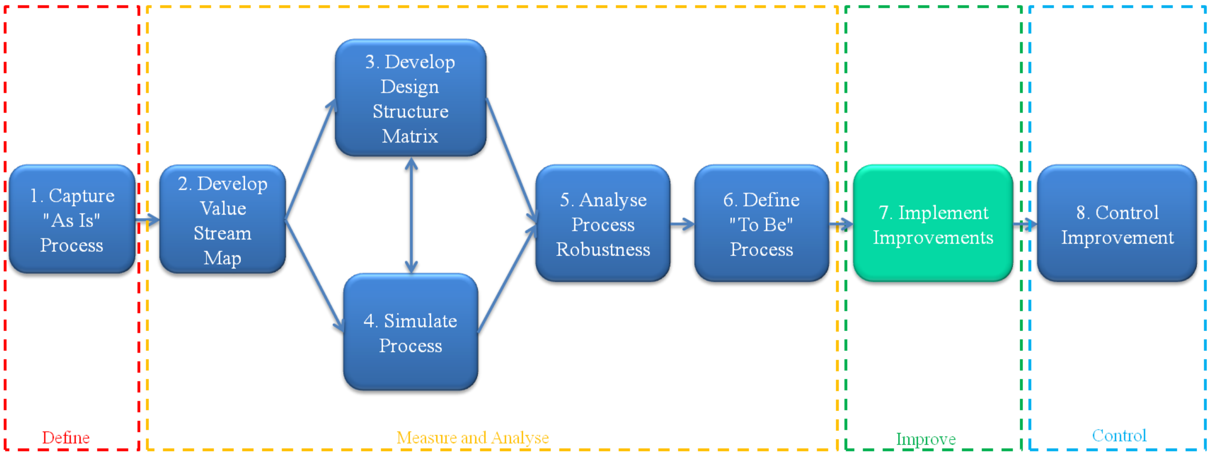


Figure 3-2: EPI and DMAIC comparison

On the following sections, a detailed explanation of each EPI phase is presented as well as an illustrative example of a product development process improvement activity.

3.2.1. Capture "As Is" Process

Product development teams follow processes for guidance on their activities through the product development cycle. However to have efficient and updated processes in place requires a large effort that sometimes companies cannot afford. It is difficult for a company to design processes with the same attention they design products. Because the goal is selling products, companies tend to focus on the product design requirements and specifications, and put less effort on the product development process design. For this reason inefficient product development processes are a common problem for companies. This problem leads to two issues: firstly teams following inefficient processes and secondly the adoption of non standardised working practices of individual team members that are hindered by the process inefficiencies. The latter will reduce efficiency through the loss of standardisation benefits (as described by Morgan and Liker, 2006).

With these issues in mind, the aim of this step is to capture the current process the product development teams follow and not the processes they should be following.

This high level goal may be divided into two parts: firstly identifying the key stakeholders and secondly capturing the process. The stakeholders should be carefully identified and studied; this group should include sponsors of the improvement project, the users of the product development activities,

senior management/leadership and everyone that may have an interest in the product development process under analysis. As seen in Chapter 3, one of the main problems identified when implementing lean in product development is the lack of senior management support, which is critical for a successful lean implementation. Bearing this in mind, a suggestion to assure the senior management support is for example engaging them as sponsors of the improvement project. Likewise an effort to engage the users of the product development process is crucial. If the users feel part of the improvement activity and see the potential benefit for them, they will be more enthusiastic and supportive. Having the support from the users has two main advantages: the users are best placed to help identifying the problems because they experience the difficulties of having inadequate methods, tools or skills. Furthermore they will feel responsible for the process improvement and be more willing to adopt new processes if they feel part of the solution. This engagement of the users was also pointed out as essential by Clegg and Walsh (2004) on the sociotechnical principles.

A stakeholders' map should be created for a better understating of each stakeholder position. In a stakeholders' map one plots the names on Influence versus Support scales as the example shown in Figure 3-3. Understanding the stakeholders' position in relation to the improvement project is essential for the success of this activity. It gives the opportunity to understand who the most influential and supportive stakeholders are. These stakeholders could be drawn on to work as sponsors and use their influence to make things happen. On the other hand, this exercise also helps to identify the unsupportive people; understanding this latter group is also crucial because their arguments may need to be addressed. Their opposition should be avoided if possible to prevent negative influence on other stakeholders. It is important to say that the stakeholders' map is for exclusive use of the responsible for the improvement process and should not be circulated to the stakeholders as it may contain some sensitive information. The stakeholders map should be used to get a better understanding of the project stakeholders, their positions and to understand how these positions should be changed to gain support for the improvement project.

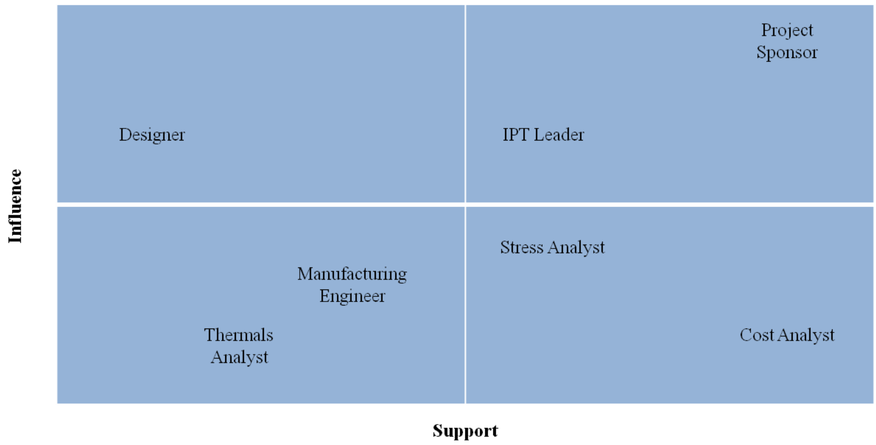


Figure 3-3: Stakeholders Map

Once the stakeholders are identified, the process capture can be started. The product development process should be captured through workshop sessions, involving experts and users from the different functional areas. The functional experts and users may or may not be the same; the users are the ones that apply the process of developing products and the functional experts are normally senior engineers with vast experience in specific functional areas; it is important to consider both stakeholders' categories.

In order to get the most benefit from these workshops, a preparation phase should include analyzing project information, such as planning Gantt charts and audits reports. Existing process maps should also be analysed before the workshops, but one should not consider that the existing process maps are actually applied in everyday practice.

In the workshop sessions, the functional experts and users are invited to describe their activities as well as input and outputs required to perform their activities. In order to represent the process in a flexible way, the process is captured using post-it notes with each activity being represented by one post-it note. This ability to change the process during the workshop is important to keep the experts engaged in the discussion and to allow the process to evolve throughout the discussion. This approach is a common practice for process map capture commonly followed by other companies.

The first phase of the session is focused on capturing the activities and respective inputs and outputs; using different colours for activities, inputs and outputs may also give some clarity to the process map. The exercise may start from the first activity and carry on with the workshop facilitator asking the experts what they do next or starting on the final output of the process and proceed with the facilitator asking the experts what they need to get to that point. Once the activities sequence is identified, the experts are asked to identify further relationships between the activities. After the introduction of the links between activities the process map may become complex, one should be careful to not lose the visual understanding that is one of the main benefits of the process maps. The other benefit is to get the experts of different functional areas to brainstorm their interfaces and to identify stress points.

During this type of workshops experts tend to get into exciting discussions. A balance should be achieved letting them discuss the important subjects but not to go into unnecessary arguments that lead the discussion away from its purpose. The workshop facilitator should be able to conduct the group discussions. The process map capture should be concluded once all the functional experts have described their activities and the process reflects the process they actually follow. If the product development process is very large it can be captured in more than one session. Two sessions, for example, give the experts the opportunity to reflect on the process map in between the sessions. The facilitator should also convert the process captured to a digital format file and circulate it through all the stakeholders, inviting them to comment on the workshop result process map.

Figure 3-4 represents a product development process map in digital format example. The rectangular boxes represent activities. Ellipses represent inputs/ outputs and the diamond shaped boxes represent decision points. Often design iterations start in these decision points when the users verify if the design concept does or does not meet the customer requirements. Iterations are represented through the lines going from right-to-left (with the “No” caption).

One can create swimlanes to allocate activities by functional areas, but for large process maps this increases the map complexity which may conduct to a loss in the visual understanding.

In this example Microsoft Visio has been used to transcribe the post-it process map to a digital form, however any other diagram tool could have been used.

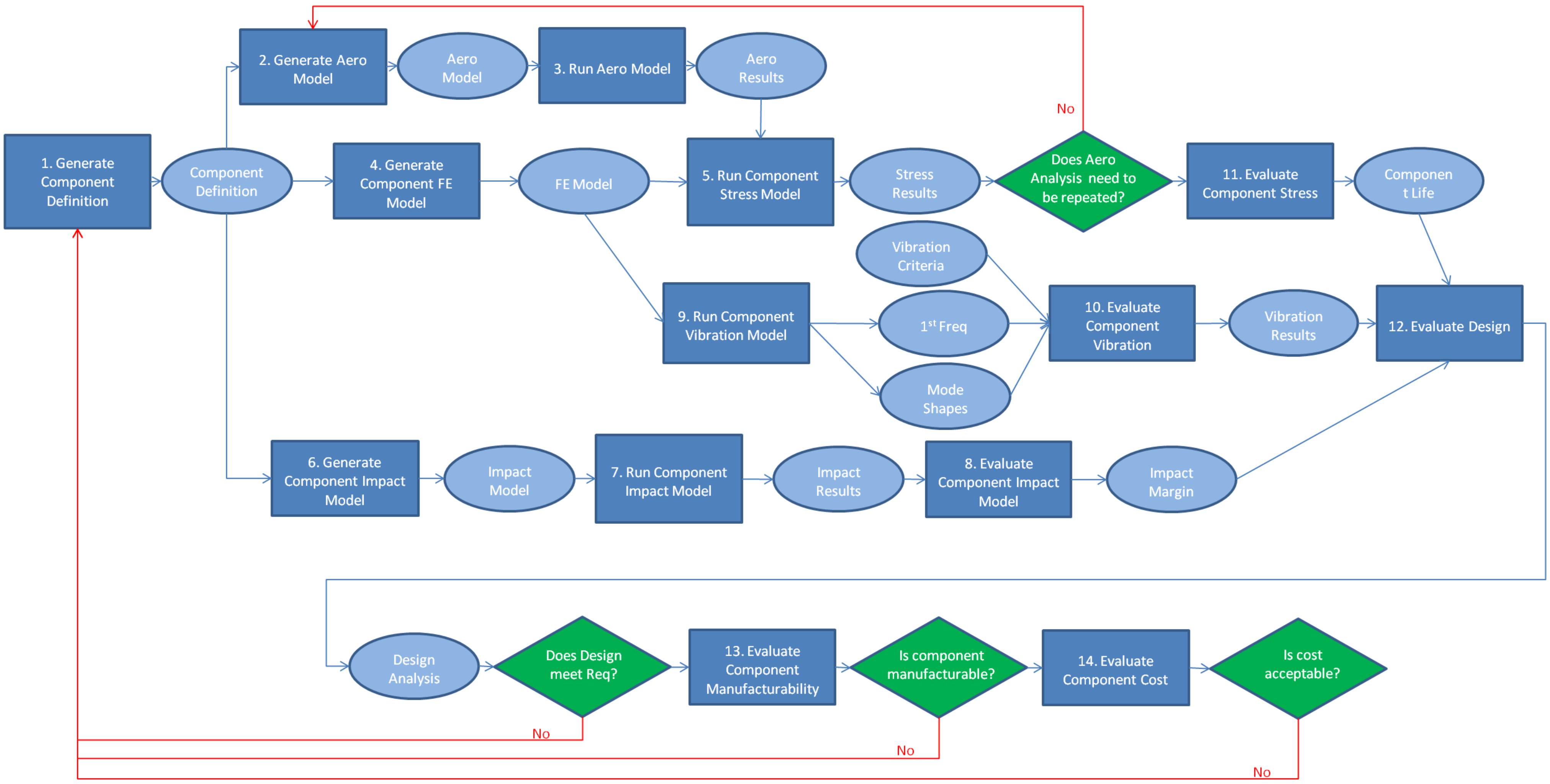


Figure 3-4: Process Map Example

3.2.2. Develop Value Stream Map (VSM)

The aim of this step is to develop and analyse the product development process Value Stream. The VSM's aim is to identify all the activities to develop a product and sort these activities in three categories: activities that add value as perceived by the customer; activities that do not add value but are required to develop the product (*muda* Type one), these activities should be reduced as possible; and those activities that do not add value as perceived by the customer (*muda* Type two) and therefore should be eliminated (Womack and Jones, 1996). As described in Chapter 3, VSM has been developed by Rother and Shook (1999) within the manufacturing environment. McManus (2005) and Millard (2001) extended the VSM theory to product development. In 2005 McManus developed the Product Development Value Stream Map Manual, which was a starting point for this research. However the author of this research felt that there was a great amount of real best practice advices still lacking in the manual. These lessons learnt and best practices developed when applying the EPI framework in industrial case studies will be reported in this thesis.

The first and possibly the most difficult VSM phase is the data capture. This phase proved to be complex for several reasons: firstly having the right stakeholders available for interviews and secondly to gain their full support and engagement. It is important to clarify that the point of the exercise is not to question their personal efficiency but to understand which improvements they would benefit from. Once one gets the stakeholders to understand this point, they become more willing to spend time supporting the improvement project.

The base for this step is the product development process and the stakeholders' map, both captured in the EPI framework's first step. In order to discuss each activity in detail in the limited time the stakeholders have available, the data collection should be done in structured individual interviews. To conduct these interviews, a data collection form was adapted from Millard's research (2001). A data collection form should be completed for each activity. Millard's form was simplified and changed to address some difficulties faced when performing interviews in a real industrial environment. As in Millard's form, the data collection form supports capturing activities' general information, time metrics, inputs and outputs details, lean waste types and other comments. Due to the limited availability of the stakeholders, the information captured was kept to the minimum required to support the improvement project. Figure 3-5 shows the data collection form.

Value Stream Mapping and Analysis Data Collection Sheet					
General					
Activity Name:					
Activity #:		**Process User:**			
Phase:		**VSM Author:**			
Resources					
		Min. (h)	**Nominal (h)**		**Max. (h)**
Elapse Time/ Lead Time					
Processing Time					
Manual Time					
Automatic Time					
Value-added Manual Time					
Value-added Automatic Time					
Chance of Rework (%)/ # Iterations					
Rework Elapse Time/ Lead Time					
Rework Processing Time					
Rework Manual Time					
Rework Automatic Time					
Rework Value-added Manual Time					
Rework Value-added Automatic Time					
Queue Time					
Computer Type					
Tools (S/W)					
Inputs					
	Name	Supplier	Quality (1-5)	Utility (1-5)	Format (1-5)
Input 1					
Input 2					
Input 3					
Input 4					
Input 5					
Input 6					
Input 7					
Input 8					
Input 9					
Input 10					
Outputs					
	Name	Customer	Transfer	Format (1-5)	
Output 1					
Output 2					
Output 3					
Output 4					
Output 5					
Output 6					

Figure 3-5: Data collection form (part I)

One of the main changes in the recommended data collection form is related with the time data. This change resulted from the difficulty of getting time data for product development activities. Once asked about the activities' duration, the users often answer "it depends" or "this is not manufacturing, we cannot measure the activities' duration". To solve this difficulty, the interview facilitator should ask for different scenarios data: "what is the worst case duration" that is the maximum time duration the users have experienced, "what is the best case duration", which is the minimum time duration and finally "what is the most probable scenario", which corresponds to the mode value. The data collection form includes now not only the mode value but also the minimum and maximum time

values; this means that the time data is now captured using a stochastic approach. Two benefits arise from this change: adding the stochastic information makes the interviewee's answer easier and simultaneously gives data for statistical analysis. This statistic analysis allows understanding where the main process sources of variation are and where the improvement should be focused to assure the process is under control. Having more time points also makes this analysis and this measurement approach more reliable.

Another change introduced was the iteration duration; this means the duration when the activity is done for the second and every subsequent time. The users were asked if they would take the same time if they have to repeat activities. This data will not only allow calculating the process time if the process includes iterations but it is also valuable for the improvement identification. For example, an activity may not add value if it is completed before the accurate inputs are available, however the total process time may be reduced if this activity can afterwards be repeated more quickly when the required inputs are supplied. Such cases need to be assessed case-by-case and discussed with the users.

The final change was related with the distinction between engineering and computing time, the first being the time the engineers need to be dedicated to an activity and the second the computing time in which the engineers can be involved in other activities. When analysing the opportunities for improvement, this distinction is important to understand if the issues are related with human resources skills or lack of Information Technologies (IT) resources.

The time metrics captured with the recommended data collection form are similar to the metrics used by Millard (2001) and McManus (2005): the elapsed time (ET), the processing time (PT) and the value-added time (VAT). Elapsed time is defined as the time from authorization until completion of an activity. Processing time is defined as the time charged to the customer for each activity (for example the time engineer register on Enterprise Resource Planning tools such as SAP); this includes all the activities' preparation and waiting time. Value-added time is only the time spent by the users on activities which the customer would pay for, activities that are adding value to the final product. Therefore it is calculated from the processing time minus the non-value added time (waiting time, setting-up time, preparation time...). This VAT which may be human or computing time is identified by the users during the individual interviews. Figure 3-6 shows the relationships between the different time metrics.

During this research it was concluded that the Elapsed Time metric is only useful when analyzing a product development process with dedicated resources. It depends on the company organisation if a project has dedicated resources or if engineers and tools are used in different work-streams at the same time. In the second case the Elapsed Time metric loses its usefulness, since it is obvious that shared resources take longer to perform activities than if used exclusively in one work-stream. In a lean philosophy, from a specific project point of view, time spent on other projects is wasted time.

The use of the Elapsed Time metric would therefore highlight the potential time saving if the process would have dedicated resources. The decision to work with shared resources is normally taken at a company level and resources should not be allocated considering processes in isolation. This is applicable for both human resources and tools such as shared software licenses or shared computer clusters.

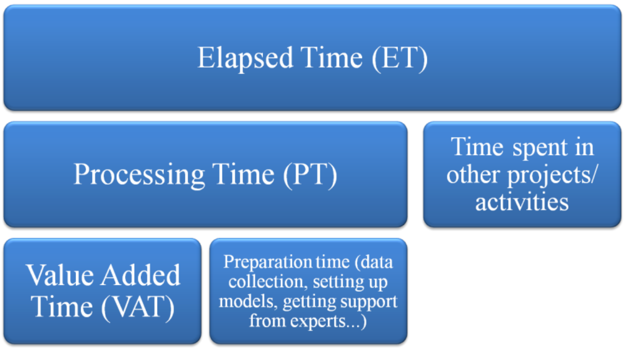


Figure 3-6: Time metrics

Besides the time data, the inputs and outputs of each activity are also captured (see Figure 3-5). The input's suppliers, formats and quality are captured as well as the output's format and receivers. Often waste is found on receiving the right information in a wrong format. A significant detail identified in this research is that often engineers know who is sending them the information they require to perform their job, but they struggle to identify the receiver of their work. This lack of knowledge makes it difficult to understand the "voice of internal customer". It could, for example, improve process efficiency and reduce re-work if a designer that is producing geometry for a stress analyst was aware of the latter's requirements.

Waste Sources
(Transportation, Inventory, Motion, People, Waiting, Over-production, Over-processing, Defects)

Comments/ Suggestions
(Risks, Improvement ideas, Problems, Stress points)

Figure 3-7: Data collection form (part II)

The second part of the data collection form is focused on capturing issues related with each activity (see Figure 3-7). To facilitate this part of the interview some examples of waste in product development can be discussed. For example the eight waste categories, seven re-defined by Morgan and Liker (2006) for product development and an extra one related with people identified in this research, can be discussed. Table 1 presents the lean waste categories definition, adapted from

Morgan and Liker (2006). Each category is illustrated with an example of waste identified during this research.

Table 3-1: Eight lean waste types redefined for engineering (adapted from Morgan and Liker, 2006)

Lean Waste	Definition	Example
Transportation	Moving information from place to place.	Copying and pasting same information in many different places.
Inventory	Information that is not being used.	Due to department policy, information ready to be passed waiting for completion of a batch of activities causing delays.
Motion	Excess motion during task execution.	Excess of meetings to present the same subject.
People	Under or over using human resources capability.	Under or over-qualified resources performing activities to overcome the lack of human resources.
Waiting	Waiting for information or decisions.	Waiting for signatures.
Over-production	Producing more or earlier than the next process needs.	Starting analysis with obsolete information, knowing that the activity will have to be repeated with up to date data.
Over-processing	Doing unnecessary processing on an activity or an unnecessary activity.	Repeating activities done by a different team due to the lack of trust in the results.
Defects	Inspection to catch quality problems or fixing an error already made.	Repetition of an activity done with out of date data.

Although the data collection interviews are planned to be structured, there is some time reserved for unstructured discussion in the last part of the interview. This final discussion should be focused on issues that have not been covered during the interview and some improvements suggestion may start to be captured. The interviewees review the process map during the interview to confirm that there are no missing activities or dependencies. This data collection form proved to be effective when collecting Value Stream Map data and it is now being embedded as company best practice in the industrial environment where the case studies have been conducted.

The information captured on the previous activities allows the development of the VSM, which can be understood as the process map presented in Figure 3-4 with the time data added as shown in Figure 3-10. In opposition to the process map, the VSM does not contain the process details in terms of inputs and outputs, but instead focuses on highlighting value added and waste in the activities. The VSM notation used in the EPI framework is an adaption of the standard manufacturing VSM notation (Rother and Shook, 1999) and of the notation used in McManus's VSM Manual (2005). Activities are represented by rectangular boxes, as shown in Figure 3-8. These include the responsible function, the required resources, the time metrics and the percentage of the activity time that is done manually by the engineer (MT) as opposed to computing time. For analysis purposes, the activities' efficiency can also be included in the VSM applying a colour code, using green, amber and red for high, intermediate and low efficiencies respectively. The activities' efficiency is defined by the ratio between Processing Time and the Value Added Time. Because time is represented by a triangular distribution in the VSM, three efficiency values can be presented and in this case the colour code can be defined by the average of the three efficiencies. Thresholds defining high, intermediate and low efficiency values should be defined considering the current efficiencies of the process under improvement.

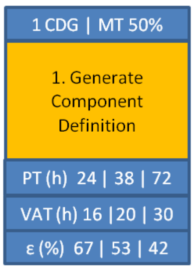


Figure 3-8: Activities representation on the VSM

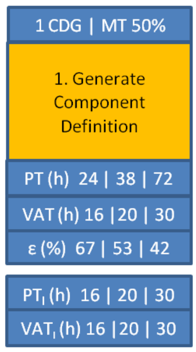
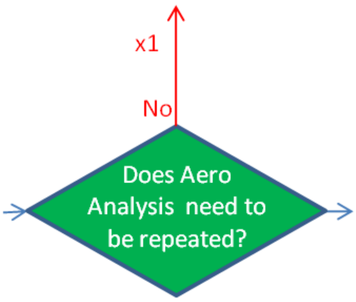
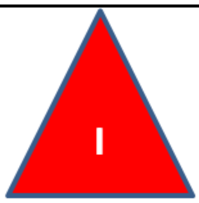


Figure 3-9: Activities representation on the VSM including iteration data

The example in Figure 3-8 shows an activity called "Generate Component Definition" for which one CDG (Component Definition Group) engineer is required and 50% of the time is spent in manual engineering work and the other 50% in computing work. Its processing time varies between 24 and 72-hours, but the most probable duration is 38-hours. If the non-value added times were removed from this activity it would take between 16 to 42-hours, the most probable scenario being 20-hours. Therefore its efficiency varies between 67 and 42%, with the most probable value of 53%. Defining the colour code as green for activities with efficiency higher than 75%, amber between 50 and 75% and red under 50%, this activity with an average efficiency of 54% is coloured in amber. The time data in case of iteration is shown in Figure 3-9. The data shows that the second time this activity is completed the PT is reduced but the VAT remains the same.

Figure 3-10 shows a VSM illustration using the example discussed above. Figure 3-11 represents the same VSM highlighting several opportunities for improvement identified after discussion with stakeholders. The VSM symbols used in this representation are shown in Table 3-2.

Table 3-2: VSM symbols description

Symbols	Description
	*Kaizen burst* represents a waste, a non value added activity in the process or an activity with low efficiency. The improvement may be the activity elimination or the efficiency increase through better tools or better methods. As described above (Table 3-1) in this section, the waste can take different forms.
	*Opportunity cloud* represents an opportunity for improvement not only increasing the activity efficiency, but also reducing the VAT.
	The *iteration number* added to the decision gate represents the number of times an activity loop is expected to be performed.
	The *inventory symbol* represents information stopped in the process. This can happen for several distinct reasons, such as waiting for signatures, approvals, department policies, etc.

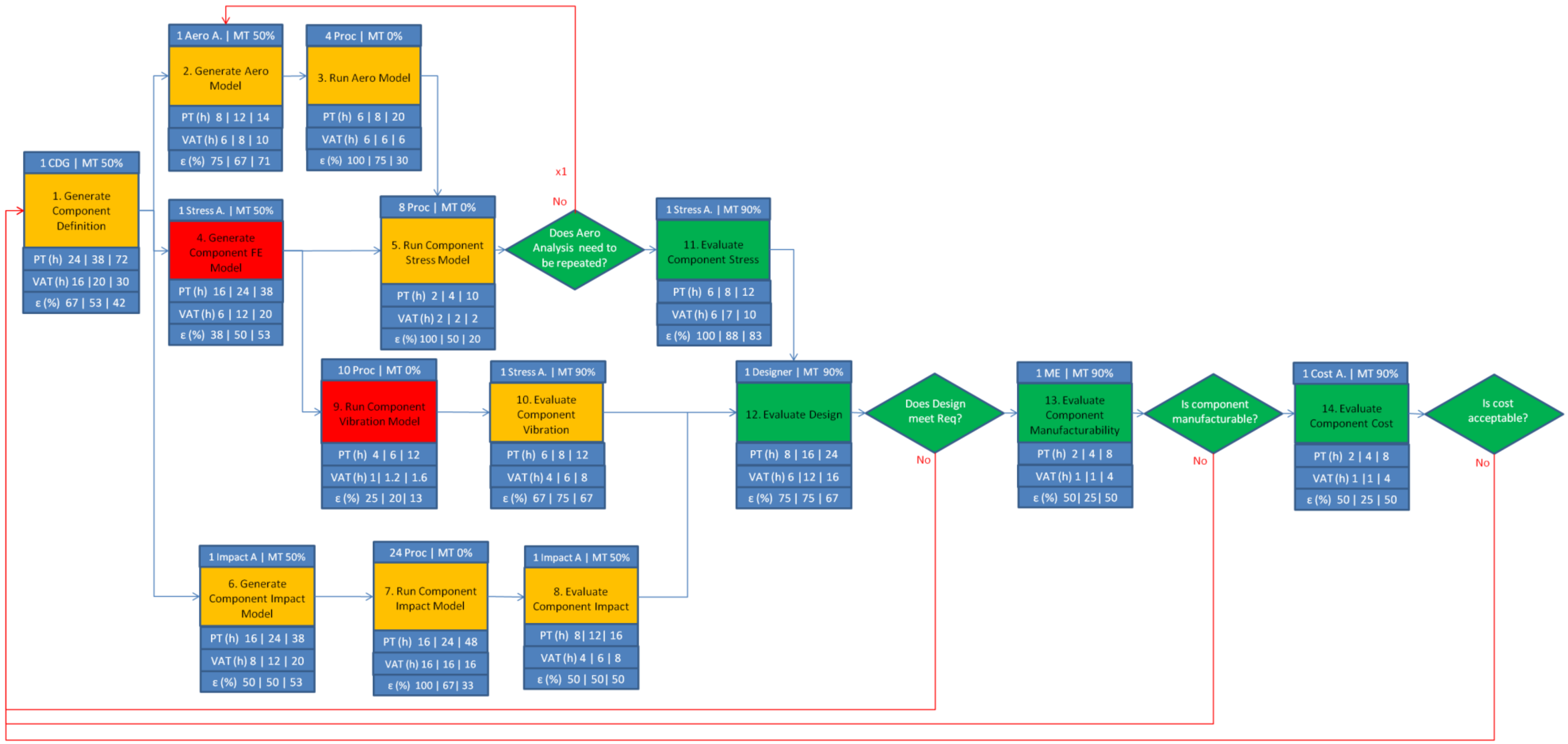


Figure 3-10: Example VSM

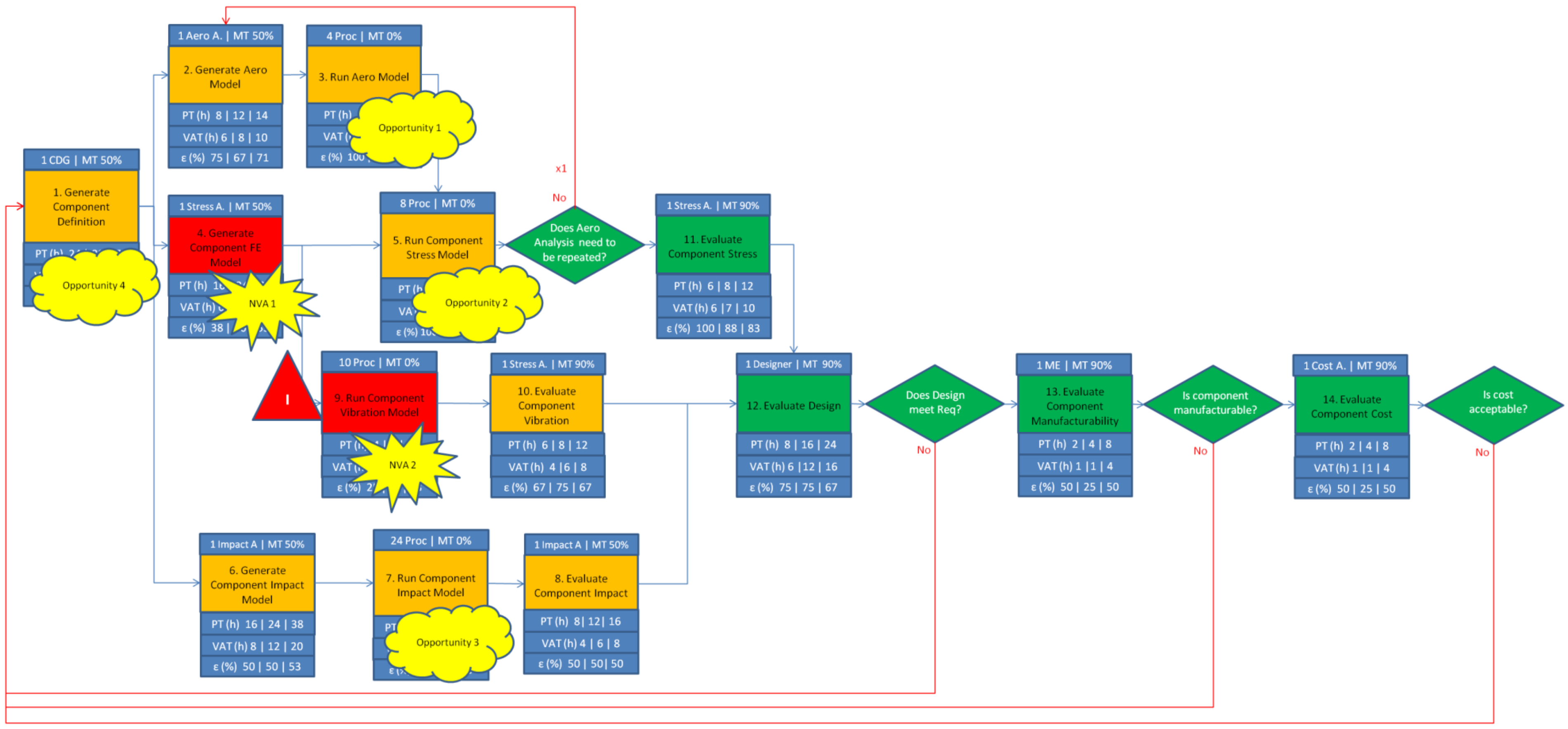


Figure 3-11: Example VSM (after analysis)

In order to analyse which activities are the main sources of variability of this process, a Pareto chart can be generated. From the Pareto analysis for this example, it can be concluded that four activities (Activities 1, 7, 4 and 6) are responsible for 60% of the process variability. This information can be useful if the aim of the process improvement is to increase the process stability or in other words to reduce the activities variation. However, it should be noted that this analysis is only focused on individual tasks and their variability. Considering that the activities are linked together in linear and parallel streams as well as loops, some tasks might affect the total process lead time uncertainty more strongly than others. To have a proper understanding of the effect of individual task variability on the process lead time, process simulation should be used as explained in the following sections.

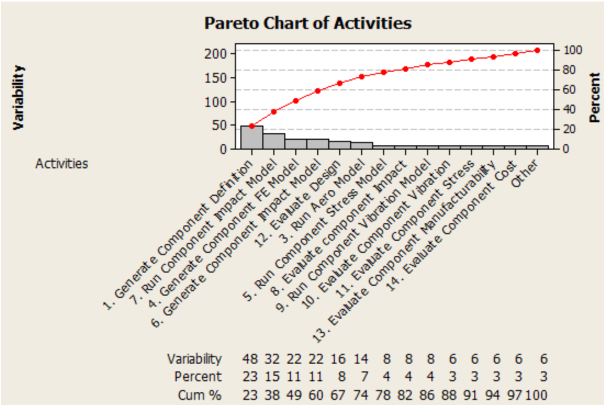


Figure 3-12: Activities Variability Pareto Analysis

From the VSM analysis (shown in Figure 3-11) and discussion with the stakeholders, it can be concluded that:

(i) VAT of Activity 3, Activity 5 and Activity 7 could be reduced improving the IT capability.

(ii) Activity 4 can be improved by providing software training to the stress engineer and thereby significantly reducing the time taken to generate the FE model.

(iii) PT of Activity 9 can be reduced. This activity is run on a computer cluster using ten processors, but as it is defined as low priority, the models always queue for several hours before running. This queuing time is represented by the inventory symbol.

(iv) Activity 1 could be improved through automation, reducing the time spent in manual work.

Although the above opportunities have been identified, the decision to implement these improvements should be dependent of a cost benefit analysis.

The VSM example illustrates several types of waste and improvement opportunities that may be found in real product development processes. The VSM representation identifying the information flow and the main waste sources in the process will support the next EPI framework steps. If required

the VSM can also be done in a first phase at a higher level, to scope the improvement or to identify the improvement potential, with more detail following in a later stage.

3.2.3. Develop Design Structure Matrix (DSM)

As demonstrated in the section above, the VSM is very useful and effective on its own when analysing the efficiency of relatively simple product development processes. However product development processes are usually complex, characterized by numerous iteration loops and crowded with activities dependencies. In order to keep the VSM simple and allow it to be easily understood, this complexity needs to be managed and in some cases omitted from the map. Considering this, one can conclude that VSM does not thoroughly support process analysis aiming to optimise the number and duration of iterations loops.

As discussed in the literature review there is currently no single method available to identify waste in the product development process and to support analysis of iterations. However the combination of VSM and Design Structure Matrix (DSM) has been proposed by McManus (2005) to both support the process efficiency analysis and the analysis of iterations. Although this approach has been proposed in literature there is a lack of knowledge on how to apply these two methodologies in a complementary way and on the benefits that can be retrieved from their combination in the industrial world.

The information required to develop the DSM is mainly covered by the data collected for the VSM (described in Section 3.2.2). As explained by Eppinger et al. (1994), the DSM is a square matrix with the activity names populating the first row and first column (as shown in Figure 3-13). Each dot in the matrix represents a dependency between two activities. This dependency can be represented in several ways; in this research a dot means that the activity in the row depends on the results of the activity on the column.

A linear and sequential process would therefore only have dots in the cells in below the diagonal. All the dots above the diagonal mean that an upstream activity depends on a downstream activity. This means that after the downstream activity has been completed, the upstream activity has to be repeated with the updated inputs and an iteration loop is therefore created. The dots in the upper part of the matrix can be used to analyse the extent of the iteration loops. The further a dot is from the diagonal the more activities are included in the loop.

The aim of the DSM is to reorganise the activities' sequence in order to reduce the number of activities in the loop. The reduction of process complexity and duration that can be achieved by this optimisation of iterations cannot be done with the VSM per se.

Two approaches may be taken to construct the DSM: one starting with the information collected in the individual interviews, also used to construct the VSM (as represented in Figure 3-13) and subsequent discussion with the process stakeholders, the other starting the DSM from scratch in a workshop session with the stakeholders. The first approach saves some time doing pre-work but loses

in terms of engaging the stakeholders in the workshop. Although the two approaches have benefits, the author recommends using the first approach and save some of the stakeholders' time in the workshop. However special care should be taken to keep the stakeholders engaged during the workshop.

Figure 3-13 shows a DSM for the example described above. This DSM was developed using the first approach, i.e. starting the DSM development with the collected information and following with discussions with the stakeholders to get an agreed DSM representation. When discussing the DSM with the stakeholders, the questions differ from the questions asked when capturing the process map. At this stage, it is important to understand which activities can be done independently and which depend on upstream activities. The result of these discussions is an updated DSM as shown in Figure 3-14. One type of dependency that may be captured in the workshop and added to the DSM is a dependency that is not based on the exchange of information but is related to planning considerations. Such dependencies may exist if one activity is not started before another has been completed not because it requires any input but because it is too time consuming to be repeated in case the previous activity shows that the design concept has to be modified.

	1. Generate Component Definition	2. Generate Aero Model	3. Run Aero Model	4. Generate Component FE Model	5. Run Component Stress Model	6. Generate Component Impact M	7. Run Component Impact Model	8. Evaluate Component Impact	9. Run Component Vibration Mode	10. Evaluate Component Vibration	11. Evaluate Component Stress	12. Evaluate Design	13. Evaluate Component Manufac	14. Evaluate Component Cost
1. Generate Component Definition												•	•	•
2. Generate Aero Model	•				•									
3. Run Aero Model	•	•												
4. Generate Component FE Model	•													
5. Run Component Stress Model	•	•	•	•										
6. Generate Component Impact Model	•													
7. Run Component Impact Model	•					•								
8. Evaluate Component Impact	•					•	•							
9. Run Component Vibration Model	•			•										
10. Evaluate Component Vibration	•			•					•					
11. Evaluate Component Stress	•	•	•	•	•									
12. Evaluate Design	•	•	•	•	•	•	•	•	•	•	•			
13. Evaluate Component Manufacturability	•	•	•	•	•	•	•	•	•	•	•	•		
14. Evaluate Component Cost	•	•	•	•	•	•	•	•	•	•	•	•	•	

Figure 3-13: DSM example built from VSM

	1. Generate Component Definition	2. Generate Aero Model	3. Run Aero Model	4. Generate Component FE Model	5. Run Component Stress Model	6. Generate Component Impact M	7. Run Component Impact Model	8. Evaluate Component Impact	9. Run Component Vibration Mode	10. Evaluate Component Vibration	11. Evaluate Component Stress	12. Evaluate Design	13. Evaluate Component Manufac	14. Evaluate Component Cost
1. Generate Component Definition												•	•	•
2. Generate Aero Model	•				•									
3. Run Aero Model	•	•												
4. Generate Component FE Model	•													
5. Run Component Stress Model	•	•	•	•										
6. Generate Component Impact Model	•													
7. Run Component Impact Model	•					•								
8. Evaluate Component Impact	•					•	•							
9. Run Component Vibration Model	•			•										
10. Evaluate Component Vibration	•			•					•					
11. Evaluate Component Stress	•	•	•	•	•									
12. Evaluate Design	•	•	•	•	•	•	•	•	•	•	•			
13. Evaluate Component Manufacturability	•	X	X	X	X	X	X	X	X	X	X	X		
14. Evaluate Component Cost	•	X	X	X	X	X	X	X	X	X	X	X	X	

Figure 3-14: DSM with Highlighted Changed Dependencies

Figure 3-15 illustrates the changed DSM after discussion with the stakeholders. The discussion identified that activities 13 and 14 only depend on activity 1, but cost and manufacturability are only assessed after having shown that the concept satisfies stress, vibration and impact requirements.

	1. Generate Component Definition	13. Evaluate Component Manufac	14. Evaluate Component Cost	2. Generate Aero Model	3. Run Aero Model	4. Generate Component FE Model	5. Run Component Stress Model	6. Generate Component Impact M	7. Run Component Impact Model	8. Evaluate Component Impact	9. Run Component Vibration Mode	10. Evaluate Component Vibration	11. Evaluate Component Stress	12. Evaluate Design
1. Generate Component Definition		•	•											•
13. Evaluate Component Manufacturability	•													
14. Evaluate Component Cost	•													
2. Generate Aero Model	•						•							
3. Run Aero Model	•			•										
4. Generate Component FE Model	•													
5. Run Component Stress Model	•			•	•	•								
6. Generate Component Impact Model	•													
7. Run Component Impact Model	•							•						
8. Evaluate Component Impact	•							•	•					
9. Run Component Vibration Model	•					•								
10. Evaluate Component Vibration	•					•					•			
11. Evaluate Component Stress	•			•	•	•	•							
12. Evaluate Design	•			•	•	•	•	•	•	•	•	•	•	

Figure 3-15: DSM example after stakeholders' discussion

As a result of the DSM discussion the manufacturing and cost assessment activities can be brought to the early phase of the product development, even if they need to be repeated once the concept selected is mature. Figure 3-16 shows the VSM addressing the changes discussed in this section.

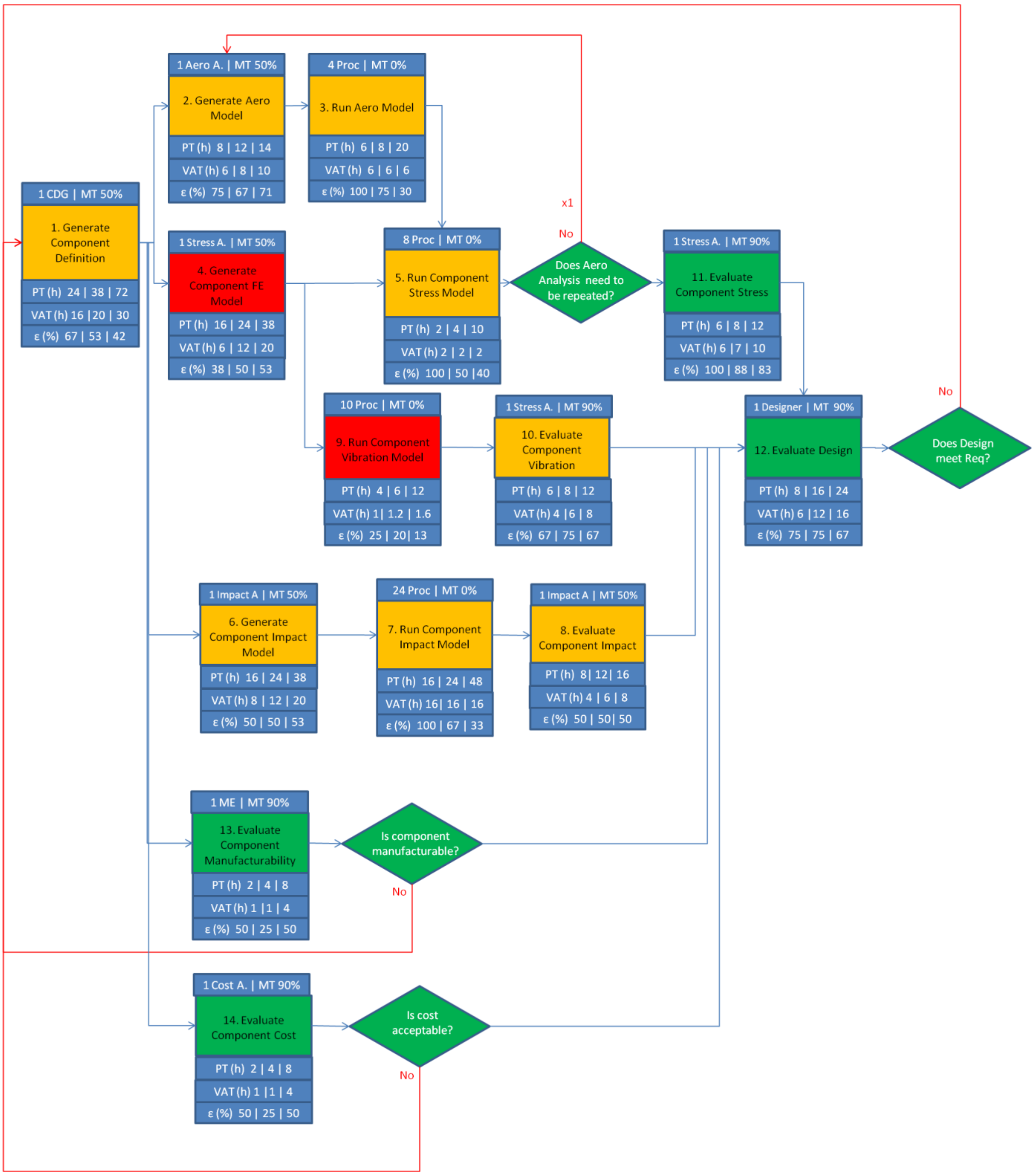


Figure 3-16: VSM after DSM discussion

This example shows a problem in product development. Often cost and manufacturing are analysed after the design is frozen which may lead to major redesigns.

As stated in Chapter 3, all key functional assessments should be done as early as possible in the process to avoid expensive redesigns later in the process. This is aligned with one of the Morgan's and Liker's (2006) lean principles, *front-load product development*.

Another improvement that could be suggested from the DSM analysis is to introduce more check points that would reduce the long iterative loop that is seen in the end of the process. Just by analysing the DSM, it is however difficult to understand the potential time reduction that can be achieved with these changes. Even if some authors (Sharman and Yassine, 2003) suggest the introduction of time duration of each activity in the matrix diagonal, it does not provide visibility of the overall process duration and does not allow simple comparison of different scenarios. For this purpose the process simulation capability, discussed in detail in the following section, is introduced in the EPI framework.

3.2.4. Simulate Process

Process simulation is used in the EPI framework to understand the process lead time, its variability and the effect of process improvements on those parameters. The simulation of the design process allows the identification of the process critical path and consequently to focus the improvement effort on the relevant activities; it also helps to understand if inefficient activities, identified on the VSM, are on the process critical path. Furthermore simulating the elimination of the lean waste in different scenarios (*what if scenarios*) aids in understanding the impact of each improvement opportunity. In addition, it allows assessment of the effect of reorganizing the iteration loops, which have been reorganised as a result of the DSM. The output of this step is essential when developing the improvement business case and discussing the required funding with sponsors and stakeholders.

Several simulation techniques can be used for this step: useful techniques to represent design processes include system dynamics, discrete event and agent-based models, as described in Chapter 3. Discrete event simulation was chosen for this research framework for two reasons; firstly, because of the level of maturity of the method and consequently the availability of software tool. Secondly, because the simple flowcharts, which visually represent the process, are easy to understand and can, therefore, be used to improve communication between product development teams.

Several tools have been analysed, such as Cambridge Advanced Modeller (CAM), PLEXUS and PROMODEL; CAM was selected as the simulation tool for this research. The choice of CAM is justified by the versatility of this tool, allowing both the creation of the process map and process simulation. Another advantage of CAM is the fact that this tool was still under development at the time of writing. This gave the author of this research the opportunity to discuss potential improvements and additional functionalities with the CAM developers, making the tool more suitable for its use in the EPI framework. For example, functions to generate the VSM from the process map have been discussed and implemented in a prototype version.

In CAM the process is represented by a flow diagram as shown in Figure 3-17. Activities are represented by rectangles, inputs and outputs by ellipses and decisions points by diamond shaped boxes. Iterations loops can be created from decision boxes as shown with a red arrow in Figure 3-17.

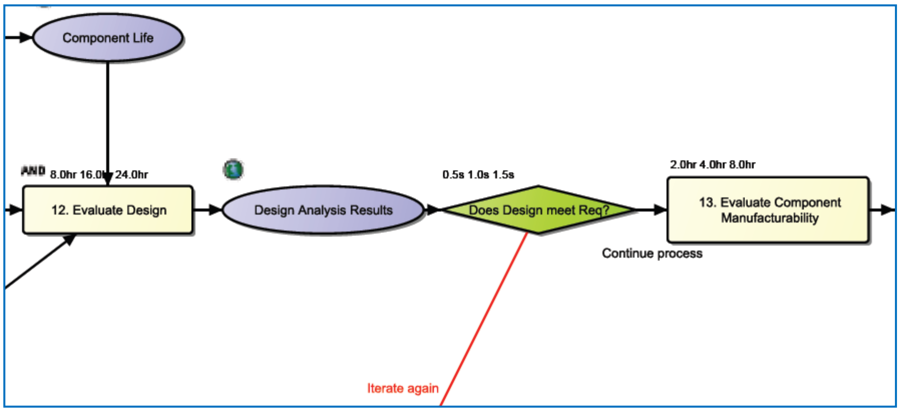


Figure 3-17: Process map representation in CAM

In CAM, activities can be defined to either start after receiving all the inputs or to start without the inputs but only be completed when the inputs are available.

CAM allows the introduction of three values for the duration of each activity as collected for the VSM – the longest, the mode and the shortest durations. This is important in design process improvement when the duration of an activity is difficult to quantify and subject to variability. In Figure 3-18 the CAM activity duration input is shown using a triangular distribution. The most probable product development process lead time can be then be calculated. Also the main sources of variability of the process lead time can be identified from the simulation. This variability should be reduced to allow more robust planning.

Iteration variability can also be modelled. The number of times an iteration is performed can be defined as a variable. As for the activity duration a maximum, mode and minimum number of times and a distribution can be defined. Additionally the activity duration when performed in an iteration loop can also be changed.

CAM also allows the allocation of resources (human and IT) required for each activity. In case of insufficient resources this will generate waiting time. Resource availability can be defined by time schedules, using for example an 8x5 schedule (eight hours a day and five days a week) for human resources and a 24x7 schedule (twenty-four hours a day and seven days a week) for IT resources.

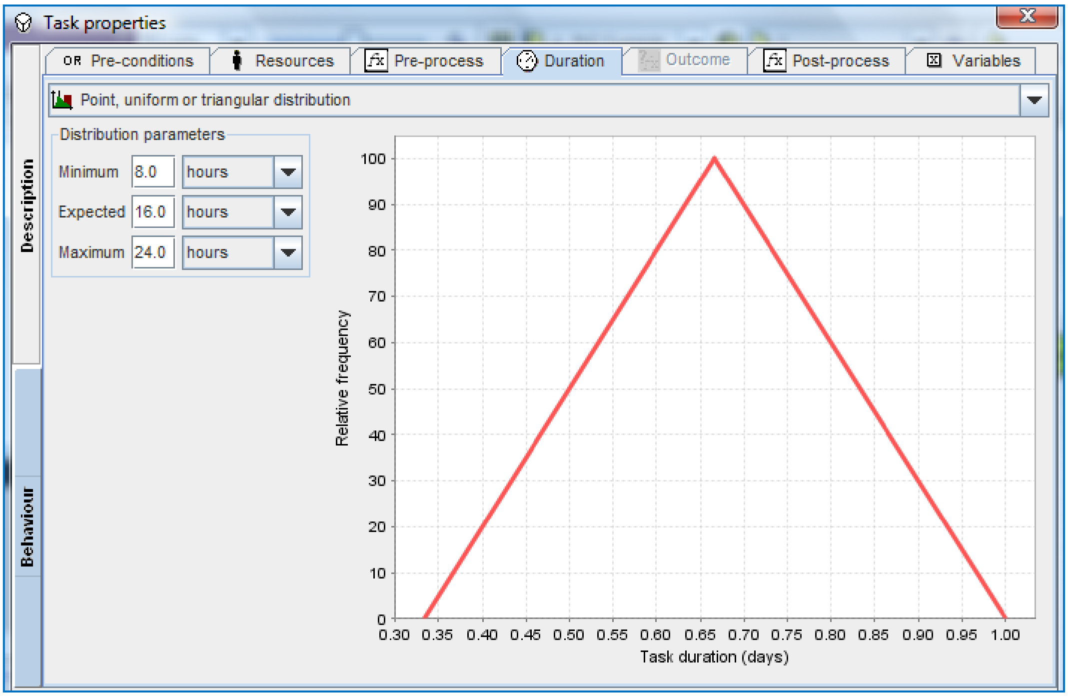


Figure 3-18: Activity time characterization in CAM

Once the process map is constructed and the activities inputs are defined, the process simulation can be started and different scenarios can be investigated. The first two scenarios that should be simulated are the case in which the activities duration is the PT data and the case in which the duration is reduced to the VAT data. The comparison between these two scenarios shows the potential time reduction if the process would be improved to its ideal state.

Figure 3-19 and Figure 3-20 show the product development process map of the example presented above transcribed to CAM. The map is divided in two parts for visual clarity. On the CAM process map, the activity duration is displayed above each activity. A globe displayed above inputs/outputs means that the input/output can be used globally, i.e. by any activity in the process and not just by the subsequent one. In the example shown in Figure 3-19 and Figure 3-20 the first activity defined on the process map is a dummy activity which is required to start the simulation. In this example it is also used to define the function that controls the number of iterations of each decision point. For this specific example, the iteration loop “Does Aero Analysis need to be repeated?” is performed zero times, once or twice, being the probability of being performed zero times 40%, performed once 40% and finally performed twice 20%.

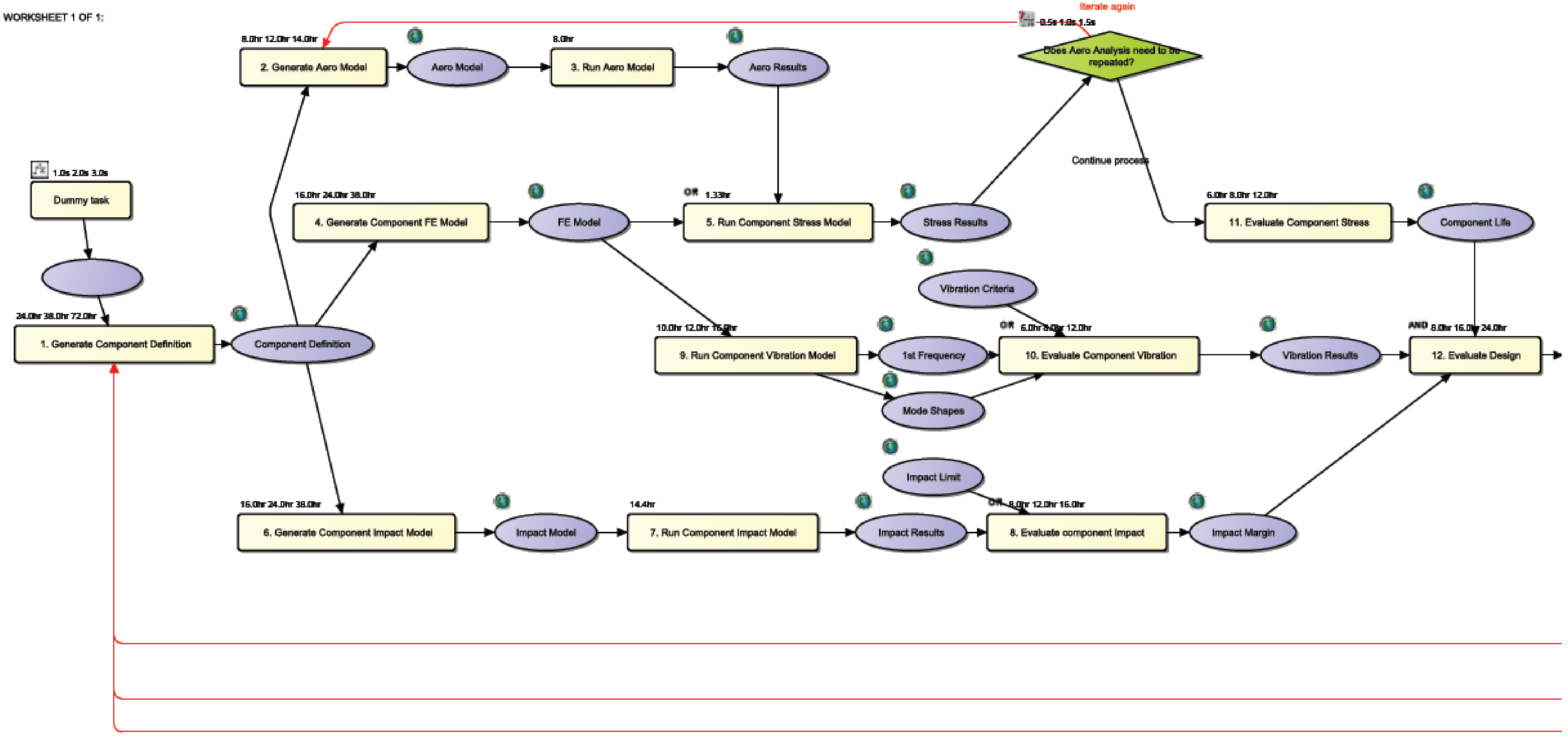


Figure 3-19: Example process map in CAM (I)

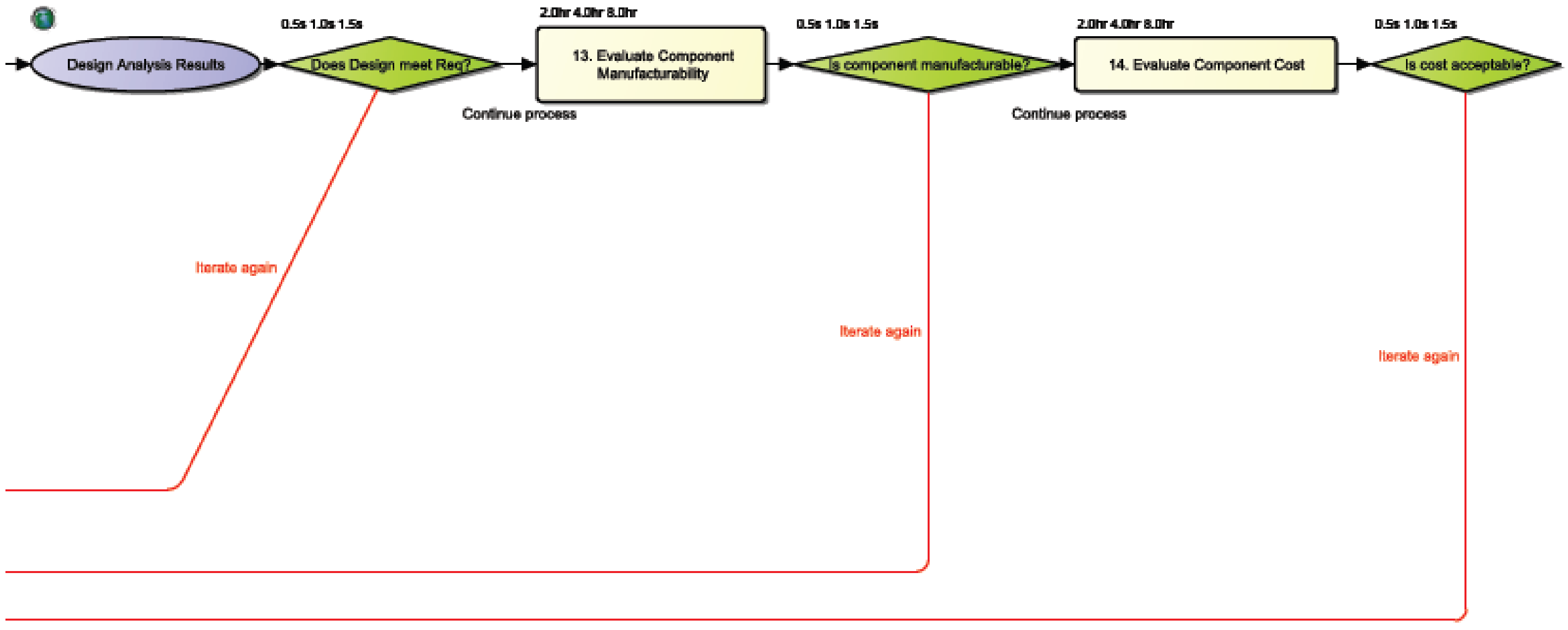


Figure 3-20: Example process map in CAM (II)

The simulation tool runs a Monte-Carlo analysis, which means that it repeatedly runs random combinations of the defined inputs generating a histogram of process lead time results. Figure 3-21 displays the simulation results for the example after 1000 runs.

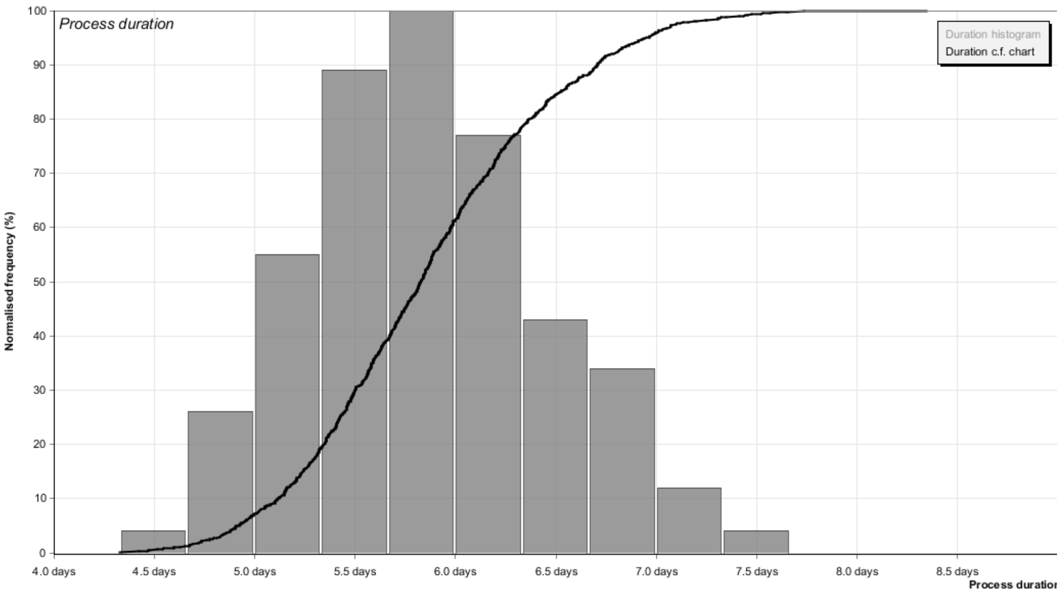


Figure 3-21: Simulation Results for Processing Time Data

From these results one can conclude that the duration of the process varies between 4 and 8.5 days. The histogram also shows that for more than 90% of the runs the process can be completed in 6.7 days.

Each individual run can be visualised. Figure 3-22 shows one of the runs within the most probable bar in the histogram, with the process lead time varying between 5.7 and 6 days. From Figure 3-22 it can be seen that in this run the iteration loop "Does Aero Analysis need to be repeated?" is repeated once.

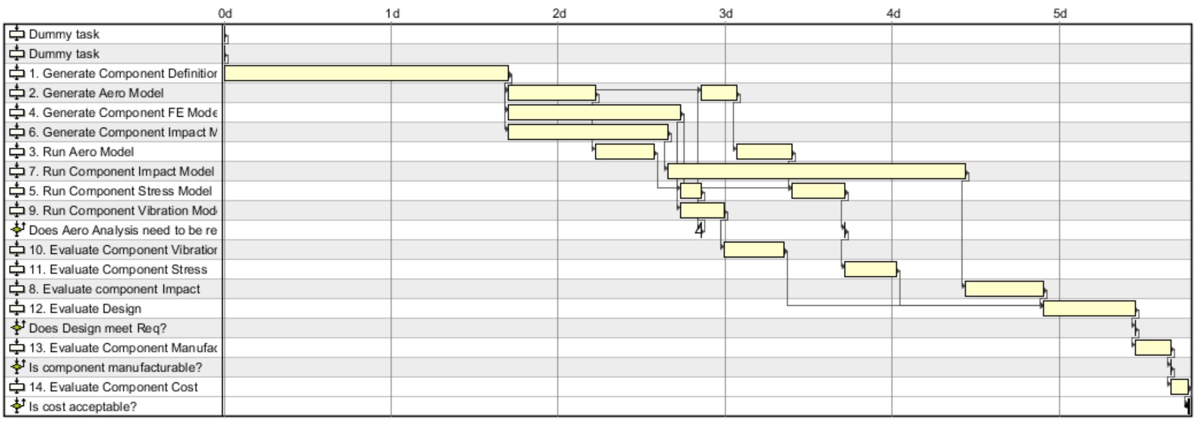


Figure 3-22: Gantt Chart of One Run within the Most Probable Bar in Figure 3-21

Figure 3-23 shows a run within the last column of the histogram with a process lead time of 7.5 days, representing the longest scenarios of the 1000 runs. In this run the iteration loop "Does Aero Analysis need to be repeated?" is repeated twice which means activities 2, 3 and 5 are performed three times.

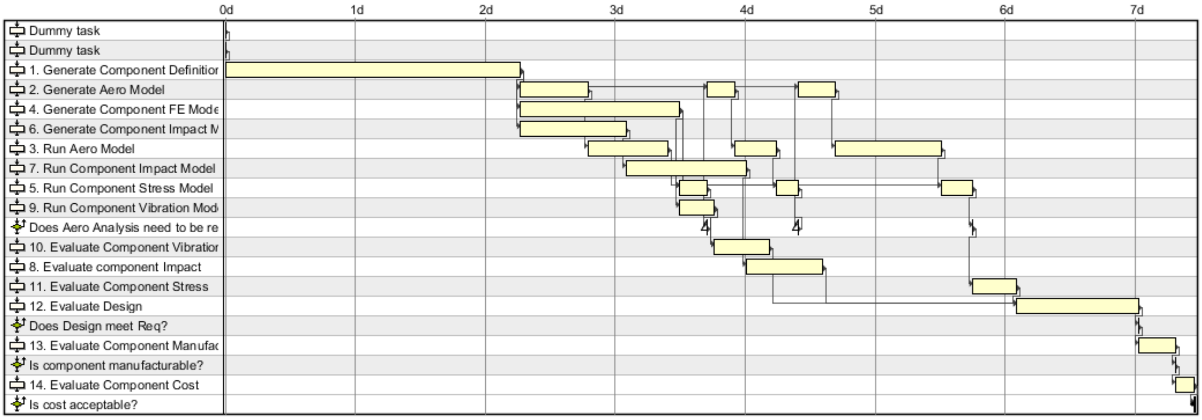


Figure 3-23: Gantt Chart of One Run within the Longest Bar in Figure 3-21

Exporting the results to a statistics software such as Minitab, the process statistical behaviour can be analysed as shown in Figure 3-24.

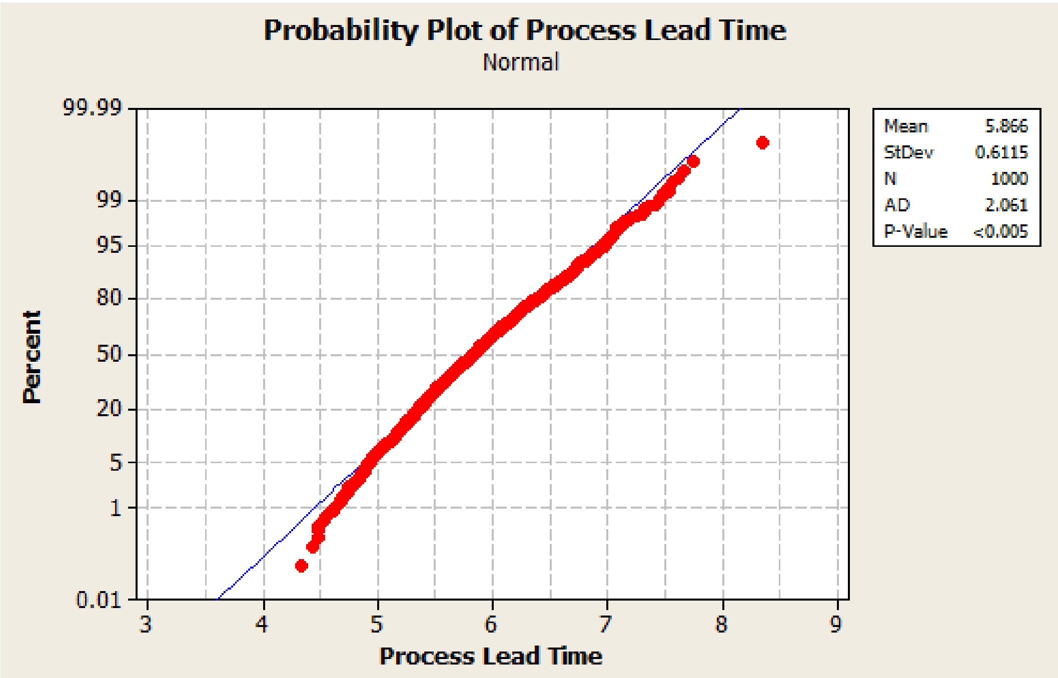


Figure 3-24: Simulation Results Normality Test

From the normality test shown in Figure 3-24 it is possible to conclude that these simulation results cannot be fitted to a normal distribution, which means that the lead time of the process under analysis is not normally distributed. Therefore instead of using the standard variation, the minimum (4.33 days) and the maximum (8.35 days) values are used together with the mean lead time (5.866 days) to analyse different scenarios.

Simulating the process using the VAT data shows the possible improvement benefit if the process would be waste-free. Figure 3-25 shows the simulation results for the VAT data scenario. It can be seen that, in absolute terms, the mean process lead time has been reduced (3.15 days) as well as the process variability (the minimum 2.55 and the maximum 4.78 days). However, in relative terms the

difference between the maximum and minimum duration is approximately constant. The fact that the variability was not reduced, in relative terms, shows that a significant part of the activity duration uncertainty is caused by uncertainty in the VAT.

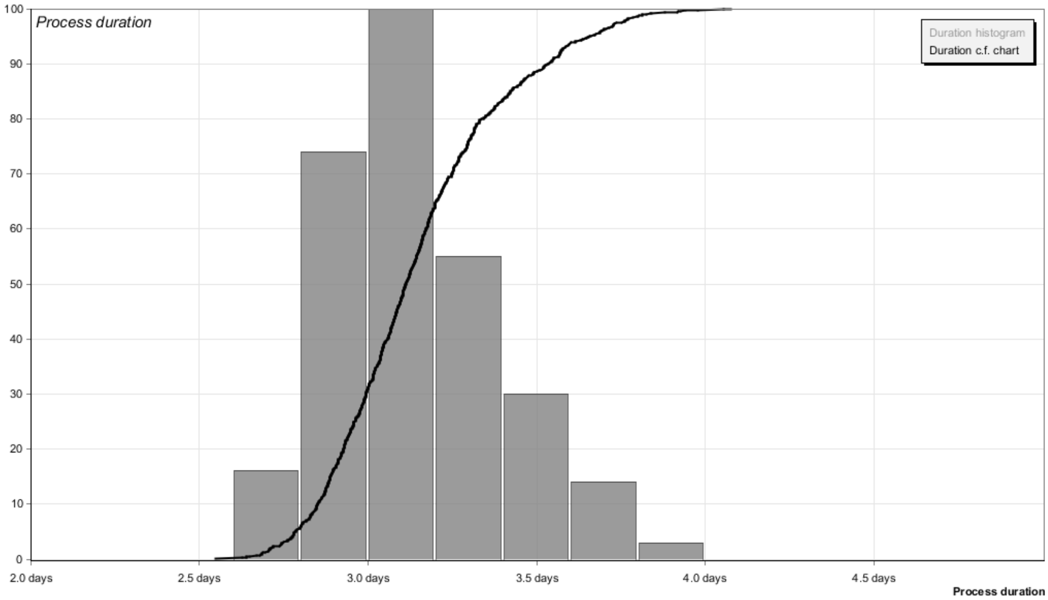


Figure 3-25: Simulation Results for Value Added Time Data

Comparing the mean values one can conclude that in average the VAT scenario duration is half of the average duration of the PT scenario.

Although the simulation results show that the process lead time could in theory be reduced by half, it is unlikely that the implementation of all these improvements would be possible in practice. It is therefore important to understand which improvements have the biggest impact on the process lead time and to weigh off the benefit of improvements with their cost.

3.2.5.Improvements Benefit Analysis

An enhancement strategy may be to improve activities in the process critical path, however considering the activities' variability the critical path may change. For this reason, a Monte Carlo simulation is recommended. Analysing the VSM data of the example shown in Figure 3-10, one may decide to improve activity 4. However activity 4 may or not be in the critical path depending of its duration and the number of times the iteration loop "Does Aero Analysis need to be repeated?" is repeated. For a complete understanding of the effect of removing the waste related with activity 4 on the overall process lead time a simulation has been run. The results of 1000 Monte Carlo simulation runs showed that reducing the duration of activity 4 to its VAT, an average reduction of 0.5 days (from 24 to 12 hours), would only change the average process lead time from 5.87 to 5.82 days. The small impact of this activity's improvement on the overall process time can be explained by the fact that the activity is not always on the critical path.

Another scenario that can be simulated is the product development process automation, which means that all the manual work would be done in seconds through automatic steps. This represents an ideal scenario, which indicates the absolute minimum process lead time not considering changes in the IT capability. In order to robustly design and optimise products, such automation is becoming more important. For automated optimisation the process needs to run quickly without human intervention. Figure 3-26 shows the fully automated process scenario results in which case all the manual time is eliminated. For this scenario both the average process duration (5.87 to 2.44 days) and maximum and minimum durations change significantly. Although the process lead time is reduced by more than half, the reduced time is still too long to run this process hundreds of times in an optimisation loop. To achieve a sufficiently low process lead time the computational time has to be reduced which would potentially require investments in IT infrastructure.

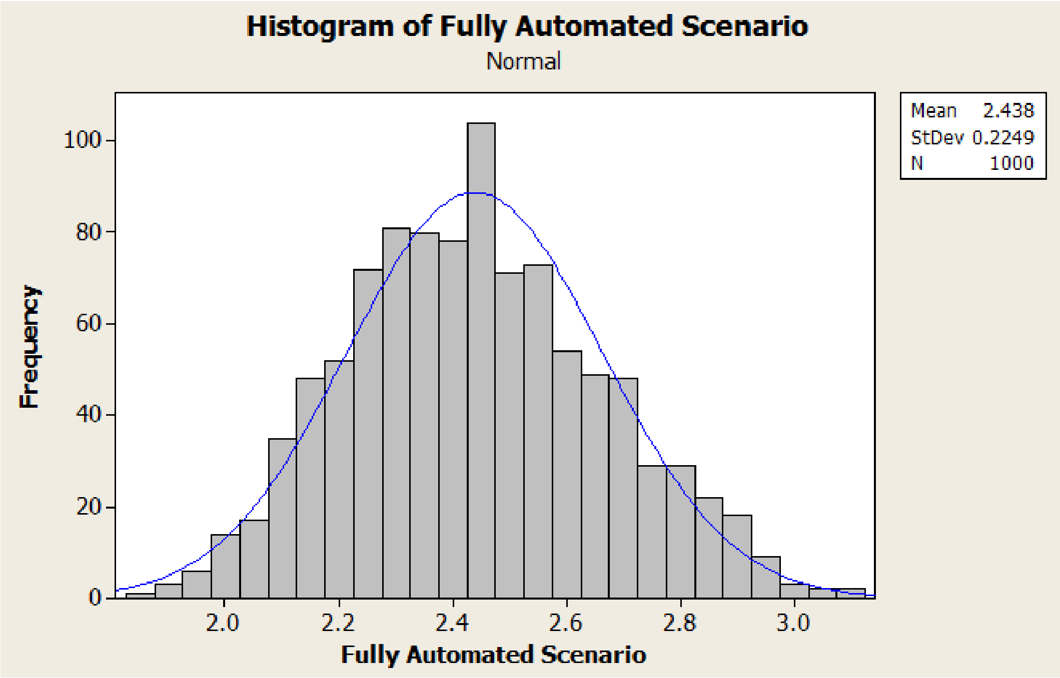


Figure 3-26: Fully Automated Scenario Simulation Results

A different question may emerge if a company is assessing how best to make use of a set budget for improvement. It may consider where to add computational capability in the form of additional processors on a computer cluster, which activities should use these additional processors. The same question may also emerge for human resources. To answer these questions one needs to understand the process behaviour, for which a Design of Experiments (DOE) analysis is recommended in this thesis.

For a better illustration the example case will be used to conduct a DOE. In the scenario described below it is considered that 24 extra processors are available on a computer cluster and can be used to reduce the process lead time. The DOE will be used to understand the ideal processors allocation to the computing activities. Assuming that activity 9 is improved reducing its waiting time as described

above (i.e. raising its priority in the queue for computation resource) and would not benefit significantly from additional processors, there are 3 computing activities in the process that could benefit from the additional capacity: activity 3, activity 5 and activity 7. These three activities' have high durations which are directly dependent on the number of available processors.

In the baseline scenario captured in the VSM, activity 3 runs with 8 processors, activity 5 with 4 processors and activity 7 with 24 processors (as shown in the VSM Figure 3-10). The following DOE example aims to determine how to best distribute 24 additional processors between activities 3, 5 and 7. Because allocating processors to one activity makes fewer processors available to the other two activities, an interdependency exists between the number of processors assigned to each activity. Allocation factors have been designed to capture this interdependency. The allocation factors N3, N5 and N7 can take values between 0 and 1 and determine the relative number of processors added to an activity using the formulas below:

$$Additinal\ Processors\ for\ Activity\ 3 = \frac{N3}{N3 + N5 + N7} \times 24$$

$$Additinal\ Processors\ for\ Activity\ 5 = \frac{N5}{N3 + N5 + N7} \times 24$$

$$Additinal\ Processors\ for\ Activity\ 7 = \frac{N7}{N3 + N5 + N7} \times 24$$

For example, setting N3 to 1, N5 to 1 and N7 to 0 would equally share the processors between activities 3 and 5. Setting all allocation factors to 1 would equally share the 24 processors between the three activities. Other combinations are captured in Table 3-3.

In order to analyse the ideal allocation of processors, a General Full Factorial DOE with three levels (0, 0.5 and 1 as values assigned to allocation factors) has been designed as shown in Table 3-3. A full factorial analysis tests that all the possible combinations of levels for the three factors. The total number of experiments is in this case 3^3=27.

It is assumed that the duration of the activities under investigation is inversely proportional to the number of processors.

As the objective of this optimisation is to reduce the analysis time, only a sub-process from geometry generation to the design evaluation is considered in the DOE. Activities 1, 13 and 14 are therefore not included in the simulation. The analysis process lead time is therefore called sub-process lead time to distinguish from the overall process lead time. As shown in the first row of Table 3-3 the sub-process lead time is 87.33 hours when no additional processors are used. In order to consider the activity variability, the sub-process lead time for each scenario is calculated as the average of 1000 Monte Carlo runs for each case.

Table 3-3: DOE Design Layout

Allocation Factor for			Additional Processors for			Factor on Activity Duration			Sub-process Lead Time [h]
Act. 3	Act. 5	Act. 7	Act. 3	Act. 5	Act. 7	Act. 3	Act. 5	Act. 7	
0	0	0	0	0	0	1.00	1.00	1.00	87.33
0	0	0.5	0	0	24	1.00	1.00	0.50	79.34
0	0	1	0	0	24	1.00	1.00	0.50	79.03
0	0.5	0	0	24	0	1.00	0.14	1.00	84.32
0	0.5	0.5	0	12	12	1.00	0.25	0.67	77.77
0	0.5	1	0	8	16	1.00	0.33	0.60	76.25
0	1	0	0	24	0	1.00	0.14	1.00	84.88
0	1	0.5	0	16	8	1.00	0.20	0.75	78.78
0	1	1	0	12	12	1.00	0.25	0.67	77.53
0.5	0	0	24	0	0	0.25	1.00	1.00	84.53
0.5	0	0.5	12	0	12	0.40	1.00	0.67	76.93
0.5	0	1	8	0	16	0.50	1.00	0.60	76.30
0.5	0.5	0	12	12	0	0.40	0.25	1.00	83.40
0.5	0.5	0.5	8	8	8	0.50	0.33	0.75	77.68
0.5	0.5	1	6	6	12	0.57	0.40	0.67	75.77
0.5	1	0	8	16	0	0.50	0.20	1.00	83.55
0.5	1	0.5	6	12	6	0.57	0.25	0.80	78.38
0.5	1	1	4.8	9.6	9.6	0.63	0.29	0.71	76.28
1	0	0	24	0	0	0.25	1.00	1.00	83.88
1	0	0.5	16	0	8	0.33	1.00	0.75	78.12
1	0	1	12	0	12	0.40	1.00	0.67	77.17
1	0.5	0	16	8	0	0.33	0.33	1.00	83.14
1	0.5	0.5	12	6	6	0.40	0.40	0.80	77.87
1	0.5	1	9.6	4.8	9.6	0.45	0.45	0.71	76.21
1	1	0	12	12	0	0.40	0.25	1.00	83.91
1	1	0.5	9.6	9.6	4.8	0.45	0.29	0.83	78.93
1	1	1	8	8	8	0.50	0.33	0.75	77.03

The effect of varying the number of processors on the three computing activities can be assessed from the response surface generated from the Monte Carlo results, which is shown in Figure 3-27. From this analysis it can be concluded that the biggest impact on the sub-process lead time is achieved by allocating processors to activity 7. However the minimum sub-process lead time is only achieved when the processors are distributed between the three activities. The ideal distribution is shown in Figure 3-28 and is achieved when N3 is 0.596, N5 is 0.5152 and N7 is 0.899. These allocation factors correspond to an allocation of 7 processors to activity 3, 6 processors to activity 5 and 11 processors to activity 7 (see allocation factor definition above). This additional processors distribution gives more than 15% improvement to the sub-process lead time (75.63 hours as shown as the minimum value y of the response surface in Figure 3-28).

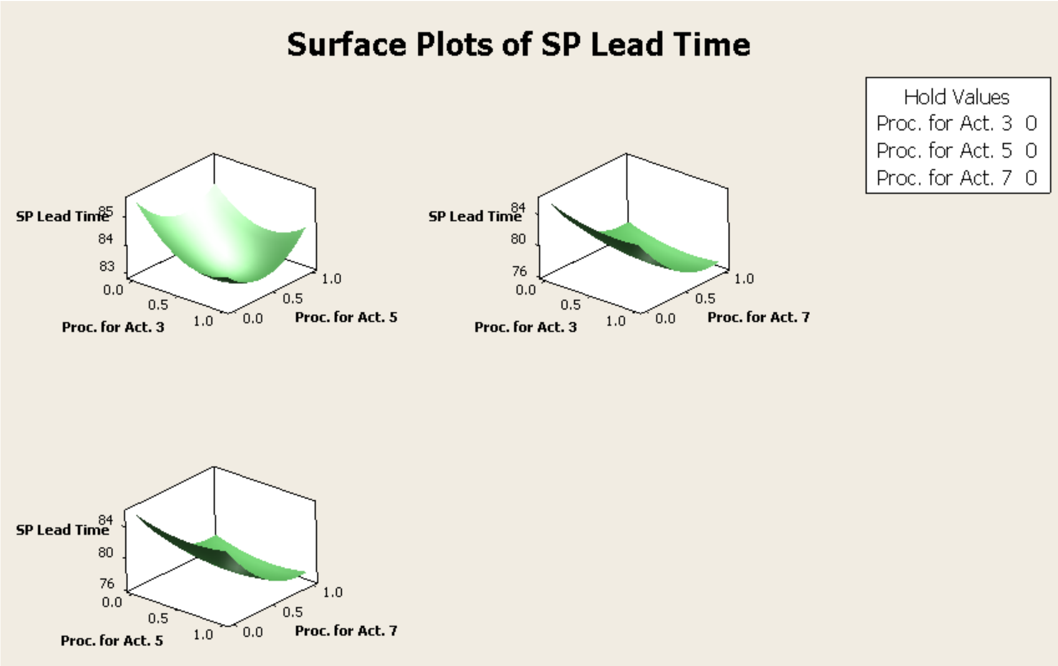


Figure 3-27: Duration Surface Plots

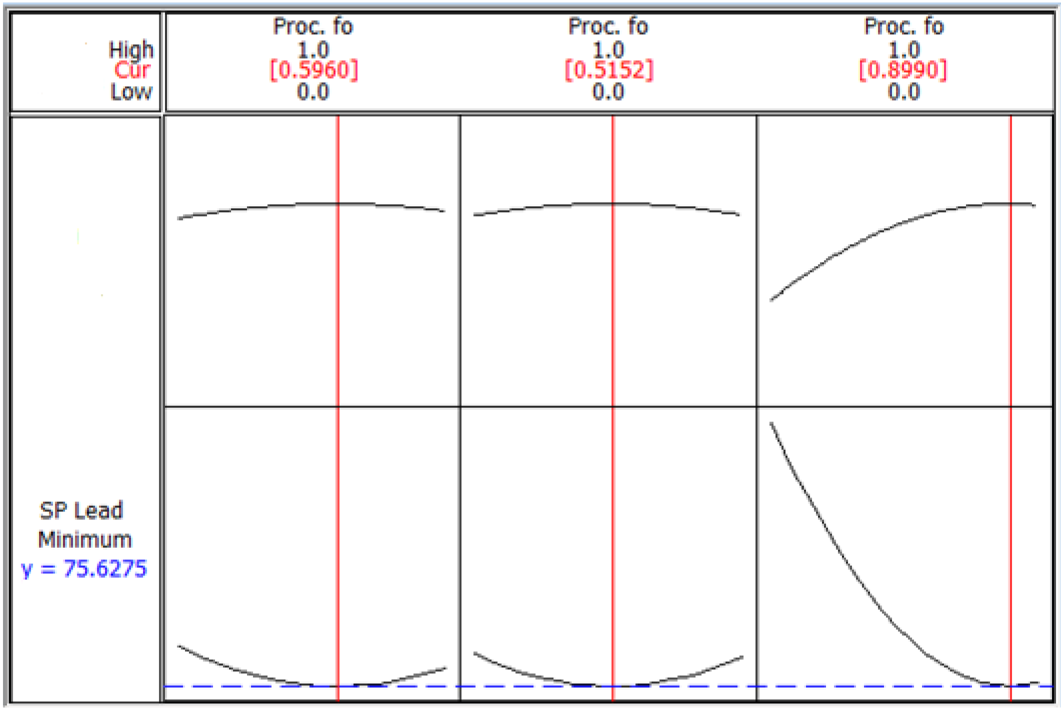


Figure 3-28: Process Lead Time Optimisation Plot

To summarise, through the application of Monte Carlo process simulation it is possible to assure the activities with the biggest influence on the process lead time are targeted for improvement, even considering the activities' and the iteration loops' variability. The process simulation also helps to understand the effect of waste in the process and the difference between the current and the ideal

process. The process improvements can be simulated with *what-if* scenarios to generate results to support the improvement business case. Finally, using the DOE and the Monte Carlo simulation it is possible to understand what the best strategies are if the improvement objective is to reduce process lead time with limited resources.

3.2.6.Define “To Be” Process

The objectives of the previous sections were to capture the product development process, to identify waste, both within activities and within loops of activities, and to analyse the potential improvements. If these steps, described above, were developed in collaboration with the key stakeholders, this last step of the EPI framework can be seen as the simple formalisation of the “To Be” process.

The main objective of this step is to get the stakeholders’ and the project sponsors’ buy-off on the future process to follow and on the improvements to implement. Therefore, all the results previously achieved should be compiled and discussed in a workshop meeting involving all the stakeholders. The improvements, as well as their respective benefits and cost, should be discussed and agreed. The simulation results are essential to support this discussion, helping to understand the impact of improving specific parts of the product development process. Simulation results, for example DOE results as described above, can be very important to understand where the improvements should aim to make the most of a limited improvement budget.

The following points represent desired characteristics of the improved product development process:

- Balanced work load for human and computational resources;
- Human resources with the required skills;
- Adequate IT infrastructure, including knowledge management tools, communication tools, automation tools, robust design tools, etc.;
- Standard procedures and when possible the use product standardisation (for example through the use of product modules or knowledge-based engineering techniques);
- Non value added activities elimination and required non-value added activities reduction;
- Iterations loop re-organization aiming to reduce process time;
- Clear understanding of the internal suppliers and customers and their respective requirements;
- Simple and visual communication.

In order to ensure that a lean product development process is achieved, a check list or matrix can be used to assess each of the Morgan and Liker (2006) lean principles as shown in the two case studies sections (Sections 4.4 and 4.6).

3.2.7.Conclusions

The EPI framework was developed to improve product development processes in a lean and robust way. It uses methods explored in other environments such as the VSM and process simulation to

analyse, identify and understand the effect of potential improvements in complex product development processes.

Although VSM originates from manufacturing, it has been theoretically explored as a potential method to improve product development processes (Millard, 2001; McManus, 2005). However, there is a lack of real examples of VSM application in industrial complex product development processes. In a similar way it has been suggested by McManus (2005) that the DSM should be use to overcome the complexity caused by the iterative behaviour of product development processes, but this author does not show how to combine these two methods in a real product development process and what the advantages of this combination are. With this framework, one can see how to do this combination and how to apply it to real complex product development processes (as described in the following sections).

An explanation of how to address product development process improvement, from the stakeholders' identification until the improvements implementation, is described in this framework. For example, the data collection method for the VSM and DSM has been improved in this research. Key improvements are related to the use of a triangular distribution to represent activities duration which not only gives more data and more confidence in the collected data but also makes it easier to the user to provide the required data. Although this approach has been suggested by Browning and Eppinger (2002) for DSM analysis, it has not previously been used in VSM analysis.

The framework uses the DSM as a tool to manage the iteration loops, as well as to support the assessment of which activities could be performed earlier in the process to achieve a front-loaded product development process. A front-loaded process, as described by Morgan and Liker (2006), will lead to a risk reduction (performing a more detailed analysis earlier in the process) and possibly time reduction (eliminating time consuming and expensive iterations later in the process) in the overall process.

The VSM application has been adapted to overcome the product development complexity, not only using the DSM but also using process simulation. The simulation was shown to be essential in the improvement process to accommodate the product development process uncertainty and complexity. Manufacturing processes are more predictable and simpler than product development processes. These latter processes are depended on many factors which lead to a large uncertainty in the process lead time. A problem that results from duration uncertainty is to understand the impact of potential improvements on the overall lead time. To defeat this difficulty a robust process analysis is recommended in this framework helping to develop robust product development processes in a similar way companies develop robust products.

Chapter 4

Case Studies

4.1. Introduction

The main focus of this research is the applicability of the EPI (Engineering Process Improvement) framework to the industrial environment, which has been validated through two case studies. This research has been mainly developed within a large engineering company, Rolls-Royce, which produces jet engines and a wide range of other power systems. However, it is important to note that the EPI framework aims to be suitable for any complex product development.

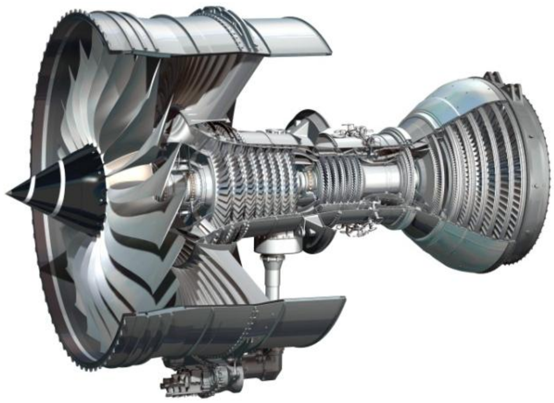


Figure 4-1: Rolls-Royce Trent XWB[1]

As explained in Chapter 1, the author of this research joined Rolls-Royce, after an intensive literature review, with a proposal to use Lean principles to improve product development processes. During two years, the author has been engaged in the EPI framework development and its validation in the real industrial environment, namely testing it in two case studies: the product development processes of

[1] www.rolls-royce.com/press/assets/images, 2012-02-19

the High Pressure Turbine Blade (HPTB) and the High Pressure Turbine Disc (HPTD) System of large civil jet engines. These case studies were conducted in Derby (UK), which is the Rolls-Royce centre of excellence for large civil jet engines (see Figure 4-1 for example of a three-shaft large civil turbofan).

In the first case study, on the HPTB, an initial version of the EPI framework has been developed and exploited within the Turbines Systems Unit of Rolls-Royce. A significant part of this case study consisted of understanding the Rolls-Royce product development structure and the complexity and difficulties faced when designing highly complex products such as jet engine components. The HPTB design process must reconcile the following requirements: providing the required thrust, minimizing cost, minimizing weight, minimizing fuel consumption, etc. For these reasons the blade design is one of the most challenging tasks when designing a gas turbine. The goal of this first case study was to improve the design process, particularly by identifying opportunities for automation.

The second case study, on the HPTD System, was conducted within the Rotatives Unit and added two particular aspects to strengthen the EPI framework's applicability. Firstly, the case study was conducted because the requirement to improve the HPTD System design had been identified as a business priority which meant that more resources were available to implement the process improvements, giving the author the opportunity to quantify the benefit of using the framework. Secondly, the design process under analysis operates at a system level, which means that the process is shared by different departments and it affects the design of several components.

The main function of the turbine disc is to locate and retain the blades while transferring the rotational force they generate to the shaft. The disc is designed to withstand a minimum number of flight cycles being submitted to high temperatures and to enormous centrifugal loads exerted by the mass of the blades rotating at high speed. Moreover the discs are considered critical parts of a gas turbine, because a disc failure could have a catastrophic effect on the aircraft[2]. A challenge of the HPTD development is in ensuring during preliminary design that the disc will meet the customer requirement for component life. The assessment of the disc life is a time-consuming part of the disc development process which is carried out during the detailed design phase when it is too late to significantly change the design concept (i.e. the system architecture). This makes it extremely important to reduce the HPTD preliminary design process lead time in order to allow the design team to assess different system architectures.

In Section 4.2 of this chapter, the Rolls-Royce company structure and product development are described. The following sections, from 4.3 to 4.5, describe the work completed in the two cases

[2] Definition from FAA (Federal Aviation Administration) Federal Aviation Regulations (FARS, 14 CFR), Part 27, Section 602 – Critical Parts (www.faa.gov)

studies, the results obtained and how these results allowed to strength and validate the EPI framework presented in Chapter 3.

4.2. Rolls-Royce Company Structure and Product Development

For a better understanding of the environment where the two case-studies were carried out, this section reflects on the Rolls-Royce company structure and product development.

Rolls-Royce's business sectors are organised by the market which develops products for: civil aerospace, defence aerospace, marine, energy and nuclear. These sectors form the Customer Facing Business Units (CFBUs) which are supported by the Gas Turbine Supply Chain Units (SCUs). The SCUs are responsible for designing sub-systems, such as Compressors and Turbines for projects run by the CFBUs. The CFBUs are the whole system integrators and responsible for delivery of specific project to the customer.

The engineering functions are organised in a matrix structure with a dual hierarchy composed by different vertical functional areas (such as stress, thermals and aerodynamics) and horizontal projects (such as Trent 1000 and BR725). Within the functions, engineers are responsible to maintain and develop the technical knowledge of their functional areas. Engineers may be allocated to one or more projects. Within projects, engineers are often grouped in Integrated Product Teams (IPT). The IPTs are set up as multi-disciplinary teams which allow using concurrent design to develop components or systems.

Rolls-Royce product lifecycle can be divided into seven stages, as shown in Figure 4-2: innovation and opportunity selection, preliminary concept definition, full concept definition, product realisation (or development), production, continuing service support and disposal.

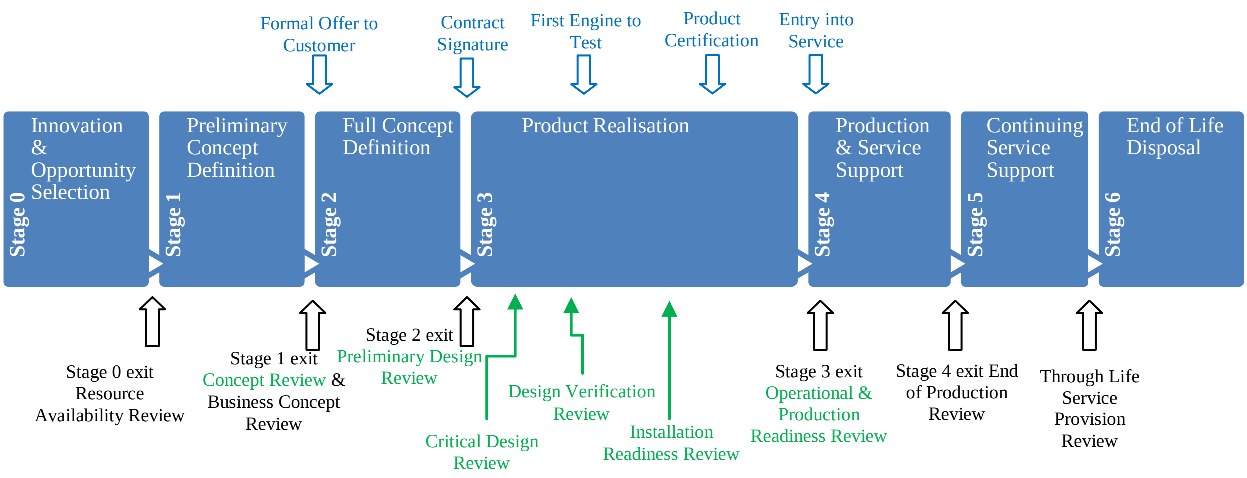


Figure 4-2: Design Phases and their Position in the Product Life-cycle (Rolls-Royce, 2005)

The stages 0 to 4 are equivalent to the product development stages defined in Chapter 2 (Figure 2-2). For a large civil jet engine, the time scale to go from stage 1 to the end of stage 3 is approximately five years.

The two case studies described below were conducted in design phases involving the heaviest engagement of design engineers and analysts from the different functional areas, namely the preliminary and detailed design phases of stages 1, 2 and 3.

4.3. Case Study 1: High Pressure Turbine Blade

The aim of this case study was to develop and validate the EPI framework for product development process improvement in an industrial environment. To accomplish this objective the High Pressure Turbine Blade (HPTB) development for the Trent XWB jet engine has been used. The HPTB is one of the most demanding components in a jet engine in terms of design due to the demanding environmental conditions which the blades are subject to. The HPTBs operate in gas temperatures well above their melting point and require a sophisticated internal cooling system to ensure their mechanical integrity; each blade suffers 18 tonnes of centrifugal force as it travels at 500 meters per second and extracts more power from the gas stream than an entire Formula 1 car engine (Jet Engine, 2005).

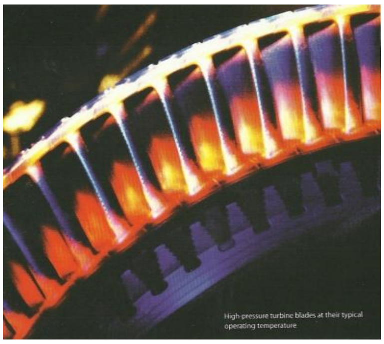


Figure 4-3: HPTB at their Typical Operating Temperature (Rolls-Royce, 2005)

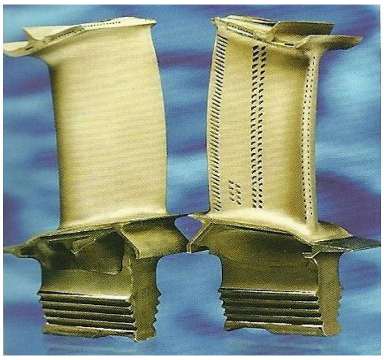


Figure 4-4: High Pressure Turbine Blade (Rolls-Royce, 2005)

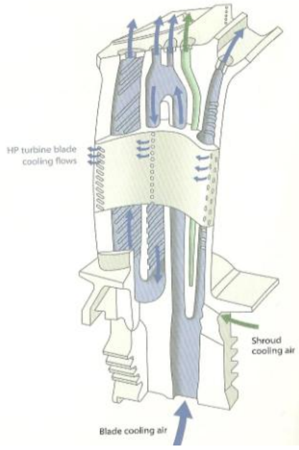


Figure 4-5: Turbine Blade Sections (Rolls-Royce, 2005)

The turbine blade is designed to generate power by translating the aerodynamic forces to the rotating disc. The blades have an advanced aerofoil shape that gives the adequate acceleration to the air flow to produce the HP shaft rotation by transferring the loads to the HP turbine disc (see Figure 4-3). The blades are commonly mounted into the disc by firtree fittings (see Figure 4-4) which distribute the load equally on a number of surfaces. The blade design is driven by the aerodynamic efficiency, the permitted stress in the material and the complex core passages required to flow internal cooling air (Figure 4-5).

The blades must be resistant not only to extremely high temperatures, but also to high centrifugal loads caused by their rotation and the bending load caused by the gas stream. They must also resist

fatigue, thermal shock, corrosion, oxidation and creep (plastic deformation that causes the blade to slowly increase its length during the operational time). Blade creep and material oxidation limit the blade life. In normal operating conditions, blade life is 35000-hours, which corresponds to approximately six-years of an engine on wing between major overhaul services.

To design this complex component in a way that it meets the customer life and performance requirements, a dedicated team composed of 10 to 20 engineers from various functions works during 2 to 3 years following the product development process represented in Figure 4-2. The work of this team was studied to support the development and validation of the EPI framework.

The first step of the case study was to engage with the team, identified as Integrated Product Team (IPT), and understand how the team members work concurrently to design the blade. The HPTB for Trent XWB was undergoing stage 3 of the product development process (see Figure 4-2) at the time of this case study. The Trent XWB HPTB team was comprised, at this time, by nine people representing six different functional areas and an IPT leader to run the project. The functional areas represented in the IPT were: Design, Stress, Thermals, Component Definition Group (CDG), Aerodynamics and Aeroelasticity. In order to gain understanding of the team, a first interview was held with the IPT leader. The result of this interview was a clear idea about the team structure and a list of the key stakeholders of the blade product development process. The identified stakeholders were everyone involved in this phase of the HPTB development. Figure 4-6 shows the different steps done during this case study.

In order to understand all the IPT members' roles and simultaneously continue gathering information about the blade development, individual semi-structured interviews with all the IPT members were held. Semi-structured means in this case that even if there was a guideline with key questions, the aim of these interviews was to let IPT members talk as much as possible about their work. The two positive results of this approach were firstly to collect information that would not possibly have been discussed with closed questions and secondly created an informal, "nonthreatening" and friendly conversation as recommended by Yin (2009) that helped the researcher to engage with the team. The interview guideline was adapted from Millard's research (Millard, 2005) and is shown in Appendix II. Each interview took approximately one hour. Because these interviews were the first contact with most of the IPT members, it was very important to explain the aim of the interview and of this research. Another important point to explain was the confidentiality policy, which stated that the interviews results would only be accessible to the research team, and that the results were going to be used to support the research. The interviews were not voice recorded to avoid intimidating the interviewees.

In parallel to these interviews, the author of this thesis has investigated project documents, such as project plans, design review gate information and technical reports; the author also attended relevant

technical meetings during the seven month case study. From the data collected in these activities, the author started to build the first draft of the process map.

The draft process map was used to support a first workshop involving all the IPT members. This workshop aimed to scope the process under analysis, to analyse the main streams of the blade development process, to further develop the draft process map - adding missing activities, inputs and outputs, activities interactions, iteration loops - as well as identifying the process critical areas. Regarding the case study scope, it was decided to restrict the research to the detailed design stage which the blade development was going through at the time the case study was conducted. The main reason for this decision was the fact that the preliminary design had been completed by a different team outside of the Turbines SCU (part of the CFBUs called Future Programmes Engineering), although in collaboration with Turbines SCU. The use of the EPI framework for improving preliminary design phases is discussed in the second case study.

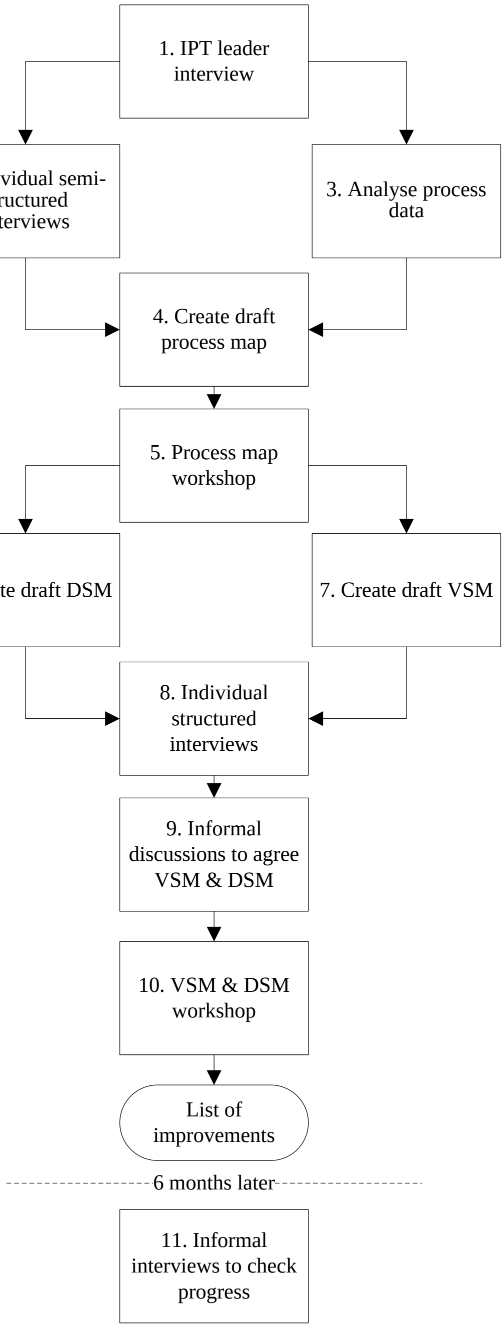


Figure 4-6: Case study steps description

In the workshop, the process map was developed using post-its notes as shown in Figure 4-7. The post-its notes allowed an interactive session in which the IPT members could discuss and change the process map throughout the discussion. During the session the main role of the researcher was to make sure that the discussions were focused on the activities under analysis and make sure that all the stakeholders discussed their activities.

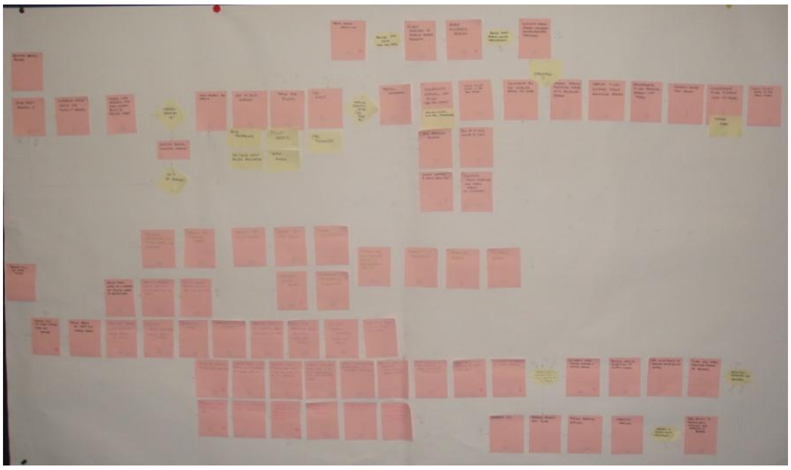


Figure 4-7: Draft Process Map to Support Workshop

The workshop took two hours and the main results of this session were an improved process map bought-off by the IPT team members and the identification of the critical process areas. Critical areas have been defined here as process bottlenecks activities and all other activities with evident margin for improvement. The critical areas identification has been done for two reasons, firstly to help on prioritising the improvement activities and second to choose a critical area to analyse in detail during the limited time available to conduct the case study. Therefore four critical streams of activities have been identified on the map, as identified in Figure 4-8.

The first stream of activities was selected because it was part of the process critical path. The stream is characterised by a propensity for iterations, partly planned but also required unexpectedly. The main reasons for this iterative behaviour, which was captured during the discussion in the workshop, are both the delays receiving updated inputs, which lead to some work having to be completed without the updated information, and design requirements changes coming from interfacing SCUs or Whole Engine Design teams. However, other reasons for unplanned iterations were identified as design errors and lack of coordination and communication. The main goal when improving this stream of activities was to reduce the time needed for each planned iterative loop and reduce the unplanned iterations caused by errors and miscommunication. Note that the goal was not to eliminate iterations, because iterations are required to optimise the design concept and reduce design risk.

The second stream of activities was chosen to allow the use of Robust Design techniques. Robust Design techniques such as Monte Carlo simulation often require running a process several times to explore the design space. In order to carry out this type of analysis in a reasonable time, a shortened process lead time was required.

The third and fourth stream of activities were chosen because novel techniques were used for the Trent XWB project which the team had limited experience with.

Figure 4-8 illustrates the process map discussed in the workshop. The process was developed using a process simulation tool developed in Cambridge University Engineering Design Centre, CAM

(Cambridge Advanced Modeller). As previously described in Chapter 3, rectangles represent activities, ellipses represent inputs/outputs and diamond-shaped boxes represent decision points.

The workshop session was ended with the identification of the owners of each activity. In this context owner means the person that does that activity in the process and consequently the contact point to discuss each activity in detail. For the first two streams of the activities a full process analysis has been recommended which will be described below. For the third and fourth streams of activities, a good knowledge capture and communication with other IPTs that use the same techniques, was recommended. The contact to the Rolls-Royce knowledge management team was therefore established to apply standard methods such as lessons learnt logs.

The information collected from the individual interviews, the documentation analysis, attending technical meetings and the workshop was used to develop the draft Value Stream Map (VSM) and draft Design Structure Matrix (DSM) of the first two streams of activities described above. To collect the information missing to develop the VSM and DSM another set of individual interviews was completed. In opposition to the first set of interviews, structured interviews have been chosen at this stage because the aim of these interviews was to collect specific data in short time. Note that normally the IPT members are very busy with their daily work and they normally find it extremely challenging to have time to spend on process improvement activities. To conduct these interviews a data collection form was used. The form was developed by Millard (2001) and it is presented in Appendix II. A data collection sheet was completed for each activity under analysis. The collected data highlighted if an activity was value added, non-value added or required non-value added. The time metrics for each activity were collected as well as activity inputs and outputs. The discussion of each activity was planned to take thirty minutes.

Appendix III shows a table with the time metrics collected for each activity. As described in Chapter 3, VAT stands for value added time and represent the effective time that the end-customer is willing to pay for. PT stands for processing time and is the time that is normally charged for each activity, it includes VAT plus the time need to set up the activity and gather the required information. Finally, ET or Elapsed Time is the calendar time that passes from the authorization to start the activity until the moment in which it is completed; this even includes time spent on other activities or projects.

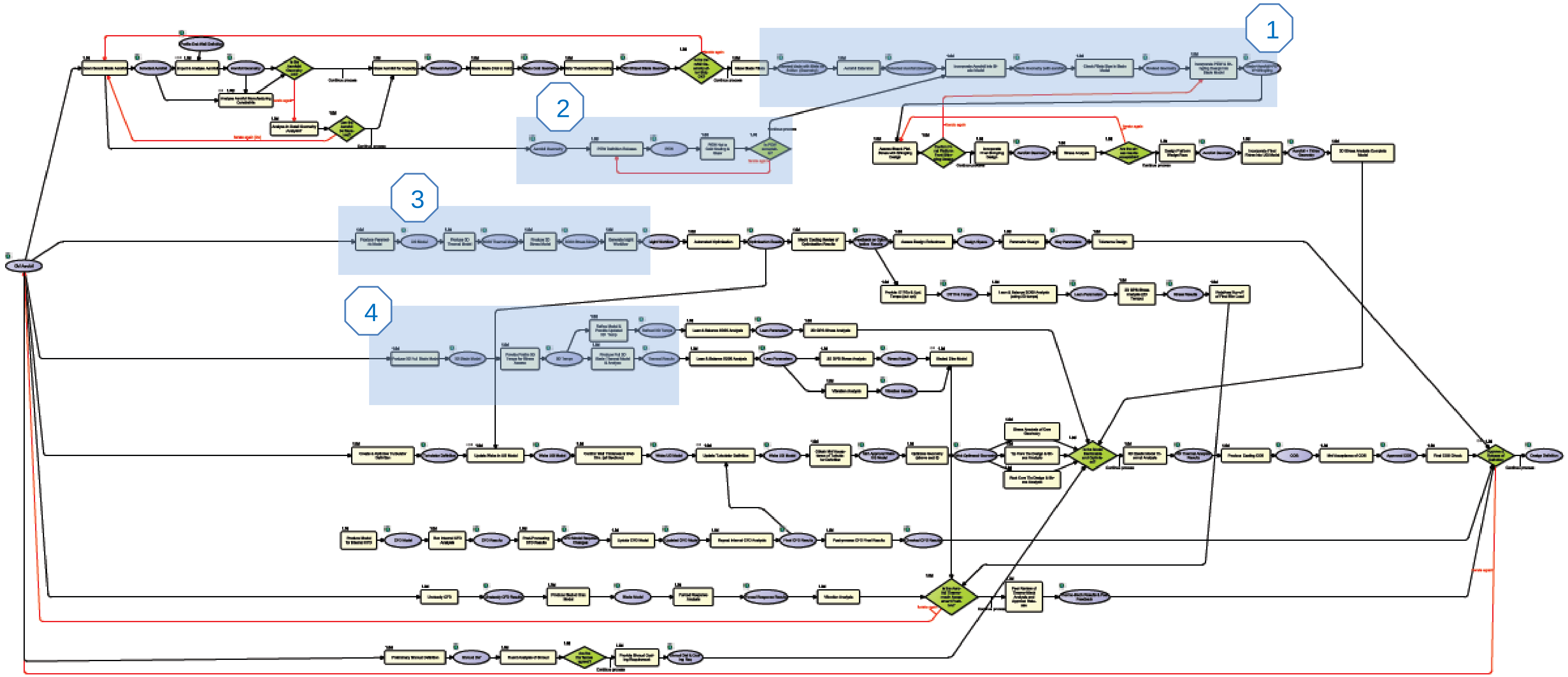


Figure 4-8: HPTB detail design process map

The VSM and DSM were constructed with the information collected. To validate both of the process representations, the VSM and DSM have been discussed with the activity owners in fifteen-minute sessions. One of the main conclusions that came out of these informal discussions was that in a company such as Rolls-Royce, where both IT and human resources are shared between different projects, the Elapsed Time metric loses its meaning. For example people who are assigned to more than one project would appear inefficient from the point of view of one project. In this case of shared resources, the ET only shows how much quicker a process could be if there would be dedicated resources to a project. However deciding on resource management would require analysing all the work streams of the projects worked in the company which is out of the scope of this research. It is also important to note that from a lean perspective, the time spent on another project is considered wasted time from the process point of view, which is not true from the company perspective. The ratio between PT and ET is presented to show the difference between the time charged on an activity and the time spent since the activity was launched. This ratio could be used for company level analysis to prioritise projects. The other ratio presented on the table is described as the activity efficiency and defined by the ratio between VAT and PT. This efficiency showed to be very useful when discussing the improvements potential and its priority, because it illustrates the potential improvement that can be achieved for each activity.

Once the VSM and the DSM were completed, a two hour workshop session was held involving the IPT members and design automation experts. The aim was to discuss the problems which the IPT members face and discuss possible solutions. Because a possible solution to many issues causing loss of time was automation, it was important to have the design automation experts to discuss the solution feasibility. The discussion was divided into two parts: one to discuss the VSM results and the other for DSM discussion. To conduct the VSM discussion, a structured approach, as shown in Figure 4-9, was used.

As shown in Figure 4-9, the VSM discussion was developed around activities with either high VAT or low VAT to PT ratio. The VAT to PT ratio, described as activity efficiency, indicates how much of the time charged for an activity is actually value added. The main objectives of this discussion were firstly to identify the activities which had high VAT or low efficiency, secondly to understand which of these activities would have a significant impact on the process lead time reduction if improved and thirdly to discuss the potential improvements.

Because the previously captured VSM and metrics were the basis of the discussion, it was important to get the VSM bought-off in advance from all participants to avoid non relevant discussions.

A first conclusion when analysing the results of this session was that the VSM, helped to create a common understanding and an appreciation for the challenges faced by the different team members. An example of improved process understanding was the realisation that a calendar week could be saved if the data exchange between aerodynamics and design would be done in reduced batch size.

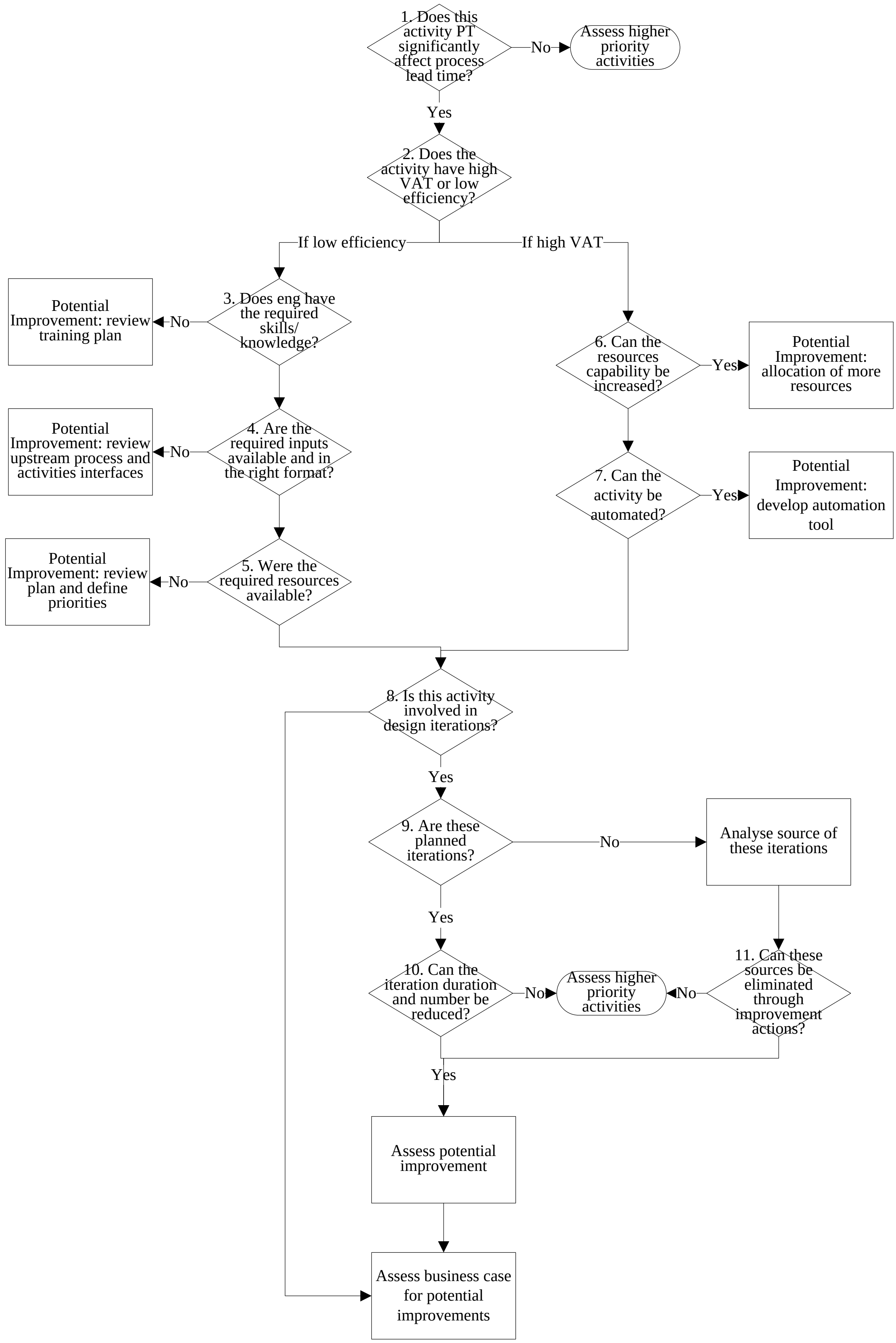


Figure 4-9: VSM Discussion Guideline

The aerodynamicists were releasing their results in batches following usual practice, but when they realised that a change of this practice could allow the designers to start their work earlier they agreed to release results in smaller batches as soon as they are available. It can thus be concluded that VSM discussion enhances communication among the IPT members. The VSM and respective discussion were also very useful to identify the waste sources during the process such as manual data handling, lack of communication, incompatible software, unsuitable data, etc.

Although the VSM is suitable to understand the process and the activities' efficiencies, a more suitable tool such as the DSM was used to analyse the iterative loops and the potential to merge activities. Analysing the DSM led to several conclusions. Firstly, as the DSM analysis only included the first and second activities stream as described above only iterations within these streams were captured and not larger iterative loops which could include these streams. Therefore the represented sub-processes appear fairly linear in the DSM.

A conclusion that was drawn from the DSM analysis was that some activities could be merged with significant benefit in terms of process time reduction. An example of this conclusion is illustrated by the two optimisation activities (manual and automated) which could be performed in one step if the automated optimisation would be improved to include more parameters.

Another conclusion that came from the DSM analysis was related with a long iterative loop which represents the blade fillets introduction. This design activity is crucial to achieve a good blade performance but is also very time consuming - approximately three months of processing time. The fillets design is followed by stress and aerodynamic checks. When analysing the DSM, the IPT members realized that if during the stress and aerodynamic checks the fillets design is not accepted the long task of designing the fillets would need to be repeated as well as all the following assessments. Analysing the DSM, the team planned interim checks that would avoid a complete redesign of the fillets by the end of the process.

All activities were discussed using the VSM and DSM material and the following improvements were identified:

(i) Improve software compatibility

(ii) Use of different types of optimisation merging two activities

(iii) Automation of data handling

(iv) Change of data exchange batch size between aerodynamics and design

(v) Better management of releasing new automation tools

(vi) Automation of parts of the design, introducing knowledge-based tools

(vii) Introduction of aerodynamic and stress standards or rules of thumb to analyse fillets design

(viii) Use of parametric application of thermal results on changed geometry

This workshop was held by the end of the seven months, when the author of this thesis left the Turbines SCU. Six-month after the workshop, several interviews have been conducted to understand which solutions have been implemented. These interviews were done face-to-face back in the Turbines SCU. One of the main curiosities found was that after six-months several people had changed roles. For example the IPT leader and the Quality Improvement leader that were key stakeholders of this research had moved to new positions at this time. Therefore the interviews were only held with the IPT members that were still in the same jobs. From these interviews it was possible to understand that not all the improvements have been implemented because other priorities took over these improvement activities. Discussing with the IPT members an estimate of the benefit for each of the non-implemented improvement was captured. With this information it was possible to analyse the achievable improvement that resulted from the VSM and DSM analysis.

The implemented improvement led to a process lead time reduction of 17%. The planned improvements were estimated to add a further 21%. The total recommended improvements would therefore introduce an overall lead time reduction of approximately 38% which corresponds to reduction of 500 hours in process lead time.

4.4. Case Study 1 Conclusions

This first case study was crucial to develop the EPI framework. Although the framework was initially based on the literature review, several improvements resulted from this industrial experience which strengthened the framework.

The first conclusion that came out of the framework was related to the stakeholders' analysis. The stakeholders' list for this case study only included the IPT members and the automation experts. It was concluded after the case study that other stakeholders should have been included, such as functional experts in the critical areas under analysis and programme management with an interest in improving this product development process. A senior stakeholder that could work as the sponsor of the improvement activity was missing in the analysis. If there had been a senior stakeholder sponsoring the improvement project with capability to "make the things happen", he or she could have given continuity to the project even if some people move jobs, and also could have ensured that all feasible and beneficial improvements were implemented and controlled.

The second conclusion achieved was related with the VSM construction. It was concluded that the VSM should be developed during the workshop with the stakeholders instead of being developed a priori. The main reason for this is to keep people engaged and motivated during the session which is crucial for the following steps of the process. With the process pre-prepared people feel that they are not adding much to the workshop session and lose the commitment.

The third conclusion is related to the interview process. Although interviews are targeted (i.e. focused directly on the case study topic) and insightful (i.e. providing perceived causal inferences and explanations) they have weaknesses (Yin, 2009). The interviews may be biased depending on the questions' and answers' quality, inaccurate or even a reflexion of what the interviewer wants to hear. It was therefore important to avoid these problems by comparing the information gathered with the project documentation, with direct observation for example in technical meetings and even discussing conclusions with the IPT leader.

The fourth conclusion raised was related with the development of knowledge-based tools or as previously called automation tools. It was concluded that the benefit and usefulness of these tools is proportional to the engagement of the users in their development. When the users are not engaged in the automation tool development, the tool may either actually not address the users' requirements or the users may perceive it this way because of the lack of engagement. In any case the willingness to change their work practice is drastically reduced. An additional conclusion that came up in the final workshop is that it is important to get feedback from the users on the newly available tool. It is essential to understand the difficulties the users may face and if possible to address them. A good communication system should be in place to make sure that the users are using the tools correctly and always obtain updated releases.

A fifth conclusion was raised concerning the communication within the IPT. The silos of expertise are efficient to create knowledge sharing within a function, but make the communication more complex between different functions within a project. During this case study, several IPT members acknowledged the lack of knowledge on the other team members' work. It was felt that the process understanding could be improved across the IPT. Additionally, it was verified that communication depends on co-location in the office; several users reported that communication with colleagues in the same office was significantly better than with other colleagues based in different buildings, even if in the same site. This conclusion is particularly relevant in a global company such as Rolls-Royce, where some work packages are split over several continents.

A sixth conclusion is related with customer awareness. In large companies such as Rolls-Royce, many people have little or no contact with the end customer. During the interviews the IPT members were asked who their customer was and in general they had difficulty to answer this question. Two issues justify their difficulty: firstly they are very far away from the end customer, i.e. the airline or airframer, that they do not identify this end customer as their customer. Secondly they do not identify the colleagues they send their outputs to as their customer either. Womack and Jones (1996) say that companies should only be focused on the end customer. They state that when identifying internal customers, a company may have good internal results but still fail to satisfy the end customer. Bearing these two points in mind, a different opinion is endorsed in this thesis. It is noted that even if the ultimate goal should be to satisfy the end customer, product developers should see their colleagues as

respectively internal suppliers or customers. This understanding of the internal customer can improve process efficiency due to an improved communication and understanding between the team members.

The seventh conclusion achieved was related with the time metrics. It was concluded that for companies operating with shared resources between projects, the key time metrics to analyse the process value added and waste in one process are the VAT and the PT. The ET loses the usefulness when considering a single process because it considers time spent on other projects as non value added.

An eighth conclusion concerns the difficulty of collecting the activity time data. During the interviews the IPT members expressed difficulty in providing values because the activity durations were subject to variation and uncertainty. Because product development cycles are much longer than manufacturing cycles, it is often impossible to collect representative samples. It was therefore concluded that a three point duration range should be captured to accommodate the activities duration variation and uncertainty.

A ninth conclusion is related with the time metrics and the entire process lead time. Some difficulty was experienced when analysing the impact of improving one activity on the overall process lead time. Firstly the improvement could not be directly translated to the process lead time unless the activity was on the process critical path, and secondly because the overall process lead time is only quantifiable if the process is relatively simple. It is important to note that even if an activity is not on the critical path, it uses resources while it is performed. Therefore if non-critical path activities duration is reduced, resources are released quicker to work on others activities. For a process with several parallel activities, iterative loops, or even with variation of the activities duration it is very difficult to calculate the process lead time. It was concluded that a process simulation tool with the ability for critical path analysis and statistical analysis would benefit this study.

A tenth conclusion is that the large amount of project work leaves the engineers little or no time for involvement in process improvement activities. As practice in Toyota (Morgan and Liker, 2006) and other companies allocating some time for process improvement would be beneficial to drive improvement projects such as this case study.

An eleventh conclusion is concerned with use of DSM. It was concluded that the DSM should be applied to the whole process instead of only to sub-streams. Since DSM is used to assess iterations some benefit was lost due to not capturing iteration loops which where external to the assessed work streams.

At this point it was also interesting to analyse how the identified improvements relate to the Lean Product Development Principles. This analysis was done using the lean principles defined by Morgan and Liker (2006) because these were found the most comprehensive set of Lean Product Development Principles reviewed in Chapter 2. Figure 4-10 shows which principles are addressed by the different improvement recommendations. The different colours show if the principle is addressed directly

(green) or indirectly (yellow). It is possible to conclude that each improvement addresses several lean product development principles.

The first principle forms the base of the entire case study. Defining the customer value and eliminating process waste was the objective of the VSM analysis, therefore all the solutions discussed aim to address this principle.

The second principle was not addressed because this case study was specifically focused on the detailed design phase. To address this principle a more complete analysis would be needed, discussing with the stakeholders which activities could be done in the preliminary design phase. The focus could be to simplify some of the calculations done in the detail design phase and perform them earlier when the design is still flexible and consequently design changes are still easy to accommodate. An exhaustive assessment including cost and manufacturing analyses, which is often carried out in later design phases, could be brought forward to preliminary design reducing the risk of late and expensive iterations.

The third principle which is focused on waste reduction is central to the entire study.

The fourth principle, focused on different types of standardisation, was partially addressed in most of the proposed improvements. However, only two of the three types of standardisation were addressed: the design and process standardisation. All of the automation improvements lead to the definition of a standard process that can be automatically repeated. On the other hand, knowledge-based tools, introducing automated rules and logic into the product development process, aim to achieve a design standardisation. A good example of this was the introduction of manufacturing constraints in a knowledge-based tool which was aimed to be used within the detailed design phase. This improvement is not listed in this chapter because it was already ongoing during this case study. The last type of standardisation, engineering skills standardisation, was judged to be achieved at a good level and therefore was not subject to improvement.

As for other principles, the fifth principle was not addressed because a whole engine development process analysis would be needed. In Rolls-Royce, and in most of the companies, there is a Chief Engineer per engine project. For a better analysis of this principle a higher level analysis at project level would have been necessary.

The sixth principle is addressed by most of the suggested improvements. For example creating rules of thumb with stress and aerodynamics constrains would improve the interfaces between the CDG, stress and aerodynamics groups. The only two improvements that do not address this principle are improvements focused on a single activity.

The seventh principle was not addressed in this specific process analysis because it was out of scope of this single process analysis and would require a higher level study.

The eighth principle has not been addressed if only external suppliers are considered. However as the author of this research suggests, the users should consider the person that sends their inputs as their internal supplier. If considered in this sense, the principle can be seen as addressed for internal suppliers because most of the improvements aim at better integration.

The ninth principle is addressed by the recommendation of knowledge capture.

	(i) Analysis of software compatibility	(ii) Analysis of the use of different types of optimisation merging two activities	(iii) Automation of data handling	(iv) Change of data exchange batch size between aerodynamics and design	(v) Improvement of management of releasing new automation tools	(vi) Automation of parts of the design, introducing knowledge-based tools	(vii) Introduction of aerodynamic and stress standards or rules of thumb to analyse fillets design	(viii) Analysis of parametric application of thermal results on changed geometry	(ix) Knowledge capture and communication with other IPTs
1. Establish customer-defined value to separate value-added from waste.	green	green	green	green	green	green	green	green	green
2. Front-load the product development process to explore thoroughly alternative solutions while there is maximum design space.									
3. Create a levelled product development process flow.	green	green	green	green	green	green	green	green	green
4. Utilise rigorous standardisation to reduce variation, and create flexibility and predictable outcomes.	green		green	green	green	green	green	green	green
5. Develop a Chief Engineer system to integrate development from start to finish.									
6. Organise to balance functional expertise and cross-functional integration.	green			green	green	green	green	green	green
7. Develop towering technical competence in all engineers.									
8. Fully integrate suppliers into product development system.	green			green	green	green	green	green	
9. Build in learning and continuous improvement.									green
10. Build a culture to support excellence and relentless improvement.									
11. Adapt technology to fit your people and process.	green		green		green				
12. Align your organisation through simple, visual communication.	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
13. Use powerful tools for standardisation and organisation learning.	green	green	green	green	green	green	green	green	green

Figure 4-10: Potential Improvements and Lean Principles Comparison

The tenth principle has not been discussed in this case study for the same reason given for the seventh principle.

The eleventh principle is an important principle to address in this analysis. This principle states that the technology should be developed to fit people and processes and not the other way around which is reflected in the conclusion about engagement of users in tool development, see above. A second critical point is that the tools should be developed to fit a waste-free process and not to adapt the process to the new tools.

The twelfth principle is indirectly addressed by the use of process map, VSM and DSM which led to identification of the improvements.

Finally, the thirteenth principle is addressed by all of the improvements. The first solution, for example, strives for tools standardisation; other improvements related to tools automation aim to support process standardisation.

The referencing of the suggested improvements against the lean principles shows that, although some principles have not been addressed by the suggested improvements because they were out of scope, the improvements led to a leaner product development process as defined in these principles.

4.5. Case Study 2: High Pressure Turbine Disc Architecture

This second case-study was developed during one year and aimed to analyse and improve the High Pressure Turbine Disc (HPTD) Architecture development process using an improved version of the framework used in the first case study.

The High Pressure Turbine Disc is classified as a critical part of a jet engine which means that the disc failure can lead to a hazardous effect on both the engine and the aircraft. The main function of the turbine disc is to hold the turbine blades and transfer the power extracted from the gas stream to the shaft. Considering the demanding load environment of the blade one can understand that the disc will be subjected to very high centrifugal loads exerted onto the disc firtree by the mass of the blades rotating at high speed (Rolls-Royce, 2005).

When negotiating a new engine project with the airlines and aircraft manufacturers, Rolls-Royce agrees to ensure a minimum life for parts before they have to be changed during overhaul. Normally this life is expressed as a number of cycles of the engine on the wing. If the disc life falls short of the agreed target, the engine life on the wing is reduced and therefore more maintenance interventions are needed, which may lead to Rolls-Royce paying heavy penalties.

Figure 4-11: High Pressure Turbine Disc (Rolls-Royce, 2005)

Figure 4-12: High Pressure Turbine Disc[3]

Currently the HPTD design process is very complex and time consuming. As in the HPTB case, the disc design is carried out by an integrated team working on concurrent activities. One of the differences from this case study to the previous one is that the HPTD development process involves engineers from different SCUs working on the design of a sub-system, instead of component design as in the blade case study. The team was constituted by engineers from Turbines and Rotatives SCUs, as well as other departments such as Air Systems (which is part of the Civil Aerospace CFBU); all working together to design both the disc and the operating environment. The term "disc architecture" is used to express that the disc is designed as part of the sub-system which includes the disc itself, the turbine blade and the air-system environment.

Figure 4-13: HPTD IPT Functional Areas

[3] http://www.shef.ac.uk/mecheng/phd/phd-studentships/idc/project2, , 2012-02-19

As in the first case study, the first step was to understand the team organisation and the team's main challenges (see Figure 4-14). For this effect, several informal discussions have been held with different stakeholders, such as functional users, functional experts and senior leadership. As previously mentioned, the quality of the disc architecture concept may have a direct impact on customer satisfaction, therefore senior leadership was very interested in optimising the way Rolls-Royce designs this architecture. The result of these informal discussions was the following list of problems:

(i) Very long disc life assessment lead time

(ii) Lack of process standardisation

(iii) Low availability of human resources

(iv) Too many time consuming manual activities

(v) Insufficient computing capability

This list of issues was identified in a general context, without any detailed analysis or any prioritisation. The only conclusion that one can take from these comments is that all these issues contribute to a non efficient disc development process and that consequently there is opportunity for improving the way the team designs the disc architecture. One consequence of a time consuming product development process is that it reduces the opportunity to analyse different concepts and therefore does not allow optimising and de-risking the selected design concept. This lack of optimisation could lead to a direct business impact materialised as customer dissatisfaction and cost related to increased maintenance. To reduce these risks a major improvement project was undertaken by the company. Part of this improvement project was the product development process analysis and improvement using the framework under development in this research.

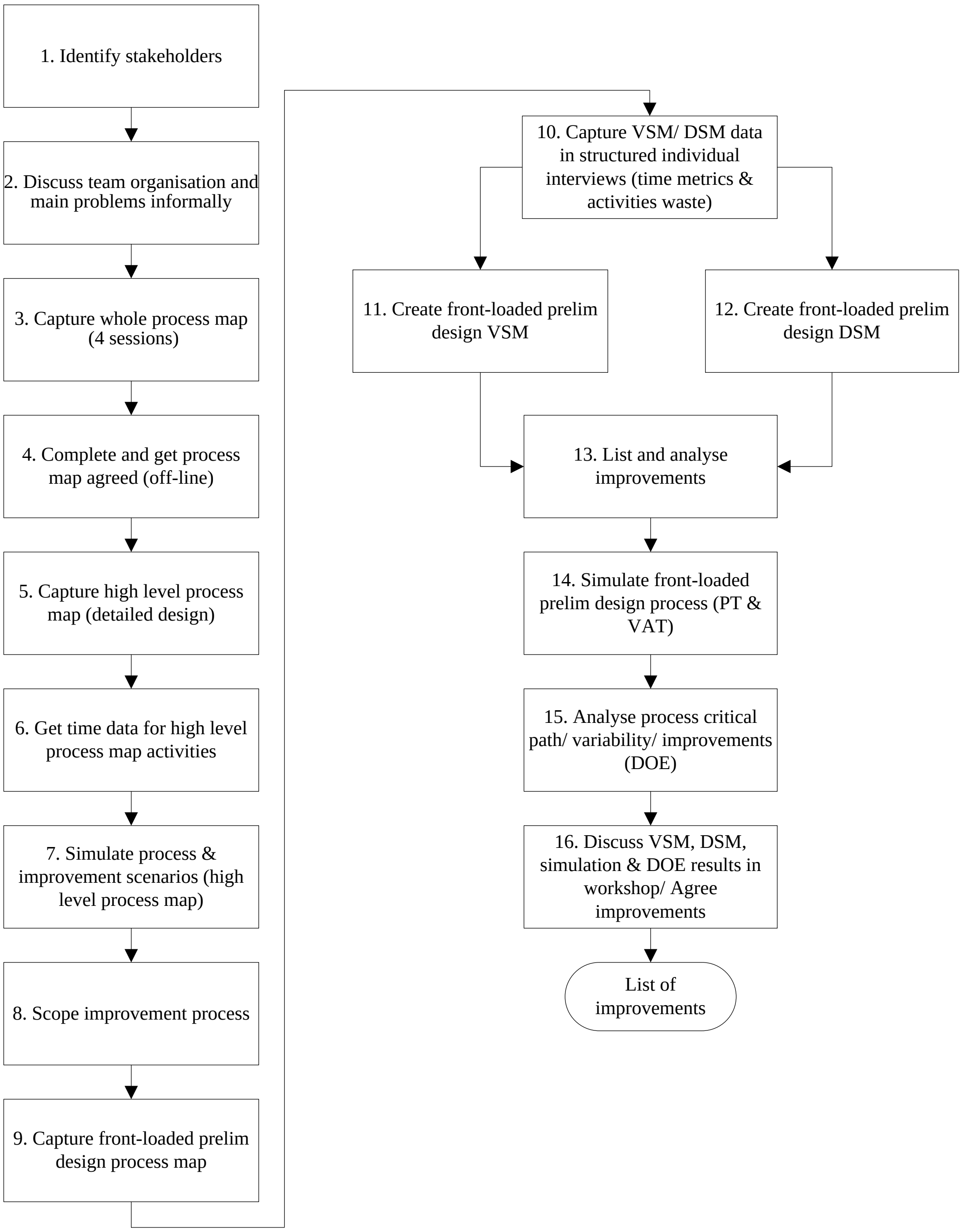


Figure 4-14: Case study 2 main steps

As described in the framework description chapter (Chapter 3) the first deliverable of the process analysis was the process map. Four workshop sessions were held to capture the entire disc architecture development process map from preliminary design to manufacturing. These sessions involved key cross-project functional specialists, the users and other stakeholders previously identified due to their interest in this process improvement process. Due to the criticality of this process and the conclusions drawn from the first case study, a senior stakeholder (Chief Engineer of Critical Parts) was identified as the sponsor of the project. The first two sessions were used to capture

the detailed design phase, the third was used to complete the process map focusing on manufacturing activities and finally the fourth was used to capture the preliminary design phase.

As noted in Chapter 3, these sessions were very interactive engaging the stakeholders and directing their discussions to focus on the process that was being generated in a white board with post-it notes. The first objective of the workshop was to capture all the activities, as well as their inputs and outputs. The interactions between activities were mainly added off-line in between the workshops through informal discussions. As shown in Figure 4-15, different post-it colours were used to distinguish between activities, inputs/ outputs and decision gates.

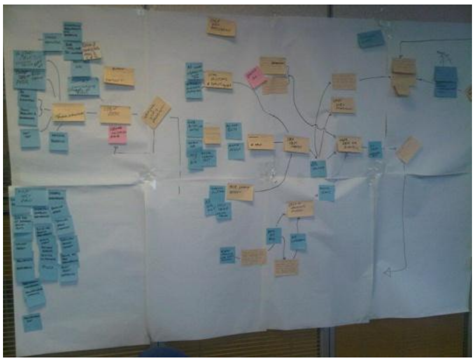


Figure 4-15: Process Map Capture on Workshop

In these workshops the disc architecture process map was captured for the first time in its entirety across SCUs. The development of this process map demonstrated its potential to improve communication and understanding of requirements across different functions and different departments which will ultimately lead to an overall improvement of the process. The discussion of the activities increased the stakeholders' awareness of the bigger picture which is the base for a better collaboration.

After these sessions the map was translated to a digital format using the software CAM and sent to all the stakeholders that were invited to comment on their areas of knowledge and validate the process. Due to the process size this buy-off step took two weeks and several iterations between the researcher and the stakeholders until everyone agreed with the captured process map.

The process map is shown in Figure 4-16. The figure is meant to show the complexity of the process map; however it is not shown in further detail for confidentiality reasons. Figure 4-17 displays a small cut-out of the process to show that activities are represented by rectangles, inputs/ outputs by ellipses and decision gates by diamond shaped boxes. In this case study an approach of separating the different functions' and departments' activities through swimlanes was used as shown below. The activities performed by each area - namely Design, CDG, Thermals, Stress, Materials and Process Modelling, Manufacturing, Critical Parts Lifing (CPL), Performance and Air Systems - were positioned in different swimlanes.

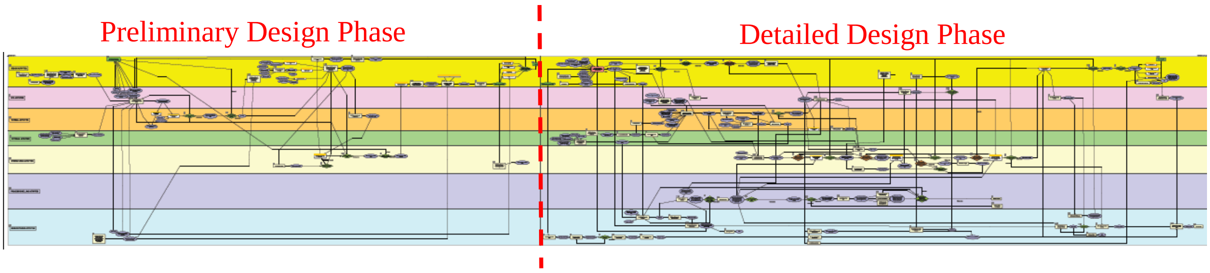


Figure 4-16: HP TD Process Map

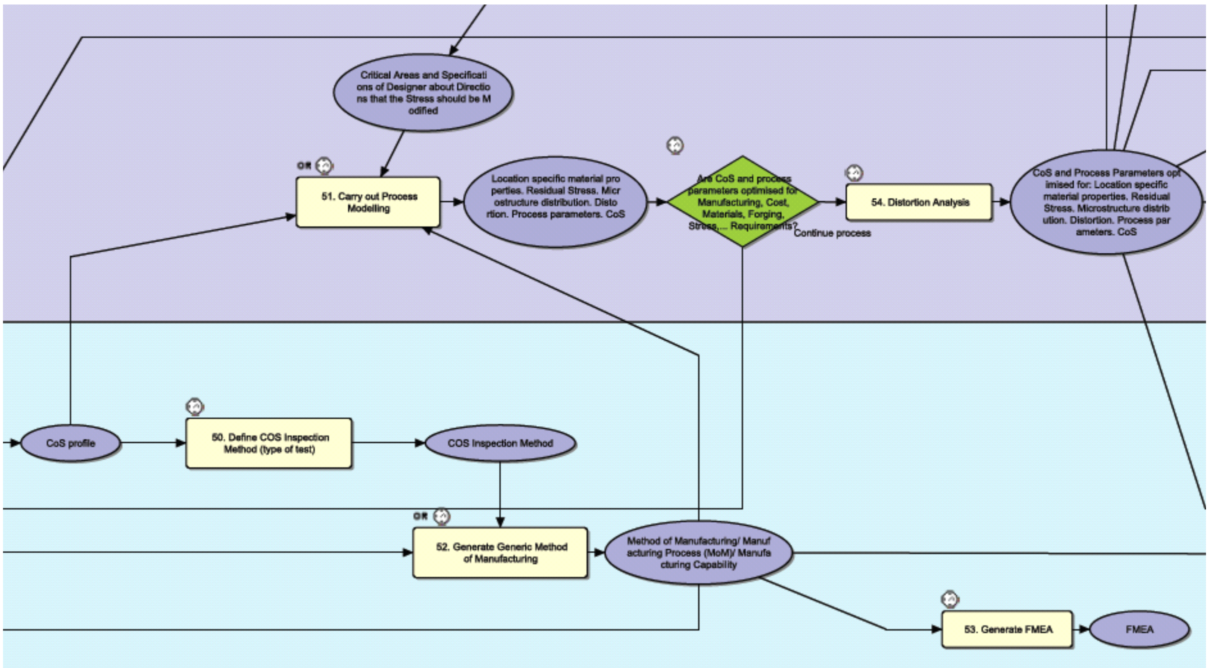


Figure 4-17: Process Map Snapshot

Figure 4-17 shows only two swimlanes populated by activities, inputs/ outputs and a decision gate. This experience of using swimlanes to represent a very complex product development process was considered not recommendable by the author of this thesis if the intent of map is to follow the value stream because it makes the quick visual interpretation of the flow more difficult. Some comments collected from the stakeholders when questioned about the usefulness of the swimlanes were for example “with swimlanes it is more difficult to follow the process” and “the map becomes even larger and more complex”. However, the author believes that swimlanes are useful for other type of analysis as for example to easily visualise which activities are performed by each functional area.

The captured process map showed the complexity of the disc architecture design which highlighted the need to better scope the potential for process improvement. In order to allow optimisation of the disc architecture concept it was believed that an iteration of detailed design would need to be turned around in 24 hours, which would represent a major reduction in process lead time. The 24 hours target was identified by the project sponsor based on what he thought would be necessary to assess several architecture concepts and not on what was feasible taking into consideration the current process. In

order to assess the feasibility of such an improvement, the detailed design phase of the captured process map was simplified to generate a high level VSM. The high level simplified process map is shown in Figure 4-18. A total of nine interviews were held with the users of each function to collect data for this high level VSM. These interviews were individual structured interviews as described in Section 3.1. Table 4-1 shows the VSM data for the different high level activities.

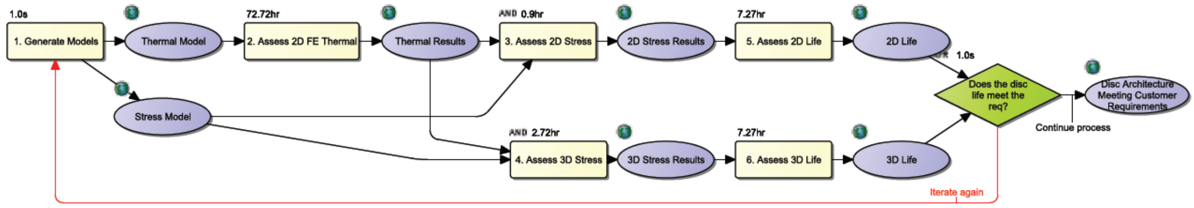


Figure 4-18: High Level Disc Architecture Process Map

Table 4-1: Time Data Collected on Interviews

Activity Name	PT [h]	MPT [h]	CPT [h]	VAT [h]	MVAT [h]	CVAT [h]	ε [%]
1. Generate Models	866	765	101	663	578	85	76.56
2. Assess 2D FE Thermal	169	89	80	118	45	73	69.82
3. Assess 2D Stress	91	90	1	43	42	1	47.25
4. Assess 3D Stress (sub-models)	53	50	3	18	15	3	33.96
5. Assess 2D Life	312	312	8	119	111	8	38.14
6. Assess 3D Life (sub-models)	297	289	8	119	111	8	40.07

Estimates of the duration of the high level activities were captured using three points (a minimum, most likely and maximum, as recommended in the first case study). However Table 4-1 only shows the most probable values for simplicity of the results representation. The PT and VAT were further broken down into time spent in computational (C) and manual (M) work. The time data was then used to perform a process simulation, as represented in Figure 4-18.

This preliminary simulation, using CAM as described in Chapter 3, was essential to scope the improvement project. No improvements were planned as part of this research for the first activity "Generate Models" because there was already a project in place aiming to improve this activity using models parameterisation. Using the time data collected and discussing the results of several simulation scenarios allowed understanding the improvement feasibility. These scenarios represented possible improvement options, such as automating all the manual activities, improving the IT

capability and eliminating waste from the process. Although other scenarios could have been simulated, these listed scenarios were identified in discussion with the project sponsor as fundamental changes that should be analysed. The simulated scenarios results are shown in Table 4-2.

Table 4-2: Simulation Scenarios Results

Simulation Scenarios	Sub-process Lead Time	Potential Improvement
Current Process (baseline)	572 h	-
Improving Entire Process (reducing PT to VAT)	280 h	-51%
Automating the Process (eliminating all manual work)	91 h	-84%
Automating the Process & Improving IT Capability (reducing VAT of computational work)	83 h	-86%

Discussing the results listed in Table 4-2 with the project sponsor it was agreed that the initial goal, of reducing the analysis time to from 572 hours to 24 hours, was too ambitious. It was concluded that even if the all of the waste was eliminated from the process, it would still take 280 hours. If on top of this all of the manual activities were automated (which would represent a major challenge in terms of tool development) the process would still take 91 hours. This result shows that to be able to complete a fully automated process in 24 hours, the IT capability would need to be significantly improved. A 10% increase in IT capability was also simulated to generate an exchange rate which relates the IT capacity improvement to process lead time reduction. With this result it was possible to conclude that to achieve the ambitious goal the IT capability would need to be increased by a factor of four on top of all the above mentioned improvements.

Two main conclusions were drawn from the high level process simulation. Firstly the high current process lead time and the large efforts required to significantly reduce it showed that the potential to iterate the detailed design phase for design optimisation was limited. To minimise the risk of the disc design not meeting the customer requirements and subsequent redesign at a late design stage it was decided to front load the design and shift optimisation activities to an improved preliminary design phase. Secondly, it was decided that the target of 24 hours for one optimisation loop was too ambitious and should be increased to one week.

A workshop was held with the users of the disc architecture design team to define which activities should be included in the front loaded preliminary design phase and how they should be integrated into a new improved process. A process map was generated during the workshop defining what the process should look like and a gap analysis was developed to implement this process. Figure 4-19 shows the captured process map. To simplify the visual reading of the map the swimlane approach

was discarded. The preliminary design process includes all the activities from the geometry generation to disc life calculation. The activities were broken down to a level of detail in which each activity is done by a single person using a single tool.

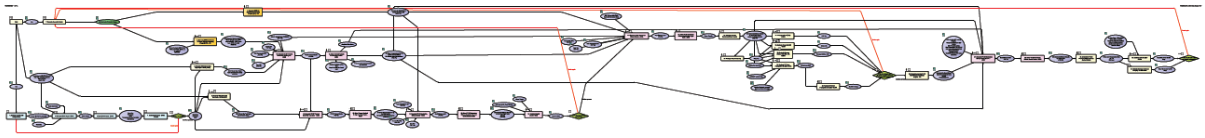


Figure 4-19: HPTD preliminary design process map

A Value Stream Map was then generated to quantify the preliminary design process efficiency and to identify the potential waste sources in the new process. As described above, individual interviews were carried out to capture the VSM data. Seven specialists were interviewed about the different activities. These specialists were representatives of the different functional areas: Air System, Stress, CPL, Thermals, Design and CDG. Appendix IV shows a table with most probable time metrics for the 26 activities included in the map. As above described, the minimum and maximum durations were also collected, as well as the time metrics for repeated activities in case of iterations.

The VSM which was created with the collected data is shown in Figure 4-20. A colour code was used to promote an easier understanding of the activities efficiencies (i.e. the ratio between VAT and PT). All the activities with efficiencies above 75% are coloured in green, activities with efficiencies between 50 and 75% are colour in amber and activities with efficiencies below 50% are coloured in red. As previously described and done in the first case study, two groups of activities were the focus of discussion when analysing the VSM: activities with low efficiency and the activities with high VAT.

Material collected in the individual and structured interviews was used to illustrate waste in the process. Sources of waste are shown as *kaizen* bursts in the VSM in Figure 4-21.

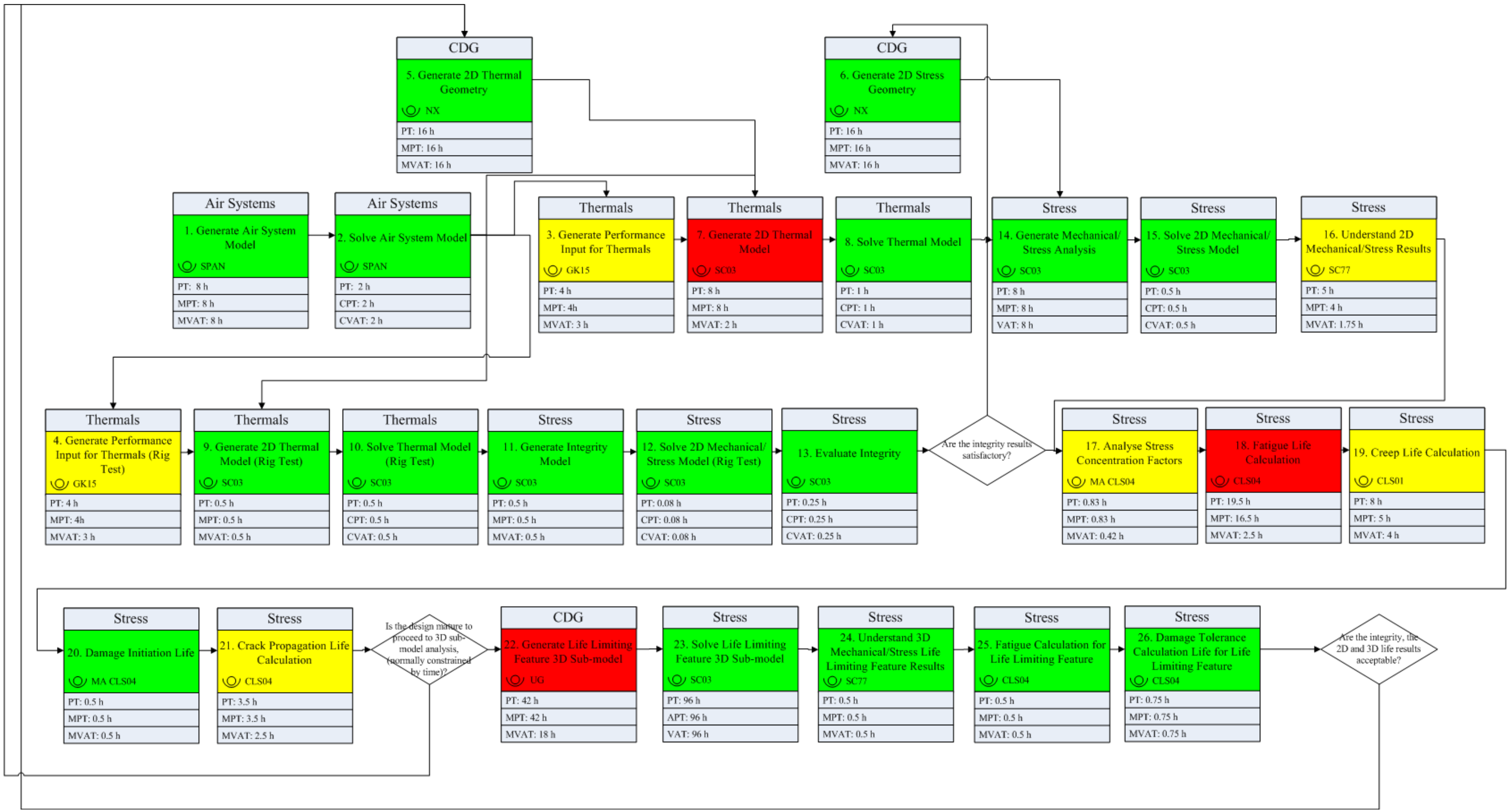


Figure 4-20: HPTD Value Stream Map

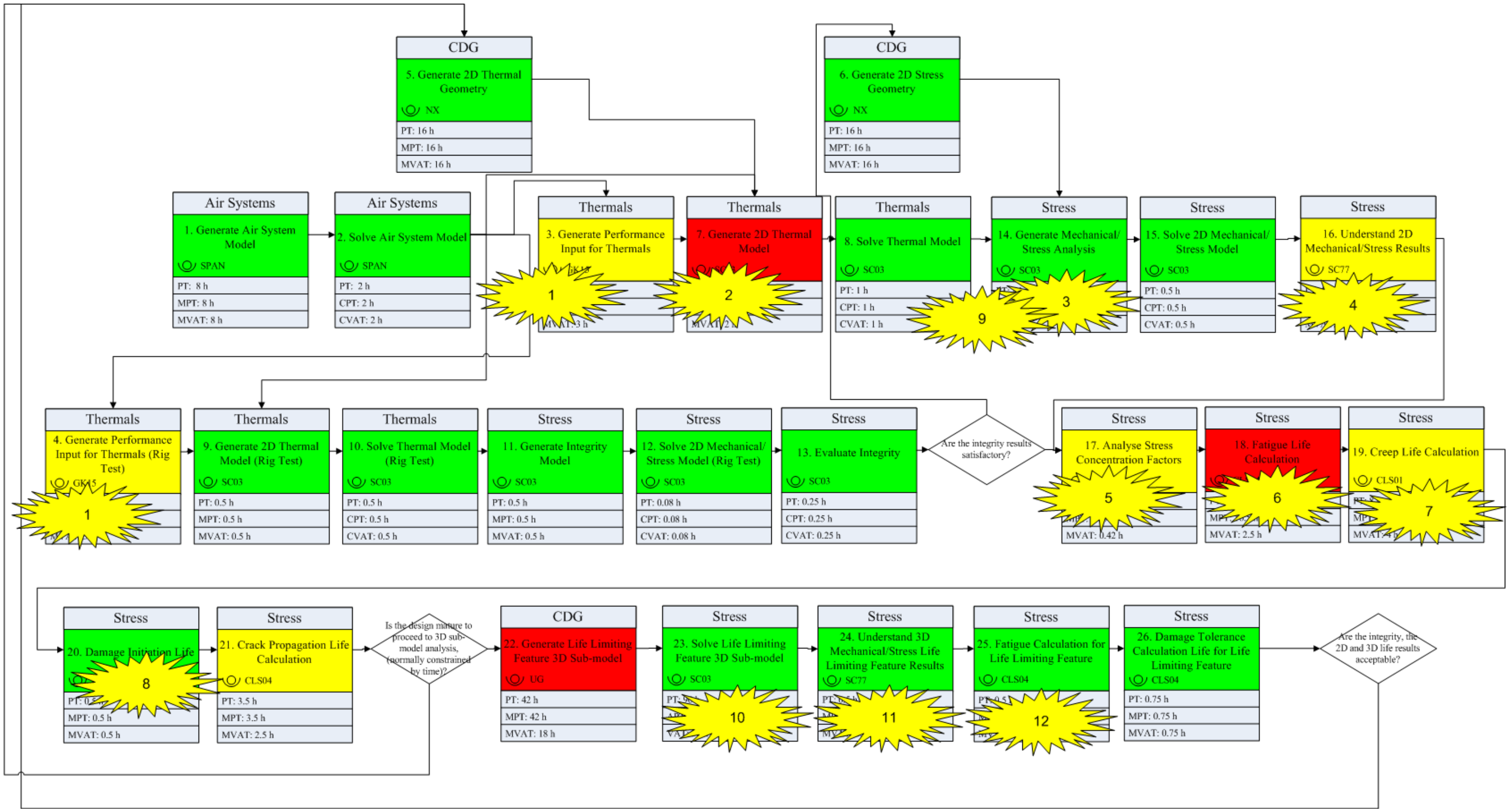


Figure 4-21: Kaizen bursts representation on the VSM

As shown in Figure 4-21, there are activities with high efficiency that were identified with a *kaizen* burst. This *kaizen* means that VAT is high and the users identified potential improvements. From the VSM analysis and the previous interviews with users, the following problems were identified:

Kaizen #	Problem
1	The performance data input file for thermal analysis is generated manually. The thermals' specialist noted that if automated this activity's PT could be reduced by 75%.
2	Application of boundary conditions on the thermal model is done manually. The automation of this activity, for example using tagging geometry techniques could reduce the PT by more than 90%.
3	High computational requirements due to the stress model complexity. In order to have an acceptable run time, the stress model needs to be simplified.
4	The 2D stress result analysis is performed manually and therefore time consuming and potentially subject to the analyst's interpretation. An automated solution had already been developed in other department but not adopted by the disc team.
5	Stress concentration values are read from curves in a plot. The analyst needs to interpret the result which can be time consuming as well as subjective – even the same analyst can read different values in different days.
6	50% of a fatigue life calculation is spent on manual data handling (such as data transfer between spreadsheets). The current process had already been automated by a sub-contractor company but it cannot be used due to IT incompatibility.
7	A large amount of creep life calculation is spent on manual data handling (such as data transfer between spreadsheets). The activity also leads to repeating material data generation that should only be done once if a good knowledge management system was in place.
8	30% of the damage initiation calculation time is spent in manual data handling. Lack of IT capability. Existing IT capability does not allow using the required software tools simultaneously.
9	Due to the long lead time of some activities, such as generating the thermal and stress models, analysts do not always work on the most updated geometry.

10	Very long computing time of the 3D stress model.
11	As on kaizen burst 4, the results analysis is performed manually on 3D stress results.
12	Inputs for 3D fatigue life calculation are introduced manually. To simplify the task, different analysts, are generating different macros to automate the manual process, leading to a lack of tools standardisation.

In order to analyse the iteration loops, a DSM was created (Figure 4-22) using the data collected in the structured individual interviews described above.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1. Generate Air System Model																										
2. Solve Air System Model	●																									
3. Generate Performance Input for Thermals																										
4. Generate Performance Input for Thermals (Rig Test)																										
5. Generate 2D Thermal Geometry											●											●				●
6. Generate 2D Stress Geometry											●											●				●
7. Generate 2D Thermal Model	●	●	●		●																					
8. Solve Thermal Model	●	●	●		●		●																			
9. Generate 2D Thermal Model (Rig Test)	●	●		●	●																					
10. Solve Thermal Model (Rig Test)	●	●			●				●																	
11. Generate Integrity Model	●	●		●	●	●			●	●																
12. Solve 2D Mechanical/ Stress Model (Rig Test)	●	●		●	●	●			●	●	●															
13. Evaluate Integrity	●	●		●	●	●			●	●	●	●														
14. Generate Mechanical/Stress Analysis	●	●	●		●	●	●	●																		
15. Solve 2D Mechanical/ Stress Model	●	●	●		●	●	●	●						●												
16. Understand 2D Mechanical/Stress Results	●	●	●		●	●	●	●						●	●											
17. Analyse Stress Concentration Factors																										
18. Fatigue Life Calculation	●	●	●		●	●	●	●						●	●	●	●									
19. Creep Life Calculation	●	●	●		●	●	●	●						●	●	●	●									
20. Damage Initiation Life Calculation	●	●	●		●	●	●	●						●	●	●	●									
21. Crack Propagation Life Calculation	●	●	●		●	●	●	●						●	●	●	●									
22. Generate Life Limiting Feature 3D Sub-model	●	●	●		●	●	●	●						●	●	●	●									
23. Solve Life Limiting Feature 3D Sub-model	●	●	●		●	●	●	●						●	●	●	●					●				
24. Understand 3D Mech/Stress Results	●	●	●		●	●	●	●						●	●	●	●					●	●			
25. Fatigue Calculation for Life Limiting Feature	●	●	●		●	●	●	●						●	●	●	●					●	●	●		
26. 3D Damage Tolerance Calculation Life	●	●	●		●	●	●	●						●	●	●	●					●	●	●		

Figure 4-22: Disc Architecture Design Process DSM (I)

From the DSM, one can see the three design loops and can discuss with the users what could be put in place to reduce the time impact of repeating any of these loops. During the discussion the users noted that extra dependencies existed that had previously not been captured. Even if the DSM represented in Figure 4-22 shows the activities dependencies, the DSM in Figure 4-23 shows these extra dependencies. The dependencies are not related to exchange of inputs/outputs, but they mean that the users do not start some activities before completing other activities, due to time considerations. For example, the users only start the life analysis stream after completing the integrity assessment stream,

even if there are no inputs required from integrity to life assessments. They justified that the life assessment is time consuming and therefore only done when they have an acceptable concept from the integrity point of view. With this approach they are not wasting time assessing unacceptable concepts; however they are extending the process lead time. This discussion helped to concluded that the ultimate goal of this process analysis, of significantly reducing the process lead time, would eliminate these dependencies. Once the activities' duration is significantly reduced, the users will not wait to start lengthy activities such as the life assessment. Moreover in an ideal completely automated process, both assessments could occur in parallel.

It was concluded from this DSM analysis that a new decision point, capturing the decision to go ahead with the lengthy life assessment stream, should be added in the process map (Figure 4-18).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1. Generate Air System Model																										
2. Solve Air System Model	●																									
3. Generate Performance Input for Thermals																										
4. Generate Performance Input for Thermals (Rig Test)																										
5. Generate 2D Thermal Geometry											●											●				●
6. Generate 2D Stress Geometry											●											●				●
7. Generate 2D Thermal Model	●	●	●		●																					
8. Solve Thermal Model	●	●	●		●		●																			
9. Generate 2D Thermal Model (Rig Test)	●	●		●	●																					
10. Solve Thermal Model (Rig Test)	●	●			●				●																	
11. Generate Integrity Model	●	●		●	●	●			●	●																
12. Solve 2D Mechanical/ Stress Model (Rig Test)	●	●		●	●	●			●	●	●															
13. Evaluate Integrity	●	●		●	●	●			●	●	●	●														
14. Generate Mechanical/Stress Analysis	●	●	●	●	●	●	●	●	●	●	●	●	●													
15. Solve 2D Mechanical/ Stress Model	●	●	●	●	●	●	●	●	●	●	●	●	●	●												
16. Understand 2D Mechanical/Stress Results	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●											
17. Analyse Stress Concentration Factors																										
18. Fatigue Life Calculation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●									
19. Creep Life Calculation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●								
20. Damage Initiation Life Calculation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●							
21. Crack Propagation Life Calculation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●						
22. Generate Life Limiting Feature 3D Sub-model	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●					
23. Solve Life Limiting Feature 3D Sub-model	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●				
24. Understand 3D Mech/Stress Results	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			
25. Fatigue Calculation for Life Limiting Feature	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		
26. 3D Damage Tolerance Calculation Life	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		

Figure 4-23: Disc Architecture Design Process DSM (II)

Process simulation has been used to assess the total process efficiency and the potential lead time reduction achievable by addressing the problems identified. In order to compare the different possibilities, several scenarios have been simulated and analysed. Figure 4-24 shows the process lead time distribution resulting from the process simulation when considering the processing time data. These results have been generated by simulating the process 1000 times using a Monte Carlo approach. The results do not show a normal distribution, therefore the average lead time (17.2 days), the minimum (13.7 days) and the maximum (21.0 days) are going to be used for further analysis instead of the standard deviation. The average process lead is the average of 1000 runs of the Monte

Carlo simulation. Figure 4-24 shows that the results distribution are skewed, making it more probable for the process lead time to be less than the average. This is caused by the triangular distribution of the longest activity, the 3D fatigue calculation which relies on computational resource. While the expected and maximum durations are 4 and 5 days respectively, the minimum is 1 day. This is due to the limited availability of a computational cluster which is shared between different projects.

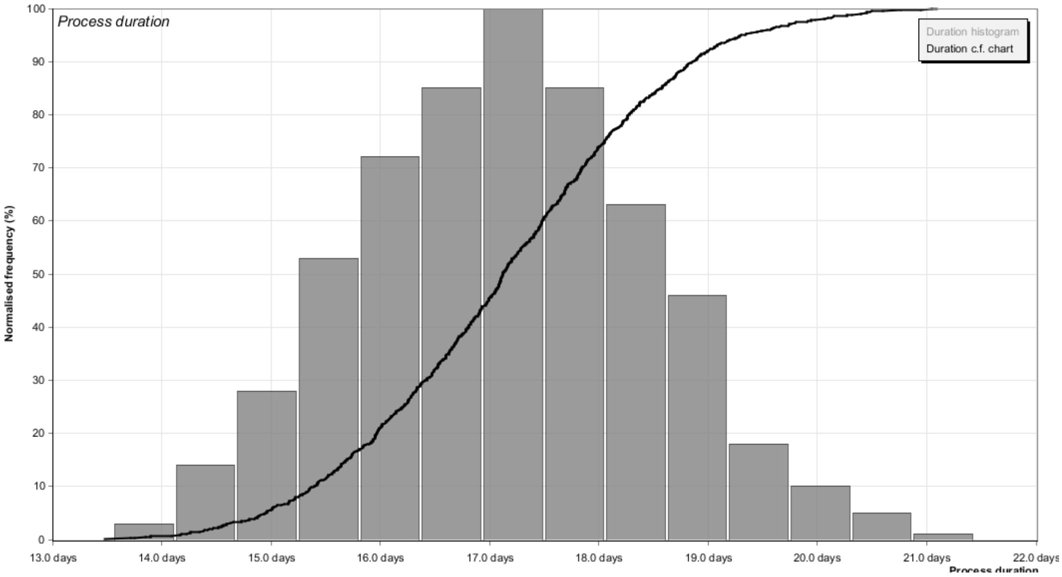


Figure 4-24: Simulation results for Processing Time Data

Figure 4-25 shows the distribution of the results when using VAT instead of the PT data in the simulation. From this simulation it is possible to conclude that by increasing the process efficiency (eliminating the non-value added time) the average process lead time can be reduced to 11.4 days, which means that 33% of the process lead time is non-value added time. However, the difference between the maximum and minimum of both scenarios is approximately the same. The fact that the variability was not reduced in the VAT simulation, shows that a significant part of the activity duration uncertainty is caused by uncertainty in the VAT. When discussing this fact with the users, it was understood that the uncertainty is mostly caused by variation in the complexity of geometry and analysis models, rather than by the non value added part of the activities.

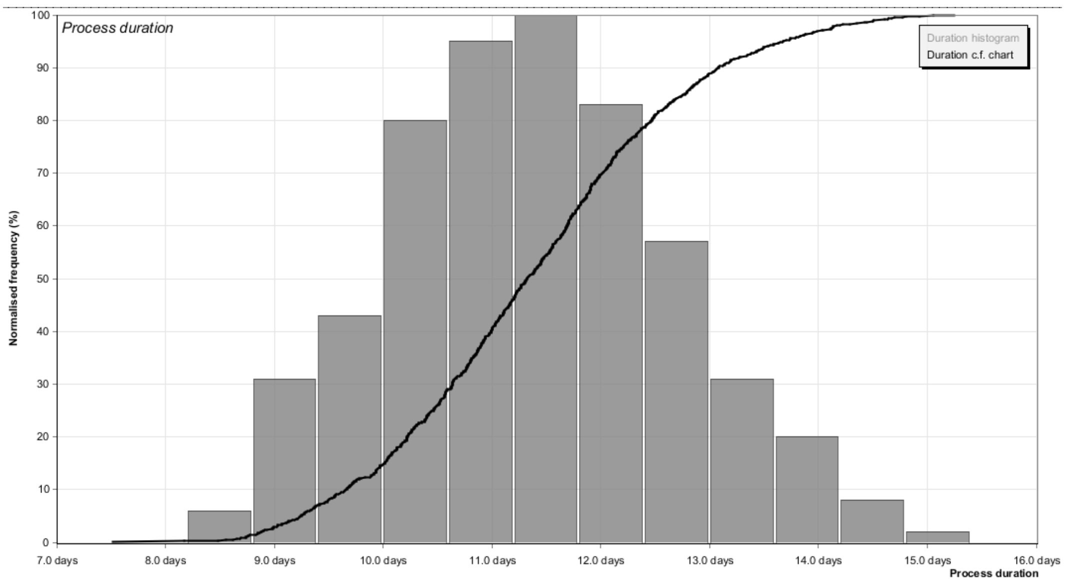


Figure 4-25: Simulation results for Value Added Time Data

One can also conclude from the simulation results which activities are in the process critical path and which have the biggest effect on the process lead time. Figure 4-26 shows the Gantt chart of one of the runs within short lead time (part of the first bar from the left in Figure 4-25). In Figure 4-26 the critical path activities are highlighted in green. Activities as for example activity 1, 7, 14, 18, 22 or 23, which lie on the critical path, would therefore have the biggest impact on the process lead time if improved.

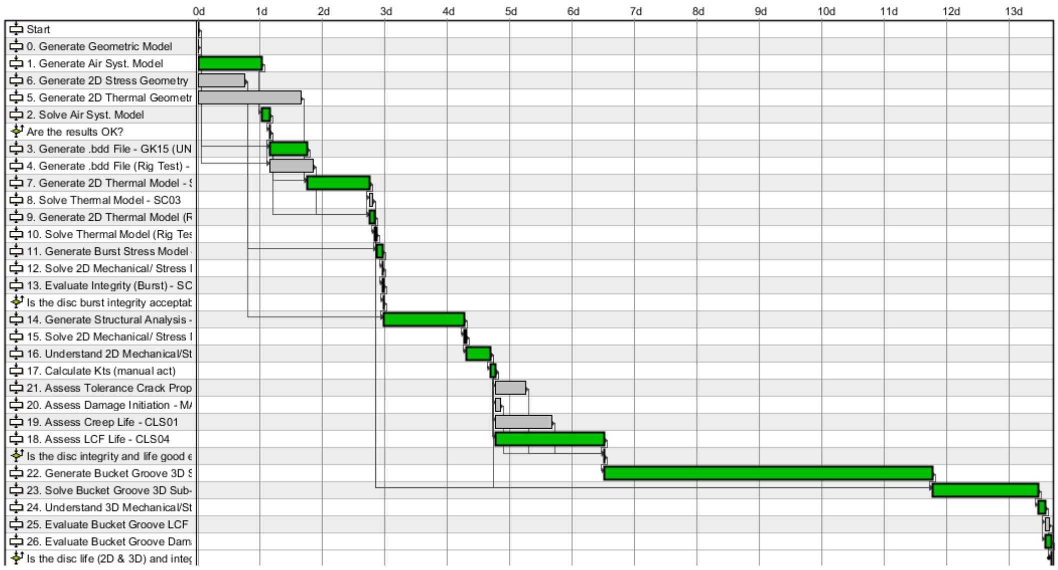


Figure 4-26: Gantt Chart of One Run within the Shortest Bar in Figure 4-25

One of the difficulties, when improving a process and analysing the improvement benefit on the process lead time, is that depending on the activity variability (where variability is defined as the difference between the maximum and the minimum activity duration) this activity may or may not be on the process critical path. Therefore it is important to understand the process sensitivity to these

activities. Figure 4-27 shows a different run within the same bar with short process lead time in Figure 4-25, where it can be seen that some activities on the critical path have changed. For example activities 1, 2 and 3 are on the critical path in Figure 4-26 but not in Figure 4-27. On the other hand, activity 5 is on the process critical path in Figure 4-27 run but not in Figure 4-26.

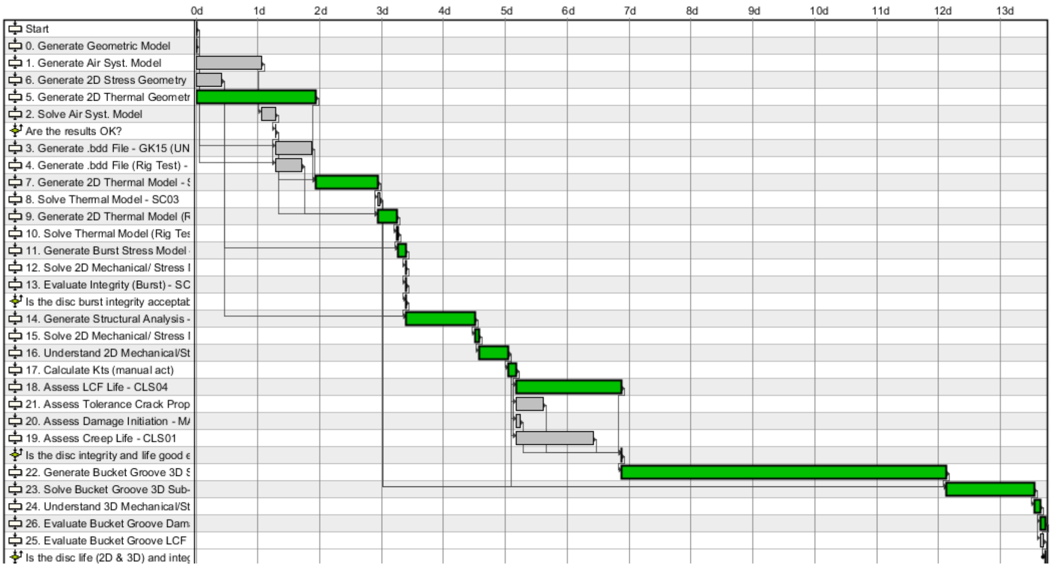


Figure 4-27: Gantt Chart of One Run within the Shortest Bar in Figure 4-25

Activities 22 and 23 always lie on the critical path and represent a significant part of the process lead time. Activity 23 is identified with a *kaizen* burst due to its long computational time and is recommended to be improved in the section below. Activity 22 is out of scope of this research because a different project is already in place to improve the parametric model generation.

In order to understand where improvements are most effective in the first part of the process (between activities 1 and 21), a Design of Experiment (DOE) was conducted. This part of the process was a priority because it includes the entire 2D analysis of the geometry and produces the 2D calculation of disc life. This 2D life is sensitive to different architecture concepts and is therefore the main parameter that this front loaded design phase was aiming to optimise.

In this part of the process, activities 1, 5, 6 and 14 are the most relevant due their relatively long PT. Considering that the main goal of this improvement activity was to reduce the process lead time with limited resources; it was useful to understand where the best place to invest was. The activities used in this study were activities 1, 5 and 14. Both activities 5 and 6 are related to generation of parametric geometry which should be out of scope of this project; however the thermal model requires the inclusion of additional geometry which is currently not covered by the geometry generation improvement project. Activity 5 has therefore been included in the investigation. Activity 14 is always on the critical path but has a shorter duration than activity 1 and 5.

Activities 1, 5 and 14 include significant amounts of manual work performed by one person. The aim of the DOE in this case study was to assess the effect on the process lead time of adding a second person to each of the three activities: 1, 5 or 14, and consequently halve the time of each activity.

A full factorial DOE with three factors (activities 1, 5 and 14) and two levels each was designed as showed in Table 4-3. The two levels represent the activity being performed by one or two people. The table shows the average process lead time (from activity 1to activity 21) for each scenario defined in each row.

Table 4-3: DOE Design and Monte Carlo Simulation Results

Run	Activity 1 (no. of people)	Activity 5 (no. of people)	Activity 14 (no. of people)	Process Lead-Time (days)
1	2	2	1	15.97
2	1	2	1	17.24
3	1	1	1	17.15
4	2	1	1	16.09
5	1	1	2	16.50
6	2	2	2	15.39
7	2	1	2	15.43
8	1	2	2	16.42

The results are illustrated in the cube plot in Figure 4-28 and the main effect plots in Figure 4-29. Figure 4-28 shows that, as expected, allocating three extra people to the process would offer the best results. However, Figure 4-29 shows the more relevant conclusion that the effect of adding an extra person to activity 5 is almost insignificant while the biggest benefit is obtained when adding an extra person to activity 1.

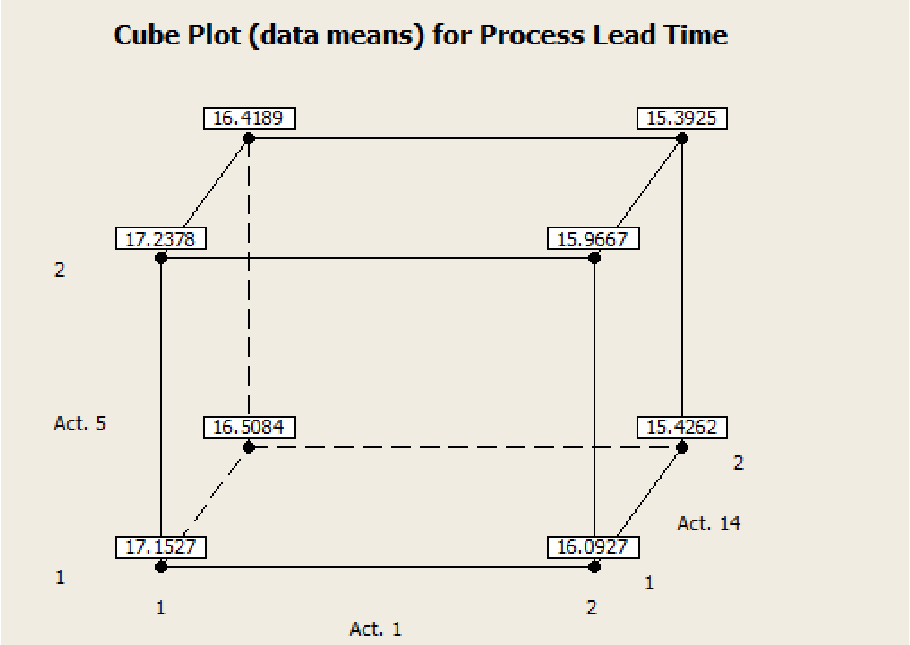


Figure 4-28: Cube Plot for Process Lead Time

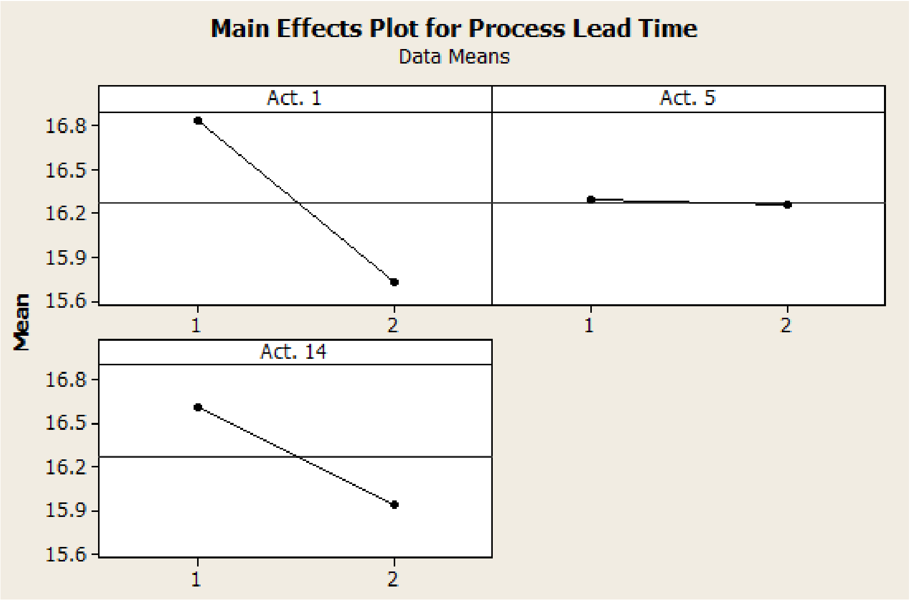


Figure 4-29: Main Effects Plot for Process Lead time

The VSM and the simulation results were used to support a final workshop that aimed to decide which improvements should be implemented. The workshop participants were the stakeholders described above. The VSM, the identified improvements, the simulation results and the level of effort to implement these improvements were the basis for discussion in this session. The list of improvements discussed in the workshop is presented in Table 4-4. The listed solutions in the table address *kaizen* burst issues on Figure 4-21. In this table, green on the right-end column means that the solution has

been implemented, yellow that the solution has been partially implemented and red that the solution has been deferred.

Table 4-4: Case Study 2 Solutions

Solution Description	Implementation status
1. Automate thermal input file generation. Agreed and implemented.	(green)
2. Tag geometry to reduce the boundary conditions application effort. Agreed and implemented.	(green)
3. Improve IT capability to avoid compromising the design quality on stress activities by replacing 32-bit machines with faster 64-bit machines. Agreed and implemented.	(green)
4. Automate results analysis within a workflow set up using optimisation software. Agreed and implemented.	(green)
5. Use of a new tool that was to be made available from a different improvement project. Agreed and planned to be implemented.	(green)
6. Automate data handling from LCF life assessment activity. Agreed and implemented.	(green)
7. a) Automate data handling from creep assessment activity. Agreed and implemented. b) Develop a database to improve creep material data knowledge management. Deferred due to other priorities.	(yellow)
8. Improve IT capability to speed-up analyses by replacing 32-bit machines with faster 64-bit machines. Agreed and implemented.	(green)
9. a) Use parametric model made available by other improvement project to ensure that models are easily applied to updated geometry. Agreed and implemented. b) Improve geometry control. Agreed and implemented.	(green)
10. a) Improve IT capability by running the model on a computer cluster. Deferred due to other priorities (concerned activity is part of the 3D assessment and not of the prioritised 2D life	(red)

calculation). b) Reduce the analysis flight time points. Rejected due to reduction of modelling accuracy resulting in increased design risk.	
11. Automate results analysis. Deferred due to other priorities (concerned activity is part of the 3D assessment and not of the prioritised 2D life calculation).	
12. Automate inputs introduction and outputs analysis. Deferred due to other priorities (concerned activity is part of the 3D assessment and not of the prioritised 2D life calculation).	

4.6. Case Study 2 Conclusions

The second case study was crucial for several reasons. Firstly, it allowed validating the EPI framework in a different context. The disc architecture design phase under analysis was not the detailed design phase as was the HP Turbine Blade in the first case study. The disc development was in a preliminary design phase, namely design stage 1 (see Figure 4-2). The conclusion that can be raised from this case study is that the EPI framework can be used for design phases 1, 2 and 3 within Rolls-Royce or similar development phases in other complex product development processes. The EPI framework applicability to the conceptual design phase (stage 0 on Figure 4-2) still needs to be analysed. The fuzziness of this initial phase, such as the lack of process definition, may generate some issues on the EPI framework application that should be analysed in future research.

Secondly, the case study helped to develop the use of process simulation within the framework. From the first case study it was concluded that simulation of the product development process could help assess the process efficiency and the effect of potential improvements. In this second case study this approach has been used and validated. As it is the case in product development, where simulation saves huge amounts of money by reducing the need of physical tests, product development process simulation can also save time and money in piloting real improvements in process improvement.

Thirdly, the case study allowed shaping a more effective way of collecting the VSM data. The main improvement on the data collection originated in this case study was the use of three points for activity duration (minimum, most probable and maximum values). This approach brought two main benefits: it helped the interviewees to quantify the durations and it allows taking the variability of the activity durations into account in the simulation. The use of the three points in the simulation showed that the critical path is dependent on the variation of the activity durations and therefore helps to assess the impact of improvements on the process lead time.

Fourthly, the case study allowed using the EPI framework at a sub-system level instead of a component level. In contrast to the first case study, where the IPT was constituted by people from the

same department working on one component, in this case study the team involved people from different departments developing not only the HP Turbine Disc but also the adjacent components and the operating environment. The main difference found in this second case study is that people from different departments have normally different work practices and the communication problems are more frequent. For both of these reasons capturing the process map and understanding the internal customers' needs was found to be very beneficial and was acknowledged to help achieve a common understanding by the different teams. Still in the communication aspect, considering that there was more complexity in terms of team and activities, the swimlane approach was not found to add any benefit in terms of process flow visualisation. The process map showing the activities allocated in swimlanes was however found to be useful to show the involvement of the different teams with the process and the cross-functional interfaces.

As per the first case study, it is also interesting here to reference the improvements identified to the Morgan and Liker (2006) Lean Product Development Principles. Figure 4-30 shows this alignment.

Since the main objective of this case study was to identify value and waste to speed up the product development process, the first lean product development principle (*Establish customer-defined value to separate value-added activity from waste)* is the basis for the whole study.

Figure 4-30 shows the second principle (*Front-load the product development process while there is maximum design space to explore alternative solutions thoroughly*) highlighted in yellow because none of the solutions was specifically focused on addressing this principle. However the whole purpose of this work that was to improve preliminary design in order to reduce the risks and long lead time of the entire product development process. The preliminary design was improved bringing forward some key activities and simultaneously improving activities that were part of this preliminary design phase as described in the previous sessions. Moreover, from the preliminary and detailed design process map analysis it was possible to understand which key activities were only done in the later phase of the design process. Once these activities were identified, their duration was reduced through the use of surrogate modelling, automation and IT capability improvement to allow their use in the early design phase.

The third principle (*Create a levelled product development process flow*) focused on eliminating waste to create a levelled product development process flow is also addressed by the improvement solutions identified. All of these solutions were focused on eliminating waste and reducing required non-value added activities from the disc architecture design process.

The fourth principle (*Utilise rigorous standardisation to reduce variation, and create flexibility and predictable outcomes*) was addressed by all of the automation improvements identified in the case study. As previously described, these automation improvements only address part of this principle, the design standardisation. Considering that there are standard automated ways to perform the design eliminates uncertainty and risks of error from the process. Moreover, identifying and agreeing the

process map, addresses the process standardisation that is one of the three aspects of this principle. The engineering skill set standardisation was not addressed by this case study which is the reason to have this principle highlighted in yellow in Figure 4-30.

As in the first case study, the fifth principle (*Develop the Chief Engineer System to integrate development from start to finish*) was not addressed. To address this principle a higher level analysis at project level would have been necessary.

The sixth principle (*Organise to balance functional expertise and cross-functional integration*) is addressed by several improvements solutions as highlighted in Figure 4-30. These solutions make the interfaces between two functional areas smoother, as for example "tagging geometry" will simplify the integration between designers and thermal analysts, reducing the amount of work needed to change the thermal model boundary conditions in a sequence of a geometry change.

The seventh principle (*Develop towering technical competence in all engineers*) was not addressed in this specific process analysis because it was out of scope of this single process analysis and would require a higher level study.

The eighth principle (*Fully integrate suppliers into the product development system*), if considered related to "internal suppliers", was addressed by several improvements that supported a better cross-functional integration.

The ninth principle (*Build in learning and continuous improvement*) is addressed by some of the solutions as highlighted in Figure 4-30. A clear example is solution 7b) which will eliminate an activity from the product development process.

The tenth principle (*Build a culture to support excellence and relentless improvement*) has not been discussed in this case study for the same reason given for the seventh principle.

The eleventh principle (*Adapt technology to fit your people and processes*) is a key principle for the same reasons identified in the conclusions of the first case study. Considering that several solutions address automation tools improvement and introduction, it is important to have in mind that these tools should be adapted to the process (if it is waste-free) and to the people that are going to use them.

The twelfth principle (*Align your organisation through simple, visual communication*) is indirectly addressed by all of the improvements as described in the first case study. However there are two solutions in this case study that directly address this principle in terms of the improvement in communication, as for example solution 9b).

Finally, the thirteenth principle (*Use powerful tools for standardisation and organisation learning*) is addressed by several solutions as for example the automation improvements as represented in Figure 4-30.

The analysis of the improvement solutions against the lean product development principles leads to two conclusions. Firstly, one can conclude that the improvements discussed lead to a leaner product

development process and secondly, that to address some of the product development principles a different level of improvement process is required.

	1	2	3	4	5	6	7 a)	7 b)	8	9 a)	9 b)	10	11	12
1. Establish customer-defined value to separate value-added from waste.														
2. Front-load the product development process to explore thoroughly alternative solutions while there is maximum design space.														
3. Create a levelled product development process flow.														
4. Utilise rigorous standardisation to reduce variation, and create flexibility and predictable outcomes.														
5. Develop a Chief Engineer system to integrate development from start to finish.														
6. Organise to balance functional expertise and cross-functional integration.														
7. Develop towering technical competence in all engineers.														
8. Fully integrate suppliers into product development system.														
9. Build in learning and continuous improvement.														
10. Build a culture to support excellence and relentless improvement.														
11. Adapt technology to fit your people and process.														
12. Align your organisation through simple, visual communication.														
13. Use powerful tools for standardisation and organisation learning.														

Figure 4-30: Lean Product Development Principles versus Identified Solutions

Chapter 5

Conclusions

5.1. Summary

This chapter contains the final conclusions of this research. It discusses the research questions presented in Chapter 1 as well as the research contribution to the academic and industrial worlds. This chapter concludes with the research limitations and the opportunities for further research in this topic.

From the literature review it was concluded that the application of lean principles is the recommended approach to improve product development processes. However, from this review it was also clear that the application of lean tools and methods in product development was not sufficiently explored. The main gap was the lack of industrial case studies to illustrate how to improve product development processes using lean principles.

Two examples of industrial application were found at the time of this research (Morgan and Liker, 2011; Baker, 2011), however both examples were developed at a company level which means that the authors did not detail the necessary changes to improve product development processes. As both levels of improvement, company and process level, are important and necessary, this research was focused on the most detailed approach, with which companies can improve their product development processes for complex products.

From the literature review it was also clear that due to its complex, uncertain and iterative behaviour, product development would need lean tools adaptation and/or additional tools to support process analysis and improvement in a robust way.

Bearing these gaps in mind, the author of this thesis developed a framework proposal to improve product development processes, the Engineering Processes Improvement (EPI) framework. The ultimate goal is to use the EPI framework to achieve leaner product development processes, which

means efficient and waste-free processes. Improving product development processes will give companies the opportunity to reduce the time to introduce new products in the market; moreover it will allow optimising and de-risking products in early stages of the product development.

The EPI framework is mainly based on combined methods to improve product development processes. These methods, VSM, DSM and process simulation, have different origins and had to be adjusted to be used together in a product development environment. For example, VSM has been proven to be very valuable to improve manufacturing processes. However, as described in Chapter 2, product development processes are significantly different from manufacturing processes. Because complex products are developed through concurrent activities performed in parallel by multi-functional teams, the development processes are very complex and iterative. Another additional difficulty is that, in opposition to manufacturing where one can follow the physical flow of material and identify waste, the flow in product development is mainly constituted by information which is stored in computers and in engineers' minds and therefore difficult to follow. To follow the flow in product development requires an important engagement of the team members involved in the process.

The team members are also essential to identify waste. Likewise in manufacturing, waste in product development is any activity that consumes resources and does not add value to the end customer. However, in product development there are activities that do not add value but reduce the risk of the design and should be undertaken. In product development, one cannot say that all re-work is waste as is the case in manufacturing, because products are optimised through design iterations which could be classified as re-work. However, there is also re-work in product development that clearly is waste, as for example repeated activities caused by lack of requirements understanding or lack of standardisation.

Additionally, the activities' duration capture in product development is a challenge. In manufacturing, one can follow the flow with a stopwatch and measure each activity's duration, which is often measured in seconds or minutes. In product development processes, activities duration can be several hours or days and subject to high uncertainty.

Because the internal requirements in product developments are not as clearly defined as in manufacturing, the author believes that it is essential and even more important than in manufacturing to identify and communicate with the internal customer in product development. It was shown in the application of VSM in the industrial environment that an understanding of the requirements of the internal customers could have led to a significant reduction in process lead time.

For all the aforementioned reasons, although very useful, VSM on its own was found to be insufficient to analyse product development processes. For example, the complexity and dependencies of activities are difficult to capture and optimise with the map; due to the concurrent activities and its uncertainty it is difficult to calculate the process lead time and to understand the benefit of potential

improvements in the process. To overcome these issues, the use of DSM and process simulation has been added to the EPI framework.

The DSM has shown to be useful not only to visualise and manage iteration loops, but also to understand the activities' dependencies. With a better understanding of the activities' dependencies it was possible to assess which activities could be performed earlier in the process to front-load the product development and consequently reduce the risk for late and expensive re-designs. Additionally, process simulation proved to be useful to understand the process duration and the effect of modifications in the process considering the activities duration uncertainty.

As described in Chapter 4, the EPI framework was validated in this research in two industrial case studies. Both case studies were developed in one of the major jet engines manufacturers, Rolls-Royce (UK), with components of a complex jet engine as studying material. The first case study was focused on the High Pressure Turbine Blade development process and the second on the High Pressure Turbine Disc Architecture development process. The exploitation of EPI in a real industrial environment was critical to strengthen the framework. For example, it was essential to understand:

- The difficulty to collect data for a VSM in complex product development and to define the required time metrics for a simple process efficiency analysis.
- The necessary level of engagement of all stakeholders and the importance of having a senior empowered sponsor.
- Real examples of waste in product development such as formatting activities, activities duplication or misuse of tools due to lack of communication.
- The utility of supporting the VSM with DSM and process simulation.
- The real identification of improvements with the EPI framework.

5.2. A Wider Perspective

An additional conclusion that became evident during this research is that improvements at process level only lead to a partial improvement in the company's product development. Many decisions of organisational structures and resource allocation were out of scope in the case studies conducted at process level because they are taken at a company level. This was evident when comparing the case studies' improvements with the Lean product development principles as defined by Morgan and Liker (2006). Higher level improvements, as described by Baker (2011) and Morgan and Liker (2011), can be developed to address companies as a whole.

A similar activity has been developed in Rolls-Royce, in which the author had an opportunity to be involved in. The results of this parallel work included the development of Rolls-Royce product development principles as well as actions to improve the whole Rolls-Royce product development

system. As this author was only a member of the team involved in this higher level work, and for confidentiality reasons, this work is not described in detail in this thesis.

From the work developed during this research and the experience gained working in two different product development companies (a small company dedicated to develop space qualified technologies and a large jet engine manufacturer), the author derives, in the following bullet points, a set of recommendations to help companies to address lean in product development:

- Companies should embrace a lean transformation both at company and process levels. Improving processes on its own may be limiting from the point of view that there are decisions taken at a company level and consequently cannot be addressed when improving individual processes. Examples of this are resource allocation and project prioritisation. However, since there is limited benefit of throwing extra engineers or IT capability at high priority but inefficient processes improvements at both levels are required.
- A product development process improvement should not be exclusively focused on reducing waste but also, and possibly more critical, on increasing value. A lean product development process may require more added-value activities, such as sensitivity analysis and robust design studies to improve the understanding of the design and reduce design risk.
- The value increase can also occur through more de-risk analysis in the early phases of the product development process, when changes in the concept are still feasible and cheap. The same activities performed later in the process may generate costly design iterations. In the case studies (Chapter 4), it was shown that the DSM proved to be useful to identify activities' dependencies and to understand which activities could be performed earlier in the process.
- A controversial idea that appears when discussing lean in product development is the conflict between standardisation and creativity. The author believes that both can be conciliated in lean product development. Lean should be seen as eliminating product development waste, such as time consuming manual work or re-work which can be done through product or process standardisation. However, creative activities that add value will be identified as such when the value stream is properly captured.
- To identify waste and value, the process users need to be engaged and understand why that process should be improved. If the users feel part of the solution they feel empowered to address their problems and motivated to support the improvement process which leads to a much better contribution.
- It is difficult to find time in users' diaries to support process improvement activities because often companies do not include process improvements in the resource plans. Toyota and some European companies include a percentage of time dedicated to business improvement in the

resource plan. This time allocation would benefit improvement activities such as the one described in this research.

- In large companies it is very difficult to keep the employees continuously considering the customer's needs. The engineers are often so far away from the customer that they have difficulty in identifying who their customer is. On the other hand, the customer is always a starting point in a lean system. To conciliate these two points, companies need to have an effective strategy to cascade customer requirements through the organisation. The author thinks that the end customer's requirements should be broken-down into internal customers' requirements through the organisation. Internal customers are closer to the engineers and a link is created to the end-customer. If the internal customers are treated in the same way as the end-customer, more efficient product development processes can be created due to a better understanding of the customer's needs.
- For engineers working in large complex product developments processes, it is difficult to keep a view of the "bigger picture". Another difficulty that engineering companies face is to achieve the balance between functional expertise and cross-functional integration. Toyota integrates the traditional silos through the Chief Engineer and with an *obeya* ("war room"). The author of this thesis believes that process maps, even if very complex, are powerful tools to improve system understanding, communication and integration.
- Technical excellence is fundamental to lean product development. However, management careers are seen by young engineers as a quicker route to recognition and senior positions. Companies should give incentives for engineers to develop in technical careers and have structures to recognise technical excellence.
- Complex product development processes rely on suppliers which can be internal (such as Rolls-Royce Supply Chain Units, see Chapter 4), industrial partners (external companies with co-located design engineers) and external (engineering sub-contractors). Integration of all these levels of suppliers in terms of requirements understanding, communication, as well as IT compatibility, is critical to achieve a lean product development process.

5.3. Research Questions Analysis

To recap, this thesis argues that product development processes can be improved using lean principles and lean tools. To study this hypothesis, two research questions have been identified:

Can tools such as Value Stream Map, Design Structure Matrix and Process Simulation be used together to improve complex product development processes? Do they need adaptation to be used in a complementary way in this particular environment?

How can these methods be applied successfully to improve real product development processes?

The first question was answered with the developed EPI framework. The development of this framework considered two challenges: firstly to adapt VSM to product development environments, secondly to overcome VSM weaknesses with the use of DSM and process simulation. It was concluded that these methodologies can be complementary and powerful when combined to improve product development processes.

The second question has been answered through the exploitation of the EPI framework in two industrial case studies. With these two case studies it was possible to understand the difficulties of using the framework and to adjust it to reduce the difficulty of getting the right information with the minimum effort.

5.4. Success Criteria

As described in Chapter 1, the aim of this research was not only to contribute to the academic knowledge but also to provide an approach that could be used in practice by companies to improve complex product development processes. The author believes that both objectives have been successfully achieved.

The research has been presented in two international conference publications (Pepe et al., 2010; Pepe et al., 2011), validating therefore the research contribution and a journal paper is work in process at the time of writing.

The EPI framework has been used in two industrial case studies in Rolls-Royce, validating the industrial contribution. Moreover it has been identified as a best practice to improve complex product development processes and to develop automated design systems. This approach has been disseminated globally in different Rolls-Royce’s sites.

5.5. Limitations

The framework developed in this research brings significant benefits to the industrial and academic world but still presents some limitations as presented in this section. The limitations are divided in two categories: framework and research limitations.

5.5.1. Framework Limitations

This research framework’s main limitation is related to the fact that it requires the use of different software tools to perform the different analyses. For example, the Value Stream Map analysis is performed using a different software tool than the process simulation. Moreover the process simulation results are post-processed using an additional software tool. As the required tools were not developed to be used for this type of analyses combination, their interfaces are often incompatible

which requires some work duplication. As often discussed during this thesis, work duplication should be eliminated and this is presented as an opportunity for future work (Section 5.6).

A second limitation identified is related with the time it takes to collect the required data from the process users, especially when competing with other day job activities the users are committed to. For a company, these improvement activities are an important but expensive investment for several reasons: the improvements implementation cost, the improvement facilitators time and the process stakeholders time. All these costs should be included in the improvement project business plan.

5.5.2. Research Limitations

In research terms, two limitations have been identified: one related with the product development phases and the other with the research industrial exploitation.

As previously discussed, the framework utilization was validated in preliminary and detailed design phases. Both phases presented defined product development processes. The framework utilisation on conceptual product development phases, which may be fuzzy, is possibly complicated because the entire framework is based on optimisation of a structured process. Further adaptation may be required to use the EPI framework to optimise conceptual design phases.

The framework was only exploited in a single aerospace company for two similar product development processes. Therefore, even if the author of this thesis foresees the utilisation of this framework outside of Rolls-Royce, the general applicability of the framework cannot be proven with this research. Additional case studies should also be addressed as potential future work opportunities.

5.6. Opportunities for Future Research

Several opportunities for future research arise from the Limitations section above. Firstly, the idea of developing a software tool or to improve an existing one to support the entire framework appears as a key opportunity for future work. Initial discussions have been held with the CAM developers and researchers from the University of Cambridge to further develop CAM's VSM capability. A prototype tool has been developed (see Appendix V) and discussed but further improvements are still needed. This prototype was developed to include the VSM graphical notation in CAM; however other features such as the VSM time metrics should also be developed. Future dialogues are also planned to discuss CAM limitations to support this framework utilisation. Having this in mind does not eliminate the idea of developing a new software tool to address the different EPI framework steps.

Secondly, further research topics can include the study of how in particular this framework and in general the lean product development principles can be applied to the conceptual product development where the concepts are still fluid and the process is fuzzy.

Thirdly, the EPI framework utilisation should be validated in other companies and industries to support the general use of the EPI framework.

Fourthly, considering the value identification one of the main difficulties faced during the data collection, further research should be done to establish a better definition for value in product development.

Finally, this framework was directly focused on reducing the product development process duration. Even if one of the goals is to reduce the activities' duration in order to be able to do robust design and consequently design products with more quality, the design quality was not accurately measured in this research. Further research can be foreseen to assess the impact of using the present framework on design quality. The design quality, ultimately aiming at reduced design risk, can possibly be quantified by the value generated in the product development process.

5.7. Conclusion

The importance of developing the right products with a minimum effort and maximum quality is increasing and becoming critical for companies to become more competitive. This thesis has introduced an approach to analyse product development processes, to identify their waste and simulate in a robust way the improvement implementation. In another words this thesis presents an approach to design product development processes with the same way companies design products. This framework has been applied and validated in two case studies in a major aerospace company, in which it is now being used has a best practice to improve industrial product development processes.

Appendices

Appendix I – Semi-structured Interview Guideline – Case Study 1

Appendix II – Initial Data Collection Sheet – Case Study 1

Appendix III – Time Metrics Collected through Interviews – Case Study 1

Appendix IV – Time Metrics Collected through Interviews – Case Study 2

Appendix V – VSM using CAM

Appendix I – Semi-structured Interview Guideline – Case Study 1

Interview Guide (VSM)

Carla Pepe | Lean Design in Product Development | February 2009

Introduction

This interview is designed specifically to characterize the HP XWB TB design. This study is part of an on-going research project involving Rolls-Royce, Instituto Superior Técnico (IST) de Lisboa and Massachusetts Institute of Technology (MIT). The research focus is the application of "lean" practices in product development. As a key person in the blade design, your cooperation is vital to the success of this work. The interview should take no more than 60 minutes to complete.

Please be candid and honest in your responses. We understand that you have concerns about confidentiality. The interview is intended to be anonymous and several measures will be taken to ensure that your answers will remain confidential. Only the researchers named below will have access to the information requested in this interview.

Research Team: Professor Dan Whitney (MIT), Professor Elsa Henriques (IST) and Carla Pepe (RR)

Background

1. Could you please describe your role/contribution in the product development process?
2. What product(s) are you attached to?
3. Who do you report?
4. Can you please describe your activities?

Value Stream Analysis

5. Do you have a plan/ check-list to all the steps taken is PD process?
6. What are the boundaries of your analysis?
7. What information do you start with? Who provides you with information, or whose work is necessary so that you can do your work?
8. Must their work be complete or can you start while they are still working as long as you have a good idea of what their final result will be?
9. Do you get the information you need soon enough and in good enough state of completion so that you can get your work done in time according to the schedule?
10. How often would you estimate that you have to do your work again and what are the reasons?
11. Who is your internal customer?
12. What do you give them?
13. How do you know that your activity is successfully finished?

14. How long after you have finished do you know that the work was satisfactory or that it met the customer requirements?
15. Do you have enough time to do each activity?
16. Do you think your work can be standardized? In terms of product/ design standardisation, process standardisation, engineering skill-set standardisation?

Tools/ Documentation

17. What tools do you use in your analyses?
18. What are your sources (consultation, literature, conferences)?

Wrap-up

19. Do you have any question about this research?

Are there any suggestions you would like to make? For example, what are possible ways to improve the process? Are there any missing steps? Is information created when it is needed? Are the right questions addressed at the start of the process? Are there enough group meetings, or are there too many? Do you know enough about what other people are doing?

Appendix II – Initial Data Collection Sheet – Case Study 1

Value Stream Analysis and Mapping Data Collection Sheet			
General		**Resources**	
Activity Name		Elapse Time (days)	
Responsible		In-process Time (hrs)	
Completion Criteria		Core Task Work Time (hrs)	
Success Criteria		Special Resources Requir.	
Other		Chance of Rework/ Time (%/hrs)	

Input #1		**Input #2**		**Input #3**	
Name		Name		Name	
Sender		Sender		Sender	
Transfer		Transfer		Transfer	
Quality	1 2 3 4 5 N/A	Quality	1 2 3 4 5 N/A	Quality	1 2 3 4 5 N/A
Utility	1 2 3 4 5 N/A	Utility	1 2 3 4 5 N/A	Utility	1 2 3 4 5 N/A
Format	1 2 3 4 5 N/A	Format	1 2 3 4 5 N/A	Format	1 2 3 4 5 N/A
Output #1		**Output #2**		**Output #3**	
Name		Name		Name	
Receiver		Receiver		Receiver	
Transfer		Transfer		Transfer	
Purpose		Purpose		Purpose	

Critical Drivers (metrics/attributes)
Context (interaction with other VSM)

Value			
Non Value Added Enabling Value Added 1-------------2------------- 3---------- -4--------------5			
Functional Performance	1 2 3 4 5 N/A	Enabling Activities	1 2 3 4 5 N/A
Definition of Processes	1 2 3 4 5 N/A	Cost/Schedule Savings	1 2 3 4 5 N/A
Reduction of Risk	1 2 3 4 5 N/A	Others	1 2 3 4 5 N/A
Form of Output	1 2 3 4 5 N/A		

Waste Sources	
Waste of Resources	
Waste of Time	
Waste of Quality	

Data Collection Sheet Legend	
Elapsed Time: days from authorization to proceed, to the completion of the activity **In-process Time:** hours of active work, as measured, for example, by time charged **Core Task Work Time:** time when core task is being worked, excluding setup, data retrieval, etc.)	**Special Resources Required:** any personnel, tools, or information that may distinguish the activity or provide constraint **Chance of Rework/Time:** percent chance of rework being required for (or because of) the activity, and the time associated with that rework
Input Criteria	
Quality 5 - Significantly more information than needed 4 - More information than needed 3 - Quality is just right 2 - Information is missing 1 - Information is inaccurate and/or untrustworthy	**Formatting** 5 - Ideal formatting for immediate use 4 - Fairly good formatting 3 - Acceptable formatting 2 - Some reformatting necessary 1 - Reformatting necessary
Utility 5 - Direct and critical contribution 4 - Important contribution 3 - Beneficial contribution 2 - Indirect contribution 1 - No contribution	**Transfer:** the method of transfer by which the input arrives to the activity **Output Purpose:** the product that the output is contributing to, or the goal of the activity
Critical Drivers: metrics that reveal the distinguishing nature and critical drivers of the process	
Context: interaction with other Value Streams (such as manufacturing and R&D), and any authority/review issues	
Value Criteria	
Functional Performance (FP) Functional performance of the end product to be delivered to the internal customer 5 - Direct specification of major FP parameters 4 - Direct specification of FP parameters 3 - Direct specification of minor FP parameters 2 - Indirect specification of FP parameters 1 - Possible specification of FP parameters	**Form of Output** The form of the output of this task (e.g. report, spreadsheet, build-to-package, etc.) 5 - Flows easily into program milestone 4 - Flows into milestone with some changes 3 - Flows easily into downstream task 2 - Flows into next task with some changes 1 - Flows into next task with major changes
Definition of Processes Definition of processes necessary to deliver the end product to the customer 5 - Direct specification of major downstream processes 4 - Direct specification of downstream processes 3 - Direct specification of minor downstream processes 2 - Indirect specification of downstream processes 1 - Possible specification of downstream processes	**Enabling Activities** Enabling other activities to occur (e.g., the other activity is required for completion of program) 5 - Major checkpoint preventing further work 4 - Moderate checkpoint in program 3 - Task necessary for continued work 2 - Necessary, but not especially time-sensitive 1 - Necessary, but not time sensitive
Reduction of Risk Reduction of risks and uncertainties associated with functional, process, or market areas 5 - Major risks greatly reduced or eliminated 4 - Significant reduction of risks 3 - Minor reduction of risks 2 - Indirect reduction of risks 1 - Possible reduction of risks	**Cost/Schedule Savings** Cost and/or schedule savings resulting from task execution (i.e., a core competency) 5 - Recognized as a core competency 4 - Major improvement over historical predecessor 3 - Improvement over historical predecessor 2 - Minor improvement over predecessor 1 - Possible improvement over predecessor
Waste Sources	
Waste of Resources: possible misuse or non-optimization of resources **Waste of Time:** possible cause for delays, waiting, unplanned rework **Waste of Quality:** possible cause for lack of quality, errors, defects **Waste of Opportunity:** possible oversight of personnel, tool, or technology potential **Info Waste:** overproduction, inventory, transportation, unnecessary movement, over-processing, transfers, scatter	

Appendix III – Time Metrics Collected through Interviews – Case Study 1

Activities (first and second streams)	Value-Added Time (VAT) [h]	Processing Time (PT) [h]	Elapsed Time (ET) [h]	Efficiency, ε [%] (VAT/PT)	PT/ET [%]
1. Base Case	4	7.6	7.6	53	100
2. Automated Optimisation	114	125.4	152	91	83
3. Results Analyse	7.6	7.6	22.8	100	33
4. Manual Optimisation	22.8	57	114	40	50
5. Blade Performance Analysis	3.5	3.5	38	100	9
6. Generate Data File	1	4	15.2	25	26
7. Import Data File	2	7.6	68.4	26	11
8. Blade Scaling	2	2	2	100	100
9. Aerofoil Change	5	5	5	100	100
10. Introduce Fillets	3	3	3	100	100
11. Incorporate Other Features	42.7	42.7	91.6	100	47
12. Adjust Fillets or Other Features	13.2	101.1	456	13	22
13. Elastic Isothermal Analysis	0.92	12.58	29.96	7	42
14. Elastic Analysis (2D Temperatures)	0.7	9.61	22.88	7	42

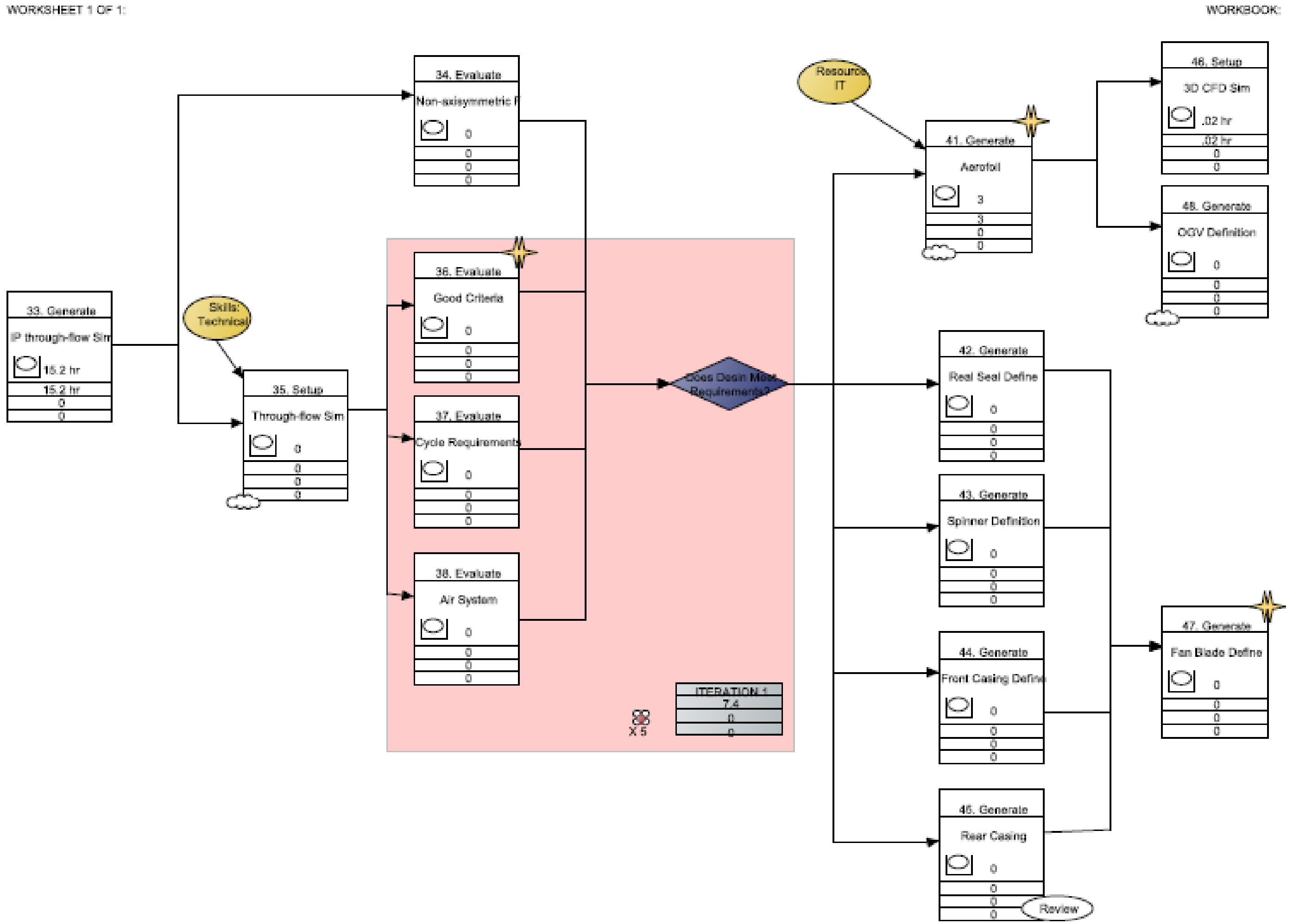
15. Elastic Analysis (3D Temperatures)	0.7	9.61	22.88	7	42
16. 3D Creep Analysis	1.67	22.88	54.47	7	42
17. 3D Creep to Failure Analysis	3.53	48.5	115.47	7	42
18. Stress Results Report	7.6	15.12	248.36	5	6
19. Total (number of hours)	235.92	484.78	1469.6	-	-

Appendix IV – Time Metrics Collected through Interviews – Case Study 2

Activity Name	PT [h]	MPT [h]	CPT [h]	VAT [h]	MVAT [h]	CVAT [h]	ε [%]
1. Generate Air System Model	8	8	0	8	8	0	100
2. Solve Air System Model	2	0	2	2	0	2	100
3. Generate Performance Input for Thermals	4	4	0	3	3	0	75
4. Generate Performance Input for Thermals (Rig Test)	4	4	0	3	3	0	75
5. Generate 2D Thermal Geometry	16	16	0	16	16	0	100
6. Generate 2D Stress Geometry	16	16	0	16	16	0	100
7. Generate 2D Thermal Model	8	8	0	2	2	0	25
8. Solve Thermal Model	1	0	1	1	0	1	100
9. Generate 2D Thermal Model (Rig Test)	0.5	0.5	0	0.5	0.5	0	100
10. Solve Thermal Model (Rig Test)	0.5	0	0.5	0.5	0	0.5	100
11. Generate Integrity Model	0.5	0.5	0	0.5	0.5	0	100
12. Solve 2D Mechanical/ Stress Model (Rig Test)	0.08	0	0.08	0.08	0	0.08	100
13. Evaluate Integrity	0.25	0	0.25	0.25	0	0.25	100
14. Generate Mechanical/Stress Analysis	8	8	0	8	8	0	100

Activity Name	PT [h]	MPT [h]	CPT [h]	VAT [h]	MVAT [h]	CVAT [h]	ε [%]
15. Solve 2D Mechanical/ Stress Model	0.5	0	0.5	0.5	0	0.5	100
16. Understand 2D Mechanical/Stress Results	5	4	1	2.75	1.75	1	55
17. Analyse Stress Concentration Factors	0.83	0.83	0	0.42	0.42	0	51
18. Fatigue Life Calculation	18.50	18.50	0	2.5	2.5	0	14
19. Creep Life Calculation	8	5	3	6	4	2	75
20. Damage Initiation Life Calculation	0.5	0.5	0	0.5	0.5	0	100
21. Crack Propagation Life Calculation	3.5	3.5	0	2.5	2.5	0	71
22. Generate Life Limiting Feature 3D Sub-model	42	42	0	18	18	0	43
23. Solve Life Limiting Feature 3D Sub-model	96	0	96	96	0	96	100
24. Understand 3D Mechanical/Stress Life Limiting Feature Results	0.5	0.5	0	0.5	0.5	0	100
25. Fatigue Calculation for Life Limiting Feature	0.5	0.5	0	0.5	0.5	0	100
26. Damage Tolerance Calculation Life for Life Limiting Feature	0.75	0.75	0	0.75	0.75	0	100

Appendix V – VSM using CAM



First Prototype of VSM using CAM (imaged supplied by EDC, Cambridge University researchers)

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