CHALMERS

Critical Success Factors for a Proactive Interaction Between Manufacturing and Product Development

A Qualitative Study in Swedish Aerospace Industry

Diploma work in the Master programme Quality and Operations Management

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Diploma work No. 173/2016
Department of Materials and Manufacturing Technology
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Gothenburg, Sweden 2016

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Cover:
GKN Aerospace splash screen.

Chalmers Reproservice
Gothenburg, Sweden 2016

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SUMMARY
This report presents a study made at the Centre of Excellence Design for Robustness at GKN Aerospace AB (GAS) in Trollhättan, Sweden. GAS is a first-tier supplier in the global aerospace industry and manufactures components within the main product areas of civil and military aircraft as well as space propulsion including nozzles and turbines. In the increasingly competitive global market the need to identify proactive working methods within product development and ways to measure these has increased.

The study has mainly addressed lessons learned and how these are brought back from the manufacturing department to the design function in order to provide a greater understanding of what manufacturing capabilities the process can handle. This research has been conducted as a case study, including thirteen interviews conducted at GAS and three benchmarking interviews in collaboration with SCA, SKF and Volvo Construction Equipment. The interviews together with a review of internal documentation and relevant literature showed that lessons learned are handled in different ways among the compared companies, that they all consider it to be an important improvement area but also that they have reached different performance levels.

It was concluded that the main critical success factors that contributed to a favourable project outcome were the choice of material and the extent of the interdepartmental collaboration in terms of working proximity between the manufacturing and design departments, the extent of the collaboration between them and the empowerment of the manufacturing function within the project group.

Five main recommendations were made in the study and arranged in short-, medium- and long-term according to their feasibility of implementation. First, GAS should standardize the team setup practices developed in project D to deal with design related failures. Second, GAS is advised to structure the spread of project-to-project learning around kick-off meetings, knowledge brokers, post-project reviews and lessons learned documents. Third, GAS is recommended to establish a core FMEA addressing the most critical factors for a specific manufacturing method where it can be universally applied as a starting point. Additionally, their current efforts in using QFD should be expanded to include all four houses of quality in order to fully connect the customer requirements to the process controls. Fourth, it is suggested to explore noise factors and sources of unwanted variation to deal with robustness failures. Lastly, several possibilities for improving the IT system were also mentioned, such as having a system bringing together all technical documentation in order to provide full traceability.

Keywords: Critical Success Factor, Knowledge Management, Lessons Learned, manufacturing capabilities, proactive product development, proactiveness, proactivity.

Acknowledgements

We would like to start by gratefully thanking Sören Knuts, our company supervisor at GKN Aerospace Sweden, for his continuous support and consideration throughout this project. Sören has been an invaluable asset for this research not only as a mentor and a guide but also as a vital source of knowledge and insights into an otherwise complex industrial environment by pointing towards potential avenues of research.

Next, we would like to thank our supervisor and examiner Peter Hammersberg for his constructive help that made us question assumptions and decisions, keep the academical relevance in the study as well as dedicating time to define the problem. Without his assistance the sharpness of the results in this thesis would not have been achieved and it would not have been possible to complete the work in the same way. Further, we hope that he will continue to inspire thesis workers in future projects in the same way that he did with us.

Additionally, we would like to send our deepest appreciation to all interviewees at GKN Aerospace Sweden, SCA, SKF and Volvo Construction Equipment that contributed to this study. One cannot take for granted their participation in an interview study where there is a potential risk that sensitive opinions might harm the interviewee. Therefore, we would like to thank each and every one for the trust in our work. The richness of the interviewees' descriptions and varied perspectives has contributed greatly to the outcome of this work.

Strong support is needed in a project like this to keep the energy and faith. Therefore, we would like to thank our families for the encouraging support throughout the whole work process. Without your feedback and helpful ideas this work would not have been possible to finish. We would explicitly like to mention Birgitta, Mårten, Víctor, Purificación, Rodrigo, Noelia, Logan and Ester as they have been our backbone and inspiration in finishing this work.

Lastly, we would also like to send dedicated appreciation to Vanajah Siva, Ida Gremyr and Julia Madrid for their assistance. Although they were not directly involved in the project as supervisors, they were willing to contribute with engaged and valuable input when we had topics to discuss.

Christian Månsson and Víctor Romera de la Fuente
Gothenburg, February 2016

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List of Acronyms

Concept	Explanation
AIM	Affinity-Interrelationship Method
CAD	Computer-Aided Design
CSF	Critical Success Factor
D-FMEA	Design Failure Mode and Effects Analysis
DFA	Design For Assembly
DFM	Design For Manufacturing
DFSS	Design For Six Sigma
DMADOV	Define, Measure, Analyze, Design, Optimize, Verify
DMADV	Define, Measure, Analyze, Design, Verify
DMAIC	Design, Measure, Analyze, Improve, Control
DP	Design Practice
DP online	System used to manage design practices at GAS
FDR	Formal Design Review
FMEA	Failure Mode and Effects Analysis
FRACAS	Failure Reporting, Analysis and Corrective Action System
GAN	GKN Aerospace Norway
GAS	GKN Aerospace Sweden
IDDOV	Identify, Define, Develop, Optimize, Verify
ISM	Interpretive Structural Modeling
KM	Knowledge Management
KPI	Key Performance Indicator
LL	Lessons Learned
NCR	Non-Conformance Report
NPD	New Product Development
OMS	Operational Management System
P-FMEA	Process Failure Mode and Effects Analysis
PDM	Production Data Management
PDP	Product Development Process
PLM	Product Lifecycle Management
PPAP	Production Part Approval Process
PPR	Post-Project Review
Q3	Quality metric for nonconformances that is corrected within the manufacturing department
Q4	Quality metric for nonconformances that need to be redesigned in the product development department
QFD	Quality Function Deployment
RDM	Robust Design Methodology
SAP	German Enterprise software system
SPC	Statistical Process Control
SME	Small and Medium-sized Enterprises
TDM	Technical Data Management
TEC	Turbine Exhaust Case
TQM	Total Quality Management
TRL	Technology Readiness Level
VCE	Volvo Construction Equipment
White book	Lessons Learned document

1 Introduction

This chapter will present the background of the study in order to make the content comprehensible, but also to create relevance for the findings, conclusions and recommendations. Further, this chapter will address the purpose, problem analysis, research questions and delimitations.

1.1 Background

GKN Plc. is a multinational corporation with several divisions including Driveline, Powder Metallurgy, Land Systems and Aerospace, mainly as a supplier offering system and parts solutions to the main actors within each field (GKN PLC, 2016). Among these the aerospace section is covered by GKN Aerospace, which is the division with equal focus on both military and civil customers. The global aerospace industry consists of a relatively small number of actors due to the high capital intensity and labour cost (Moller, 1999) and GKN Aerospace is a first tier supplier to several big companies being present in this market, such as Airbus, BAE Systems, Boeing, Bombardier and Lockheed Martin among others (GKN Aerospace, 2016). The focus for this thesis is GKN Aerospace Sweden AB, from here on denoted as GAS, located in Trollhättan, Sweden, which is the main plant for the development and production of products within the Aerospace Engine Systems area. In thesis, however, some references will be made to GKN Aerospace Norway, denoted as GAN, that is located in Kongsberg, Norway.

In the increasingly competitive global aerospace market, GAS is constantly striving towards improvements, and one step in this direction is to become more proactive in the early stages of product development. Their logic supporting this approach is the level of difficulty and related cost in making changes early in the product development process (PDP), compared to the later stages. Therefore, instead of having to address issues in the later production stages, where considerable costs occur, proactivity and problem solving in the early product development phases may save money in the long run before severe problems arise later on. In this study proactivity is to foresee problems and solve them before they appear or become severe issues.

By conducting this thesis work the aim is to contribute to a move towards this long-term goal. Today, there is a struggle in becoming more proactive and a measurement of proactivity is missing. Developing this measurement based on current best practices and by studying leading research is an important focus area for GAS in the near future.

Connected to the issue of being proactive, there is the constant struggle with internal communication between departments, especially in product development projects. This is often referred to as "throw-it-over-the-wall-syndrome" where one department creates something without consulting the other (Heim & Compton, 1992, p.72). By involving both departments in the proactivity efforts it should be possible to achieve considerable improvements concerning these issues.

In order for an improvement to prove manageable it needs to be measured, a statement attributed to both Deming and Drucker according to McAfee and Brynjolfsson (2012). Applied to the case of proactivity at GAS it was found that a specific metric, KPI, was needed in order to create a solid foundation for decision making, based on this criterion. By measuring using a KPI, the decision-making time would be reduced when assessing performance in product development stage gates or reviews. This could also be used as a way of assessing performance or following trends between projects, gates or reviews.

To be able to create a robuster product development environment, by enhancing proactivity efforts, it is essential to have the ability to identify and understand different sources of variation affecting the performance of a product or process (Gremyr et al, 2003). This emphasizes the importance of grounding knowledge and awareness of variation in relation to robust design, robustness and proactivity within the organization.

One way to illustrate the urgency to improve product development in terms of early changes and proactivity is through a framework presented in Wheelwright and Clark (1992, p.32) showing that changes early in the PDP are cheaper and easier to make compared to those later on. Another means to become more proactive and successful within product development is through Knowledge Management (KM). Lan (2014) argues that product development is becoming more and more collaborative, and therefore the need for having an effective system for knowledge sharing and management is crucial. Further, Lan (2014) states that several of GAS customers are actors who have worked with implementing KM systems, including Boeing, Rolls-Royce and NASA, which strengthens the motivation to improve in these aspects.

The importance of making efforts early in the PDP has been emphasized widely. Thomke and Fujimoto (2000, p.129) defined the concept as *"shifting the identification and solving of problems to earlier phases of a product development process"* and denoted it as front-loading. By front-loading it is possible to shorten lead-times and free up resources in later development stages. Further, efforts later on result in vastly higher costs than if changes and modelling can be made early on (Thomke & Fujimoto, 2000).

1.2 Purpose

The purpose of this thesis is to investigate the Critical Success Factors (CSF) in the evolution from a problematic project to a more successful one and how these can be used as a way of enhancing proactivity within robust product development.

1.3 Problem Analysis

A central concept in this thesis to consider in relation to product development, robust design and proactivity is Lessons Learned (LL). These learnings should be transferred between project teams (Goffin et al, 2010) in order to bring existing solutions and knowledge into continuous practice. At GAS these learnings should primarily be moving from the later stages of the PDP, primarily manufacturing, into the different design stages. By doing this, existing solutions are secured and brought back into practice. Design for manufacturing (DFM) is a concept where manufacturing experience is considered in the early stages of design to develop products using less resources (Poli, 2001), and thus a link to the LL concept could be looked into.

Apart from DFM, the Design for Six Sigma (DFSS) methodology is related to proactivity and robustness. Yang and El-Haik (2003) emphasize that DFSS should contribute to minimize the number of redesigns, and therefore that the design is right from the first time.

Robust design, robustness or Robust Design Methodology (RDM), has been defined by Hasenkamp et al (2009, p.645) as *"systematic efforts to achieve insensitivity of products or processes to sources of unwanted variation"*. The goal should be to disconnect the product or process from sources of variation, also known as noise factors (Bergman & Klefsjö, 2010). Achieving a higher degree of robustness means that noise factors have less impact on the performance, and thus improving it. By linking LL to robust design it is possible to reuse and apply existing solutions and knowledge to create a more robust product or process. Learnings acquired in diverse projects with different characteristics might be applicable, yet risking to get lost due to data overload. The goal with KM is to effectively link up individual knowledge to build social knowledge, by creating, storing, distributing and applying it to current and future problems (Shin et al. 2001).

The linkages between robust design, proactivity and LL are well-connected to the current practice at GAS. In the recent years it has been found that several projects within the company struggle with similar challenges during the PDP. What they have in common is a lack of proactivity. Therefore, as a result of the continuous strive for improvements, GAS has formulated the wish of becoming more proactive within the PDP and to study whether there could be a way of assessing proactive performance.

KM practice is about to be investigated as well. The main source of improvement potential regarding proactivity is thought to be the distribution of LL in PDP as these can offer a possibility to solve previously known problems with existing solutions instead of developing new ones. This approach to KM would save much resources and allow for more efficient PDP efforts, resulting in more proactive methods. The initial wide scope for this study and the variety and diversity of the topics already mentioned were visually arranged in the following graph (see figure 1.1).

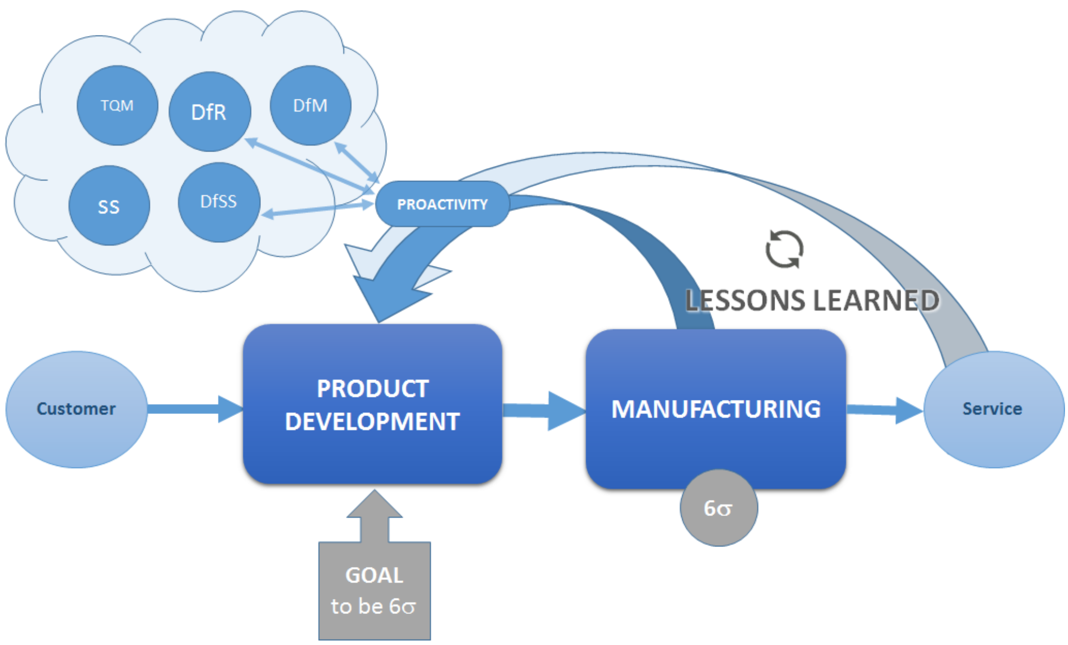

Figure 1.1 - Scope of the project analysis.

Hasenkamp et al. (2009) showed that a robust design methodology consists of three parts; principles, practices and tools. All three of them are needed to become successful in this matter. Currently, it seems that GAS has the tools, goal and ambition to be proactive and robust. The question is whether there are clear practices on how to achieve it, or if it is needed to explore this further in order to create the missing link between the system goal and the toolbox. This concept of principles, practices and tools will be further dealt with in *chapter 3*.

The literature review shows that the main goal of having project management is to be successful, which was expressed by Müller and Jugdev (2012, p.758) as: *"The subject of project success is at the heart of project management"*. The critical success factors for a project are commonly understood as the "*organizational strengths and weaknesses seen as affecting the success of an endeavor*" (Kurian, 2013, p.75). These critical success factors for a technology project may share interrelationships, and it is important to understand them so that management can highlight which ones may effectively contribute to the project success (Iamratanakul et al., 2014). The relevance of the study in this thesis is supported by Mousavi and Darvishi (2014) stating that both CSF and KM positively impact the performance of NPD.

1.4 Research Questions

According to Iamratanakul et al. (2014, p.602) *"Despite the abundance of studies on CSFs, their importance has still not been fully explained"*. By conducting this study the authors can contribute to bridge this gap by highlighting the interdependencies between CSFs of an industrial project, based on the ISM approach suggested in Iamratanakul et al. (2014).

The first research question addresses the current situation in terms of critical success factors to achieve proactivity at GAS, by comparing two projects; one being considered as struggling and one as successful. It was formulated as:

RQ1: *What were the critical success factors in the evolution from a problematic project to a more successful one that contributed to proactivity?*

The second question aims to clarify what factors and aspects related to proactive product development are outside of GAS, i.e. in other large industrial manufacturing companies in Sweden as well as in literature. It was formulated as:

RQ2: *What are the main critical success factors for a proactive product development process that are considered by large industrial manufacturing companies in Sweden?*

The intention with third question is to bridge the gap between GAS current practice and findings from the benchmarking study, i.e. to go from the present stage to a future state with the goal of becoming more proactive in the PDP.

RQ3: *What critical success factors in the product development process should GAS consider in order to improve its proactivity in the product development process?*

1.5 Delimitations

The GKN Aerospace division is present with several plants in the world, but this thesis will focus on the GKN Aerospace plant in Trollhättan, Sweden. The main reason for this is the availability to collect and access data, but also due to the need to set up boundaries to formulate a feasible scope. Further, the focus has been set on GAS, which means that all stakeholders upstream or downstream, suppliers and customers, are outside of the system under study.

This thesis will focus mainly on the higher-level concepts regarding proactivity, robustness and product development. Therefore, details regarding related methodologies and tools will be left out of the scope in order to leave room for elaborations on qualitative considerations on the system's level, e.g. details on how DFSS is implemented will not be elaborated upon.

GAS is a large company and the findings in this thesis are therefore not necessarily applicable in other, smaller companies such as SMEs. Further, the unique characteristics of the aerospace sector might result in findings that are not applicable outside of this area either. The goal is, however, to create a contribution with as high generalizability as possible, in order to serve a relevant contribution to fields and environments similar to the ones for GAS.

Due to the limited amount of resources, this master's thesis will only focus on the product development in relation to manufacturing, and other stages of the product life cycle will be left out of the scope, e.g. the service phase (see figure 1.1). Valuable LL can certainly be acquired after this point, but these will not be considered, hence there is a risk of leaving out useful experience that has been considered when formulating the scope of this thesis project.

There is a risk of facing incomplete or biased results in this thesis due to the fact that mainly two recent projects from the so-called hot structures division have been considered, one that is de facto more successful in terms of Non-Conformance Reports (NCRs), project A, and another one with a significantly higher number of NCRs, project D. This selection has been made to get relevant comparisons with the purpose of finding possible differences that affected the outcomes. A wider selection of projects could have contributed to enhance the results of this research but had to be discarded due to resource constraints.

2 Method

In this chapter, the research methods used in the thesis will be motivated and explained in detail with an emphasis on research validity, reliability and ethical considerations.

In order to answer the proposed research questions in this master's thesis a *qualitative research strategy* was adopted. According to Bryman and Bell (2011) this is a research strategy that puts more emphasis on words rather than in the quantification of collected data, an approach consistent with the fact that interviews, literature reviews and archival research were the main data sources for this study. Additionally, previous master's theses conducted at GAS will also be considered as a source of secondary data. Throughout the process questions and procedures emerged, and data was collected in the participant's setting (Creswell, 2009).

Both Bryman and Bell (2011) and Creswell (2009) state that this qualitative research strategy implies an inductive process of finding the relationships between theory and research, in which an emphasis placed on the generation of theories out of research, building from particular to general themes, and where the researcher has to interpret the meaning of the data (Creswell, 2009). These six main steps in qualitative research described in Bryman and Bell (2011) were followed throughout this research (see *figure 2.1*).

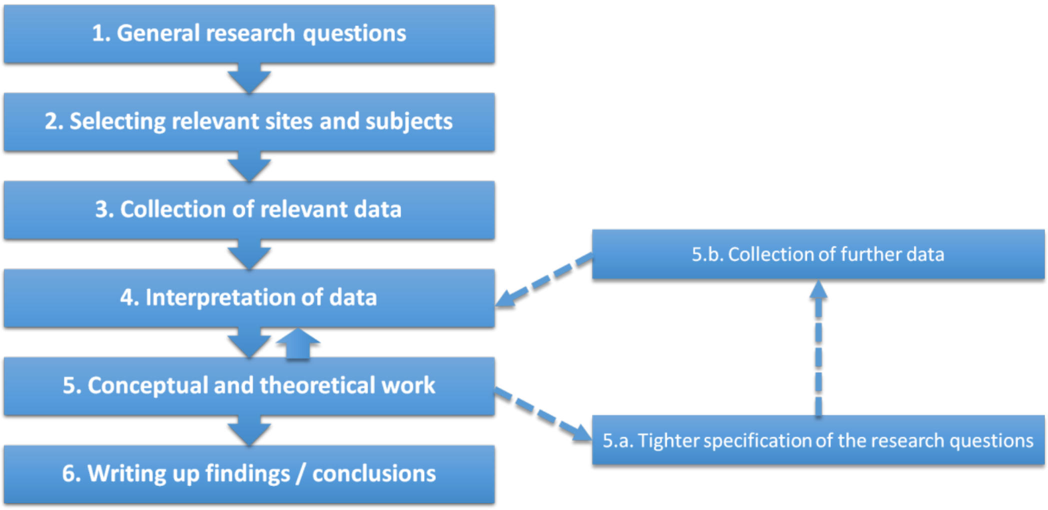

Figure 2.1 - Main steps of qualitative research (Bryman & Bell,2011, p.390)

During this process there should be a feedback loop between the interpretation of data and the conceptual and theoretical work. This means that the interpretation of the collected data should lead to a tighter specification of the initial research questions, and this in turn results in an additional collection of data that will have to be further interpreted.

This inductive process started with three preliminary research questions related to the topics addressed in the problem analysis. Based on these questions the site and those persons in the organization relevant to the investigation were selected and interviewed following an interview template. These interviews were then transcribed and these transcriptions became the main data source. This data was interpreted through two successive analyses, an affinity and an interrelationship analysis, leading to a tighter specification of the research questions. Further, data was collected using follow-up questions in order to cover up for blanks in the data set.

The analysis strategy for the data gathered using this inductive research approach was *grounded theory*. According to Strauss and Corbin (1998) found in Bryman and Bell (2011, p.576), by using grounded theory, theory is derived from data that is "*systematically gathered and analyzed through the research process. In this method, data collection, analysis and eventual theory stand in close relationship to one another*".

Based on Bryman and Bell (2011), the process begins with the researcher formulating general research questions. Then relevant people are theoretically sampled out of whom data is collected and coded and this coding in turn may generate concepts. There is a constant iterative process between these first four stages that will continue with the generation of categories. Relationships between categories will then be explored and out of this analysis hypotheses about connections between categories emerge. Finally, further data is collected in order to test these hypotheses.

The grounded theory process in this research began with the formulation of three preliminary research questions. These were the basis of an interview template that was used to retrieve the data that was later analyzed. All through this process data, analysis and theory were closely related to one another, e.g. the theoretical framework was the basis for the interview template that was used in the data collection. Additionally, the affinity and interrelationship analyses were conducted regarding some categories that were based on the theoretical framework.

Topic	Contents
Overview	A statement of the overall aims of the research
Field procedures	The procedures to be adopted during the field research, including how to gain access, how to capture data, time plan for data collection, etc. for each case
Research questions	The specific research questions should be stated, including clear links to the theory/literature where appropriate
Data collection matrix	A matrix (table) can be used to show the types of evidence to be collected, along with their relationships to each other and to the research questions identified above
Data analysis and case study reports	How you will analyze individual cases, conduct cross-case analysis and create the case study reports

Table 2.1 - Case study protocol topics
(Remenyi et al. 1998, and Yin 2009 in Rose et al. 2015, p.7)

The research design is the way of linking the collected data and the conclusions drawn from it to the initial research questions (Yin, 2014). According to Bryman and Bell (2011) there are several different types of designs for qualitative research, i.e. experimental, cross-sectional, longitudinal, case study and comparative. For this master's thesis a case study was adopted. A case study is the preferred method when the research questions are "how" or "why", when the researcher has no control over behavioral events and when the focus of the study is a contemporary phenomenon (Yin, 2014). A case study is defined in Yin (2014, p.16) as "*an empirical inquiry that investigates a contemporary phenomenon (the "case") in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident*".

The next step is to design the case study itself (Yin, 2014). This design will work as a logical plan for getting from the initial set of questions to be answered to a set of conclusions for these questions (Yin, 2014). Between these two points there are a number of major steps, including the collection and analysis of data (Yin, 2014). In order to fulfill this goal of linking the research questions with the conclusions the case study protocol suggested by Rose et al. (2015) as seen in *table 2.1* was followed.

2.1 Reliability and Validity

When dealing with qualitative research, Creswell (2009) makes a specific distinction between qualitative validity and qualitative reliability. Qualitative validity means that *"the researcher checks for the accuracy of the findings by employing certain procedures"* (Creswell 2009, p.190). Through the validity analysis we assess whether or not an indicator devised to gauge a concept actually measures it (Bryman & Bell, 2011). Creswell (2009) suggests a list of eight primary validity strategies and from these we will mainly use the following:

- Triangulation of data sources, using more than just one method or data sources in the study of social phenomena (Bryman & Bell, 2011).
- Usage of a rich description to describe the findings with the goal of providing many perspectives about the theme and adding to the validity of the findings (Creswell, 2009).
- Showing discrepant information that may run against the findings can contribute as a starting point to discussion (Creswell, 2009).
- Spend long time on the field as a way to develop a deep understanding of the phenomenon under study (Creswell, 2009).

Based on the work by LeCompte and Goetz (1982), Bryman and Bell (2011) argue that within qualitative research validity must be examined both internally and externally. *Internal validity* points to whether there is or is not a match between the observations made by the researchers and the theoretical ideas developed by them (Bryman & Bell, 2011). Internal validity was enhanced by conducting regular meetings with both academic and company supervisors that oversaw that these matches existed and that the conclusions were correctly grounded. *External validity* refers to the "*degree to which findings can be generalized across social settings*" (Bryman & Bell, 2011 p.395). The scope of this master's thesis was kept to a level high enough that allowed for a holistic perspective suitable for generalization to similar industries. Another way of reaching external validity was through a series of benchmarking interviews with relevant persons of interest working for other important industrial corporations in Sweden within similar areas as the subject area under research. The companies that have been used in this thesis are SCA, SKF and VCE.

"Qualitative reliability indicates that the researcher's approach is consistent across different researchers and different projects" (Gibbs, 2007 cited in Creswell 2009, p.190) and it relates to how consistent a concept is being measured (Bryman & Bell, 2011). The goal with the

reliability design is to guarantee that a subsequent researcher should arrive at the same conclusions by conducting the same case study over again, minimizing errors and biases (Yin, 2014). *External reliability* refers to the degree that a study can be replicated (Bryman & Bell, 2011). Even though it is hard to capture a social setting in order to make it replicable, there are several tactics to achieve this goal (Yin, 2014); in our case the reliability of this study was secured by documenting the procedures followed during this research. *Internal reliability* is a similar term to inter-observer consistency and it expresses the degree of agreement between the different members of the team about what they hear and see (Bryman & Bell, 2011). Since this study was conducted by two researchers it was vital for them to be aligned on the way they perceived its development and the qualitative value of the data collected. This was done by having continuous discussions and reviews about the ongoing status and progress of the research.

2.2 Ethics

Diener and Crandall (1978 in Bryman & Bell, 2011) broke down the main areas related to ethical principles into four items, i.e. whether there is *harm to participants* and non-participants (Gorard, 2002 in Bryman & Bell, 2011), a *lack of informed consent*, an *invasion of privacy* or *deception* involved. Accordingly, it is of the utmost importance for this master's thesis to both safeguard the rights of those individuals involved in the research and to respect the confidentiality rules adopted by the company and by the university. All participants in the research were informed about the objectives of this research and their identities were concealed.

Creswell (2009) suggests a list of ethical issues that should be considered for each one of the stages in the research, and out of these the following were adhered to:

- When writing the research problem, a problem that benefits the individuals being studied, meaningful for others beside the researcher, should be identified (Punch, 2005 in Creswell, 2009).
- When developing the purpose and the research questions, the purpose of the study was conveyed to the participants to avoid deception (Sarantakos, 2005 in Creswell, 2009). Also, the sponsorship of the project was communicated to them to establish trust and credibility (Creswell, 2009).
- While collecting data the researchers will respect the participants and the sites for research, not putting participants and vulnerable populations at risk (Creswell, 2009). The researchers will identify themselves, the sponsor of the research, the purpose of the research and its benefits, guarantee the confidentiality to the participant, and assure the participants that they can withdraw at any time (Creswell, 2009).
- During the data analysis and interpretation, the researchers may consider using aliases or pseudonyms for individuals and places to protect identities and data will be deleted two months after finalizing the research (Creswell, 2009).

In writing and disseminating the research report the researchers will pay attention not to use terms that may be biased against persons because of their gender, sexual orientation, racial or ethnical group, disability or age (Creswell, 2009). A proactive stance against fraudulent practices like suppressing or falsifying data will also be adopted (Neuman, 2000 in Creswell, 2009). The researchers will anticipate the consequences of their research, will credit the authorship of contributors and will release the details of the research in order to assess the credibility of the study (Creswell, 2009).

3. Theoretical framework

In this chapter the theoretical framework will be explained. It has been divided into three different sections, where the first and second provide the context and pre-understanding of the study, whereas the third is more applied to the study itself. In the first section quality management and Robust Design Methodology (RDM) are covered, the second refers to knowledge creation and management and the last one sums up the most relevant areas to cover the scope of the study.

3.1 Quality management and Robust Design Methodology

In this section of the theoretical framework different areas related to quality management and RDM will be addressed. The aim of this review is to highlight the contributions of RDM to the overall quality performance of the organization and what are some of the techniques and tools supporting it.

The researchers want to investigate the contribution of LL to proactivity in product development in order to enhance robust design. To understand and define the concept of RDM, some terms like the quality loss function or noise factors need to be addressed first. Then it will be possible to see the role of reliability engineering tools in avoiding design and robustness failures.

3.1.1 Quality management

The ISO 9000:2015 standard defines quality as *"degree to which a set of inherent characteristics of an object fulfils requirements", being a requirement a "need or expectation that is stated, generally implied or obligatory"* (International Organization for Standardization, 2015).

The multifaceted nature of the Quality concept has already been studied since as early as 1931 when Walter Shewhart discussed the measurable and the subjective aspects of it (Bergman & Klefsjö, 2010). The progress of the quality work started with *quality inspection* of finished products, and moved into *quality control*, in which the information coming from defective products served as the basis for the analysis and improvement of the production process itself (Bergman & Klefsjö, 2010). The next step in the evolution of the quality movement was the *quality assurance,* whereby quality efforts moved onto an earlier stage than the production process as a way to avoid production problems (Bergman & Klefsjö, 2010). Total Quality Management (TQM) aims at systematically determine the wishes and demands of the customer by performing well planned experiments and making robust designs, and it comprises quality inspection, quality control and quality assurance (Bergman & Klefsjö, 2010).

Bergman and Klefsjö (2010, p.37) interpret TQM as "*a constant endeavour to fulfil, and preferably exceed, customer needs and expectations at the lowest cost, by continuous improvement work, to which all involved are committed, focusing on the processes in the organization*". Based on this definition, the quality work rests on on a culture with a series of values: committed leadership, base decisions on facts, focus on processes, improve continuously, let everybody be committed and to which the focus on customers is the central one (Bergman and Klefsjö, 2010). These values are reflected in the Cornerstone model of TQM as shown in *figure 3.1* (Bergman and Klefsjö (2010).

Figure 3.1 - Cornerstone model of TQM
(adapted from Bergman & Klefsjö, 2010, p.38)

In 1994 James W. Dean, Jr. and David E. Bowen suggested an approach to quality characterized by principles, practices and techniques (or tools) with the goal of developing theory on this field, see *figure 3.4*. According to this view, quality principles are implemented through a set of practices, which in turn are supported by a number of tools (Dean & Bowen, 1994). Some examples of these tools are Quality Function Deployment (QFD) as a support to the principle of customer focus (Cristiano et al., 2000 in Siva, 2012) or process control to support the principle of continuous improvement (Siva, 2012).

3.1.2 Quality loss function

Quality, or rather the lack of it, was defined by the Japanese engineer Genichi Taguchi as "*the losses a product imparts to the society from the time the product is shipped*" (Taguchi & Wu, 1979 in Bergman & Klefsjö, 2010, p.23). Traditionally, there is no such loss as long as the value for the parameter of interest lies within the limits of a tolerance interval. A constant loss will only arise when the parameter value is outside of one of the tolerance limits (Bergman & Klefsjö, 2010, p.202). Taguchi´s views, however, is that any deviation from the target value will cause a loss that grows quadratically with the deviation from the intended target value (see *figure 3.2*) (Bergman & Klefsjö, 2010, p.202).

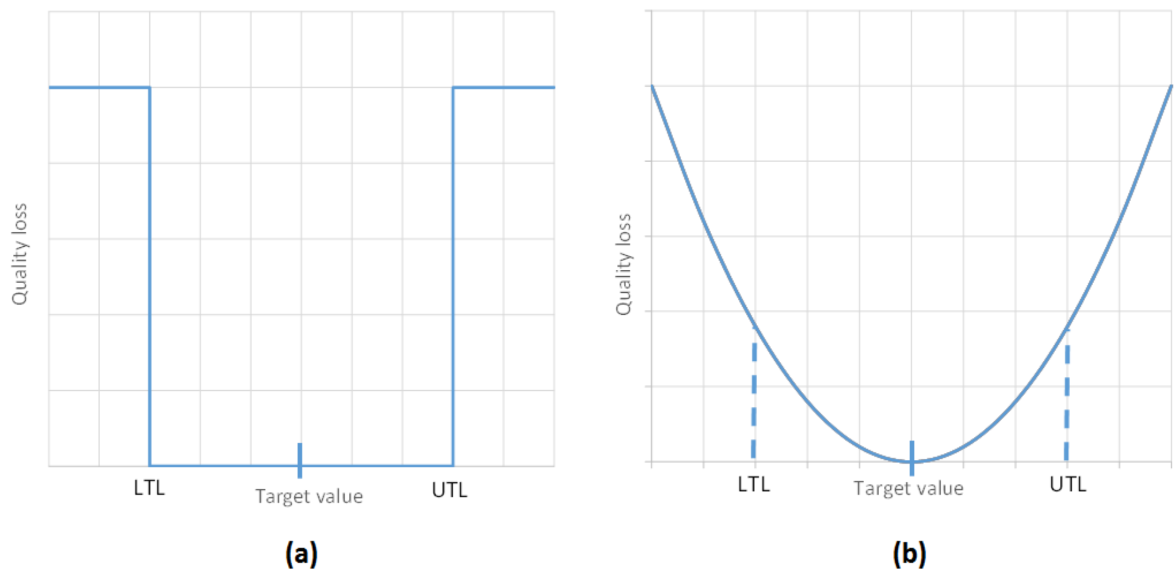

Figure 3.2 - Traditional view on quality loss (a) and quadratic loss function (b) (adapted from Bergman & Klefsjö, 2010, p.202)

The quality loss function serves as a starting point for understanding the relation between the variation in performance and the perceived quality of a product. This serves to prioritize robust design activities on functions with the largest expected quality losses (Christensen, 2015). The concept of key characteristics is also needed in order to explore the sensitivity to variation (Thornton, 2004).

3.1.3 Noise factors

Noise factors are the different sources of variation that a system is exposed to during its life (Bergman and Klefsjö (2010, p.199). The P-diagram is a graphical tool used to analyze conceptually these noise factors and their influence on a product or process (see *figure 3.3*) (Phadke & Dehnad, 1989 in Siva, 2013). Given an input, signal, to the system the deviations from the targeted response can be explained by the exposure of this system to noise factors and the interaction of these noise factors with the system itself and its control factors, also known as design parameters (Bergman and Klefsjö, 2010).

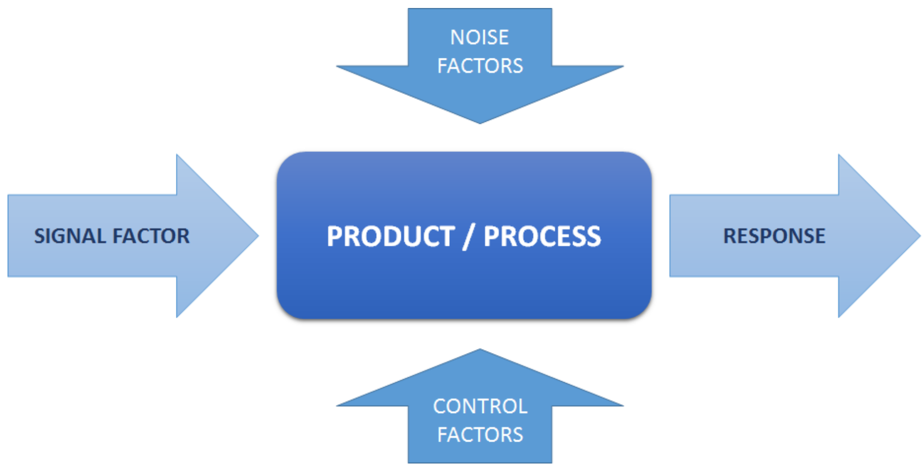

Figure 3.3 - P-diagram (adapted from Phadke & Dehnad,1989 in Siva, 2013, p.7)

3.1.4 RDM - Robust Design Methodology

By RDM we refer to a set of systematic efforts during all developmental stages to achieve products which are less sensitive to different sources of unwanted variation (Hasenkamp et al., 2009). Lack of functionality, reduced product lifetime and variation in the performance as a result of noise, wear and deterioration can be some of the consequences of an insufficiently robust design (Krogstie et al., 2014).

However, despite the costly losses caused by non-quality are a common motivation for the industrial adoption of robust design, still its implementation and use is considered to be challenging in the product development context (Krogstie et al., 2014). As Hasenkamp et al. (2009) point out, the application of a RDM tool without understanding the underlying practices that motivate its use may lead to suboptimal or even wrong effects.

In order to study the driving forces or principles of RDM, Hasenkamp et al. (2009) adopted the previously mentioned approach suggested by Dean and Bowen (1994) structured in a three-tier model of principles, practices and tools (see *figure 3.4*). Through the extensive literature review conducted by Arvidsson and Gremyr (2008) and Hasenkamp et al. (2009), three are the *principles* of robust design which are identified: *awareness of variation*, *insensitivity to noise factors* and *continuous applicability*.

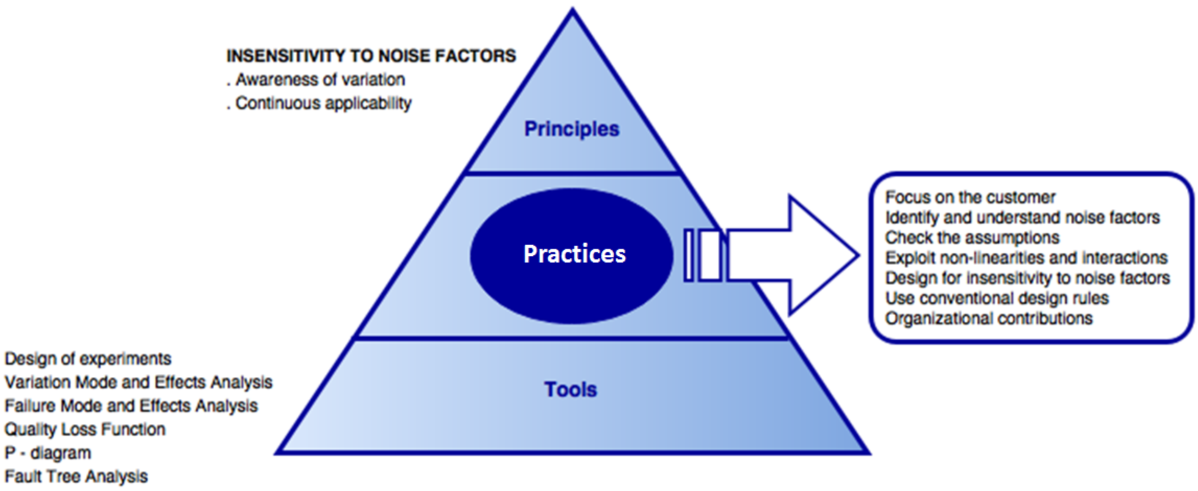

Figure 3.4 - Principles, practices and tools of RDM
(adapted from Hasenkamp et al., 2009, p.647)

Hasenkamp et al. (2009) point out that the main focus in the literature has been predominantly placed on those *tools* that support the creation of robust designs rather than exploring the *practices* that need to be done to fulfill the principles, i.e. the link joining the how (tools) with the why (principles). These practices are *focus on customer*, the i*dentification and understanding of noise factors*, *checking the assumptions*, the *exploitation of non-linearities and interactions*, the *design for insensitivity to noise factors* and the *usage of conventional design rules* (Hasenkamp et al., 2008)

3.1.5 Reliability Engineering

Reliability Engineering is about the avoidance of failures (Lönnqvist, 2010) and it has a double aim: First to find the *causes* of failures to try to eliminate them and second to find the *consequences* of these failures and mitigate or even eliminate them if possible (see *figure 3.5*) (Bergman & Klefsjö, 2010).

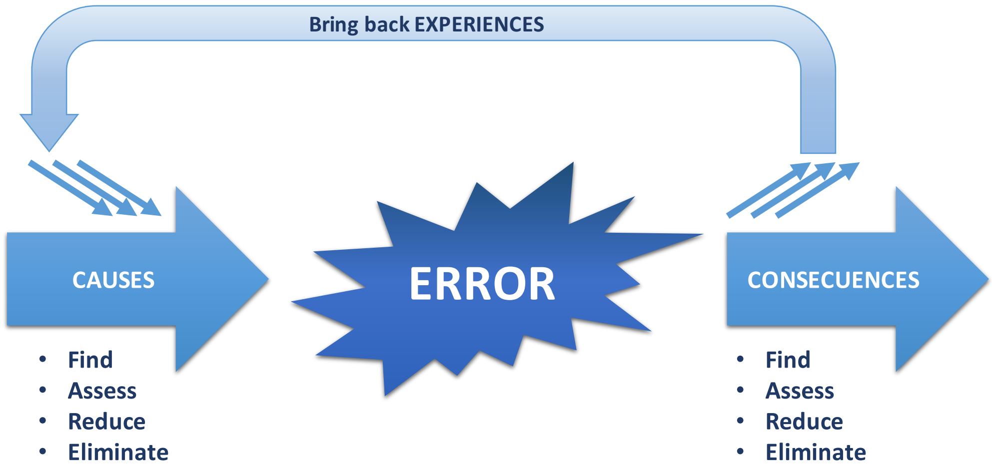

Figure 3.5 Reliability engineering (adapted from Bergman & Klefsjö, 2010, p.138)

Despite that reliability is traditionally part of the Improvement phase works in continuous improvement frameworks, Bergman and Klefsjö advocate for an earlier consideration as soon as the concept generation phases (Bergman & Klefsjö, 2010). Fault Tree Analysis, Reliability Block Diagram or the Failure Modes and Effects Analysis (FMEA) are some of the methods used for reliability analysis (Lönnqvist, 2010).

Bergman and Klefsjö (2010, p.159) state that FMEA "*involves a systematic review of a product or a process, its function, failure modes, failure causes and failure consequences*". The *design-FMEA* (D-FMEA) is used during the development stages and can be the basis for a systematic analysis of the design by a group of specialists with different background, while the process-FMEA (P-FMEA) can be used for improving a process both before and after the beginning of the manufacturing and for designing the process control (Bergman & Klefsjö, 2010). The results of a FMEA analysis are entered in a FMEA form that can be adapted to the purpose of the analysis (Bergman & Klefsjö, 2010).

3.1.6 Design failures and robustness failures

Based on their frequency of occurrence, product failures can be sorted into two categories: design failures and robustness failures (see *figure 3.6*) (Christensen, 2015). *Design failures* take place at nominal conditions and due to their high probability of occurrence are easy to identify during the prototyping phase, hence their relatively low cost of correction (Christensen, 2015). However, *robustness failures* have a low probability of occurrence and are therefore harder to identify during the development process (Christensen, 2015). It is during the production ramp up with higher volumes and a larger manufacturing variability when these robustness failures become manifest and the cost of fixing them is comparatively higher (Christensen, 2015).

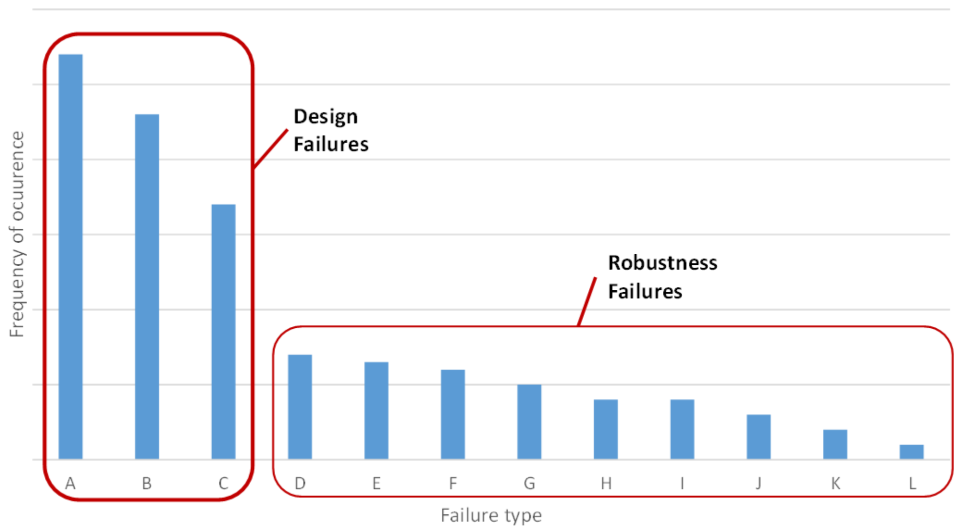

Figure 3.6 - Design failures and robustness failures (adapted from Christensen, 2015, p.10)

3.1.7 Reliability and robustness approaches

According to Phadke (1989 in Lönnqvist, 2010), *RDM*, *tolerance design* and *Reliability Engineering* are the three fundamental approaches that should be applied during the design phase to improve product reliability. The aim with the first one is to reduce the sensitivity of the product's function to the variation in the product parameters, the second aims to reduce the rate of change in the product parameters while the third approach includes redundancy when the cost of the failure is higher than providing redundant components (Lönnqvist, 2010).

Even though the overall purpose of the reliability and robustness approaches are quite similar and despite that both employ same or similar methods to detect potential failure modes, these two are not exactly the same, something which has lead to some confusion among engineers (Lönnqvist, 2010). While the aim with reliability engineering is to avoid failures and to mitigate or eliminate the consequences of a fault by using a wide range of activities, the focus of *RDM* is to minimize the effects of unwanted variation caused by noise factors that could eventually result in an underperformance which could be interpreted by the user as a failure (Lönnqvist, 2010).

The hazard function, commonly denoted as the *bathtub curve,* serves to illustrate the failure rate of a product over time (Capstone, 2003). It has three distinct areas and the shape of a bathtub in which the failure rate for the leading edge becomes increasingly lower as the product is worn-in and faults are fixed (infant mortality), and a flat segment during the product's normal working life that gains steepness as the failure rate increases as the product begins to wear out (Capstone, 2003) as seen in *figure 3.7*.

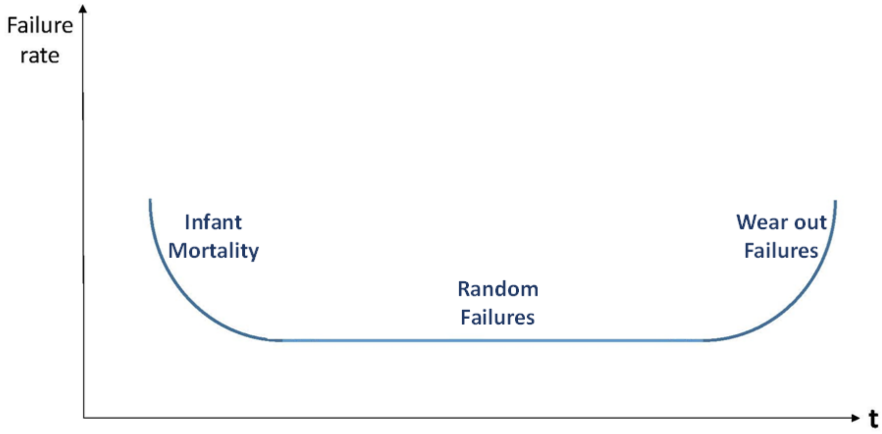

Figure 3.7 - The bathtub curve (adapted from Klutke et al., 2003, p.126)

It is possible to explain reliability phenomena in terms of robustness (Lönnqvist, 2010). To this effect Bergman and Gremyr (2006) in Lönnqvist (2010) apply the bathtub curve to describe the relation between sources of variation and reliability. Variation in manufacturing during the infant mortality phase decreases as the weaker components are removed (Bergman & Gremyr, 2006 in Lönnqvist, 2010). Environmental variation is the main source of random failures in the constant part of the curve while the long term variation of the environment explains the failures that take place in the wear out phase (Bergman & Gremyr, 2006 in Lönnqvist, 2010).

3.1.8 Application of back-end data

QFD (Shen et al. 2000 in Siva, 2012), customer surveys (Peterson and Wilson, 1992 in Siva, 2012), focus groups (Kaulio, 1998 in Siva, 2012) and product seminars (Cooper & Kleinschmidt, 1986 in Siva, 2012) are some of the tools that many customer-oriented organizations have adopted for handling data originated in the front-end of the product development process.

However, according to Siva (2013) problems at the back-end, i.e. manufacturing stage, are costly to rectify and this is why not only customer considerations but also design considerations should be brought into the product development process as soon as possible. Siva (2012) suggests that the flow of information from the back-end to the early design phases should be channeled through a quality improvement tool such as the FMEA.

3.1.9 Six Sigma

Six Sigma was introduced by Motorola as a name for their improvement programme aiming to reduce unwanted variation. In recent years the methodology has spread to other companies than Motorola with top management taking incentives to conduct Six Sigma projects such as Bombardier, AlliedSignal, SKF, Lockheed Martin, Polaroid, Solectron, American Express, Sony and Honda (Bergman & Klefsjö, 2010).

In Six Sigma there is a strong focus on addressing unwanted variation since this has been identified as main source of dissatisfied customers and costs. Sigma is defined as standard deviation and the logic is that a process under control should have a distance from the process mean to the nearest tolerance limit of at least 6 sigma (Bergman & Klefsjö, 2010).

Six Sigma is implemented using the DMAIC (Define, Measure, Analyze, Improve, Control) cycle methodology (Shankar, 2009). According to the same author this methodology allows an organization to move from the identification of a problem to a sustainable solution using a number of techniques and tools in a logical way.

3.1.10 DFSS - Design for Six Sigma

According to Yang and El-Haik (2003, p.50) Design for Six Sigma can be defined as *"a scientific theory comprising fundamental knowledge areas in the form of perceptions and understandings of different fields, and the relationships between these fundamental areas"*. Bergman and Klefsjö (2010) argue that it is not enough to work on reducing variation within the production processes, but that it is needed to consider early in the product development process. To overcome the lack of variation mindset in the early product development the concept of Design for Six Sigma was launched and Bergman and Klefsjö (2010, p.573) refer to a definition made by De Feo (2002) saying *"an established data-driven methodology based on analytical tools that provide users with the ability to prevent and predict defects in the design of a product, service or process"*.

According to Bergman and Klefsjö (2010) the stages in DFSS are formulated somewhat differently from the ones in the Six Sigma DMAIC cycle and there is no cycle that has been universally agreed upon. The most common ones are the IDDOV (Identify, Define, Develop, Optimize, Verify), the DMADV (Define, Measure, Analyze, Design, Verify) and DMADOV (Define, Measure, Analyze, Design, Optimize, Verify) (Bergman & Klefsjö, 2010; Gremyr, 2014).

3.1.11 QFD - Quality Function Deployment

QFD had its origins in the Japanese industries and it is commonly understood that it was successfully applied for the first time in Toyota Auto Body during the mid-seventies (Lager, 2005). The system was originally developed by Professor Akao and introduced in the USA at the beginning of the eighties (Larger, 2005). It is a method that is used to identify critical customer attributes and to link these to design parameters (Wheelwright & Clark, 1992). The two main components are bi-dimensional matrices correlating two PDP environments and a framework that connects these matrices (Maritan, 2015).

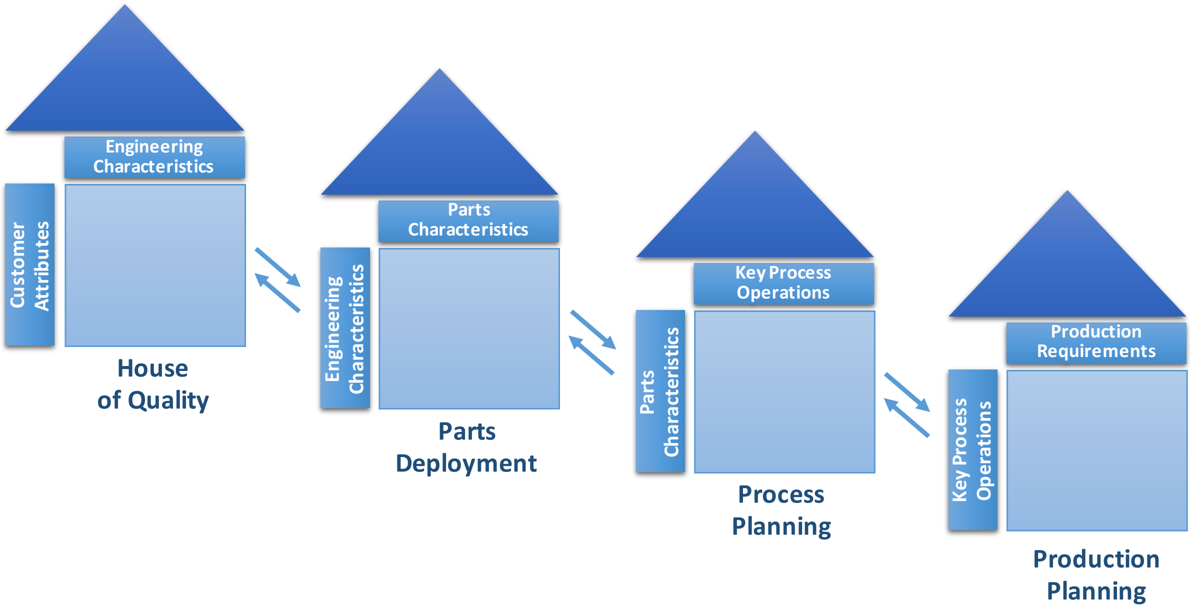

Figure 3.8 - The four phases of the QFD (adapted from Bergman & Klefsjö, 2010, p.127)

Depending on the framework, there are two main models that are best known: the Hauser and Clausing (1988) four-matrix framework and the more complex model proposed by Akao (1990) called the *Matrix of matrices* (Maritan, 2015). Customer needs and expectations are transferred from a higher to a lower level level through a chain of interconnected phases (Bergman & Klefsjö, 2010). The four phases are *product planning* (documented in a matrix called the *House of Quality*), *product design*, *process design* and *production design*, and each one of these phases is documented in a different kind of matrix (Bergman & Klefsjö, 2010) as seen in *figure 3.8*.

3.1.12 PPAP - Production part approval process

The Production Part Approval Process (PPAP) is a process developed by Chrysler, Ford and General Motors with the purpose of ensuring that all customer engineering design records and specification requirements are correctly understood by the organization (Hermans and Liu, 2013). It is employed to assess whether the manufacturing process will produce products that meet the requirements during the production run at the quoted production rate (Hermans and Liu, 2013). According to Hermans and Liu (2013, p.49), "*P-FMEA, Control plan and MSA are the most important steps in the PPAP*". To fully deploy the PPAP in an organization it should consider the review of product development processes, to follow the process steps and to include the suppliers in the process (Hermans and Liu, 2013).

3.2 Knowledge creation and management

A proactive use of the accumulated experiences from manufacturing can contribute to improved robust designs in product development. It is therefore essential to understand how knowledge is generated and transmitted both between functions and between projects.

In this section eight different areas related to knowledge creation, management, reuse and Lessons Learned (LL) will be covered, where a compilation of the most relevant studies and frameworks related to these areas will be presented. The rationale is to study how organizational knowledge can contribute to an improved project performance.

3.2.1 Process knowledge and process control

Slack and Lewis emphasize the fundamental importance of learning as a way of improving operations (Slack & Lewis, 2011), and even though they admit it is impossible to attain an absolute perfect knowledge about a process, still it will benefit by aiming towards it (Slack & Lewis, 2011). It is easier for a process to be improved when we understand the relationship between how the process is designed and run and how it performs (Slack & Lewis, 2011). As a consequence, there is a cyclical relationship between process control and process knowledge, and this relationship drives the operation's learning (Slack & Lewis, 2011). The learnings that foster process knowledge are triggered by process control as seen in *figure 3.9*).

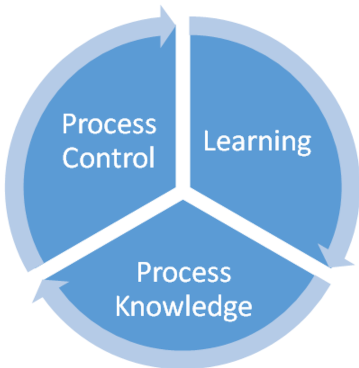

Figure 3.9 - Process knowledge and process control (Winroth, 2015)

Between the two extremes of total ignorance and absolute knowledge about a process lies the path of process improvement (Slack & Lewis, 2011). Slack and Lewis suggest an eight-stage scale developed by Roger Bohn as a way of identifying some points along this path, as seen in *figure* 3.10 (Slack & Lewis, 2011, p.234).

STAGE	FORM	KNOWLEDGE	TYPICAL FORM OF KNOWLEDGE
1	Complete ignorance	NONE	Nowhere
2	Awareness		Tacit
3	Measurement		Written
4	Control of the mean		Written and in hardware
5	Process Capability		Hardware and operating manual
6	Know How		Empirical equations
7	Know Why		Scientific models
8	Complete Knowledge	FULL	

Figure 3.10 - Bohn's eight stages of process knowledge
(Adapted from Bohn (1994) in Slack and Lewis, 2011, p.235)

3.2.2 Organizational learning

Organizations have to be strategically flexible when running operations in an environment of uncertainty instead of adhering dogmatically to predetermined plans (Slack & Lewis, 2011). This strategic flexibility is based on a learning process that connects past actions, their results and future intentions and which develops insights and knowledge (Slack & Lewis, 2011). In order to understand how an operation can exploit learning a way of developing strategic flexibility it is important to make a distinction between single and double-loop learning.

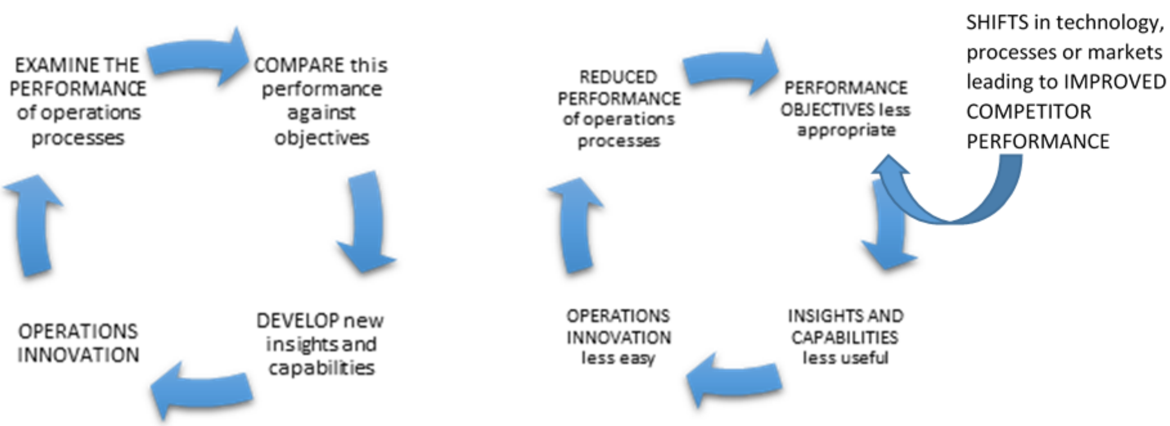

Figure 3.11 - Single-loop learning in operations and its potential limitations (adapted from Slack & Lewis, 2011, p.330)

Single-loop learning, see *figure 3.11*, takes place when input and output are repetitively associated, i.e. by correcting a problem every time it is detected, but "*without questioning the underlying values and objectives of the process*" (Slack & Lewis, 2011, p.330). There is the risk of developing an inertia difficult to overcome if the operation want to adapt to a changing environment (Slack & Lewis, 2011). While single-loop learning serves to improve what has been done before it exposes the operation to those risks associated with those things that it does not do well (Slack & Lewis, 2011).

Double-loop learning, see *figure 3.12*, is a learning mechanism by which an operation can avoid becoming too conservative. (Slack & Lewis, 2011) It challenges fundamental objectives, underlying *culture* and market positions with the goal of being open to any changes in the competitive environment by leaving existing operating routines at certain points in time (Slack & Lewis, 2011).

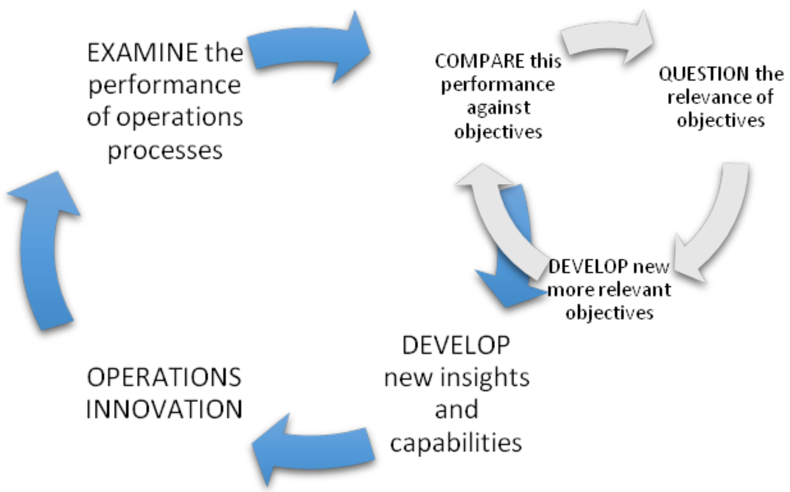

Figure 3.12 - Double-loop learning (adapted from Slack & Lewis, 2011, p.331).

All operations need a balanced combination of single and double-loop learning mechanisms; single-loop to develop specific capabilities and double-loop as a way of reflecting upon their internal and external objectives and context (Slack & Lewis, 2011). Slack and Lewis (2011, p.331) formulated the idea as "*This means a degree of tension between preservation and change*".

3.2.3 The Wisdom Hierarchy

The data-information-knowledge-wisdom (DIKW) hierarchy model is referred to by several terms, such as the *Knowledge Hierarchy* or the *Wisdom Hierarchy* and it is one of the most recognized models in the literature (Rowley, 2007) (See *figure 3.13*). As Rowley (2007) points out, ever since this hierarchical model was initially articulated in Russell L. Ackoff's groundbreaking article *From data to wisdom* published in 1989, the definitions of these terms have been frequently reviewed by different authors in information systems and Knowledge Management (KM), such as Chaffey and Wood (2005), Awad and Ghaziri (2004), Choo (2006) to quote just a few.

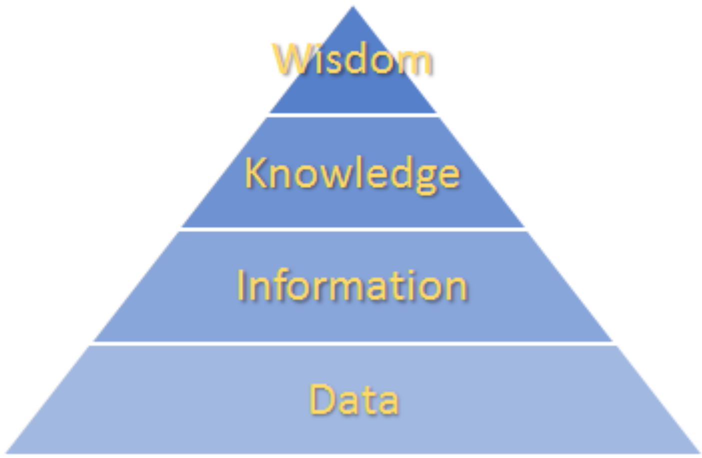

Figure 3.13 - The DIKW hierarchy (Rowley, 2007, p.164)

These authors agree that data, information, knowledge and wisdom are the key elements to this model (Rowley, 2007). Ackoff (1989) explains that data is used to create information, information is used to create knowledge and knowledge is used to create wisdom. However, Rowley (2007) calls attention to the fact that there is not a wide consensus in how processes involved in the transformation of an entity at a lower level in the hierarchy to another at a higher level should be described, to the point that for some authors there is no clear distinction between the concepts of data, information and knowledge (Rowley, 2007).

According to Rowley (2007) the two main factors that differentiate data from information are meaning and structure, and these two in turn have an impact on how information is encapsulated in either systems, people's minds or both. However, the classical description of knowledge as a combination of information, understanding and capability suggest a conceptual difficulty in distinguishing between information and knowledge, especially in the case of explicit knowledge (Rowley, 2007). Additionally, Rowley (2007) explicitly criticizes how the concept of wisdom has been neglected in the KM literature and suggests more academic debate around the concepts of individual and organizational wisdom.

3.2.4 Knowledge creation

The growing competition in an increasingly global and complex market makes both creativity and knowledge two important competitive resources that should be exploited by an organization's business strategy in order to achieve competitive advantage. Several studies show the contribution of KM to quality improvement initiatives (see Durcikova & Gray, 2009).

KM aims to integrate the existing different organizational strategies, each one with their own compatible and conflicting factors, into a holistic model of knowledge creation that describes the interactions between individuals and the organization. However, organizations are still struggling to understand how to create and manage knowledge dynamically, and this can be explained by the general lack of comprehension of what knowledge is and of the knowledge-creating process (Nonaka et al., 2000). The static and passive traditional Western view on organizations fails to capture the dynamic process of knowledge creation (Nonaka et al., 2000) as it is mostly based on the development of knowledge through the action of problem solving (Nonaka et al., 2000) following a single-loop structure (Slack & Lewis, 2011).

According to Nonaka et al. (2000) the organization should be viewed as a dynamic system in which problems are created and defined, knowledge is developed and applied to solve these problems and then further developed through problem solving. Rather than merely stocking knowledge at some point in time, the organization should continuously create it out of existing capabilities (Nonaka et al., 2000).

This dynamic approach to knowledge creation is founded on a model initially presented by Ikujiro Nonaka and Noboru Konno in 1998 called the *SECI model*. According to this model, knowledge creation is based on a dialectical spiral process of interaction, see *figure* 3.14, that goes through apparently opposite concepts such as order and chaos, micro and macro, part and whole, mind and body, tacit and explicit, self and other, deduction and induction, creativity and control (Nonaka & Konno, 1998; Nonaka et al., 2000).

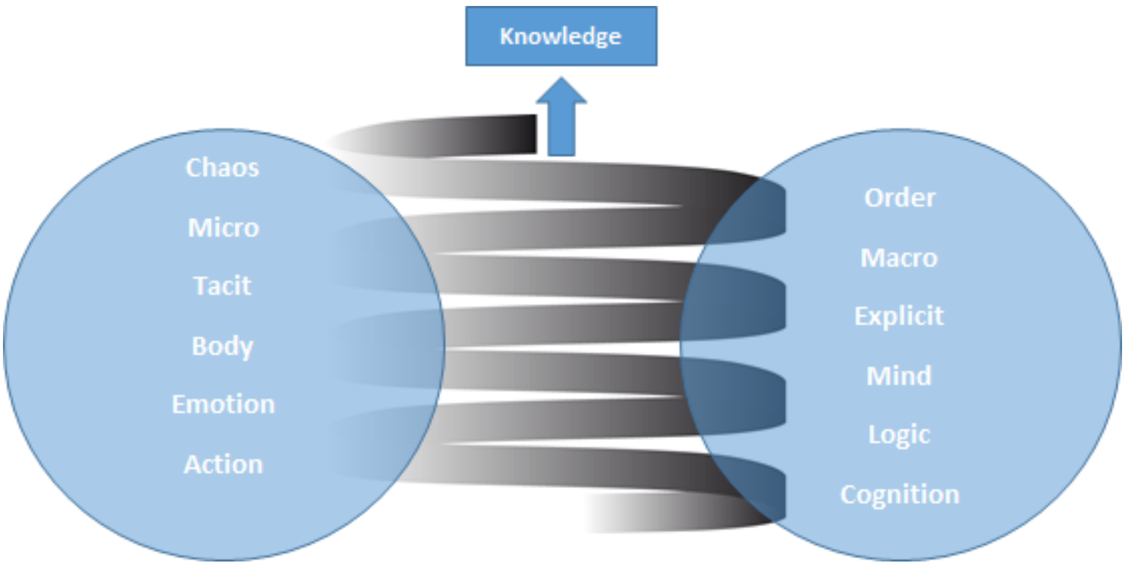

Figure 3.14 - The spiral process of knowledge creation (adapted from Nonaka et al., 2000, p.6)

The process of creating new knowledge is explained in the SECI (Socialization, Externalization, Combination, Internalization) model by the four possible interactions between tacit and explicit knowledge (Nonaka & Konno, 1998) as seen in *figure* 3.15. *Explicit knowledge* is expressed in words and numbers, shared as data and can be transmitted both formally and systematically between individuals (Nonaka & Konno, 1998). It is sometimes referred to as *know-that* (Goffin et al., 2010). *Tacit knowledge* relates to intuitions and subjective insights rooted on the individual's experience, ideas, values and emotions, being highly personal and difficult to characterize (Nonaka & Konno, 1998). It is deeply connected to the way problems are carried out and solved and is sometimes referred to a *know-how* (Goffin et al., 2010).

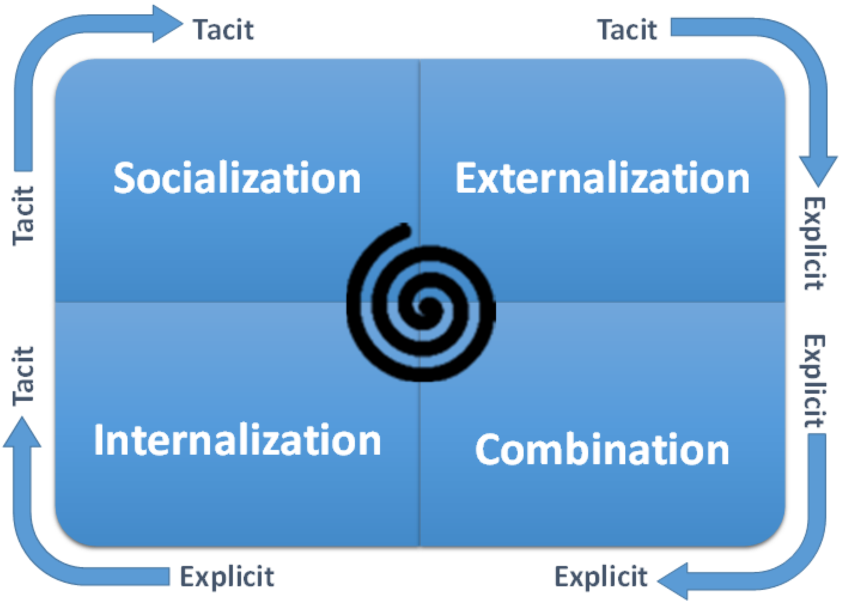

Figure 3.15 - Spiral evolution of Knowledge Conversion (Adapted from Nonaka et al., 2000, p.12)

There is *knowledge conversion* when an interaction between two types of knowledge takes place (Nonaka et al., 2000). The four possible interactions are *socialization* (sharing of tacit knowledge between individuals), *externalization* (process of articulating tacit knowledge into explicit knowledge by translating highly professional knowledge into explicit forms that can be understood by other members in the group), *combination* (the knowledge generated in the externalization transcends the group) and *internalization* (when individuals convert into tacit knowledge the explicit knowledge created throughout the organization) (Nonaka & Konno, 1998; Nonaka et al., 2000).

Knowledge requires a physical context to be created, and such a concept is denominated by the Japanese word *ba*. Ba is a place where information is interpreted to become knowledge, not necessarily a physical space but a locality that unifies physical and mental space by simultaneously including space and time (Nonaka et al., 2000). *Interaction* is a key idea for understanding ba, and the previously mentioned four interaction modes are tightly related to the four different types of Ba (Nonaka et al., 2000). Individual face-to face interactions define the *originating ba* and it provides a context for socialization; collective face-to-face interactions define the *dialoguing ba*, offering a context for externalization; *systemizing ba* is defined by collective and virtual interactions and it offers a context for the combination of existing explicit knowledge; and the *exercising ba* offers a context for internalization, being defined by individual and virtual interactions (Nonaka et al., 2000).

This model describing the process of linking knowledge created by individuals to an organization's knowledge system has been around since 1998 and all the research and findings ever since then has led to a large amount of concepts and issues that had to be readdressed by Nonaka and von Krogh in 2001 in an effort to clarify several questions raised by the previous work by Nonaka (1998).

3.2.5 KM - Knowledge Management

KM is conventionally defined as the process of capturing, developing, sharing, and effectively using organizational knowledge (Davenport, 1994). However, as the comparative study by Shin et al. (2001) points out, a universally accepted definition for this term does not yet exist, and this is the reason why these authors attempted to outline a practical concept of KM applicable in a business context.

The lack of awareness of other's capabilities or the waste of resources in re-inventing the wheel are potential risks of losing business opportunities when organizations start to grow in size (Liu et al., 2013). This is why both knowledge and its management are critical for an organization as a basis for sustainable competitive advantage (Nonaka, 1994; Miller et al., 2007 in Kumar & Ganesh, 2010). According to Shin et al. (2001) the KM process is widely described by the authors in the academic literature as a value chain and it should be strategically driven in a continuously cycling process in order to achieve the objectives of the organization (see *figure 3.16*).

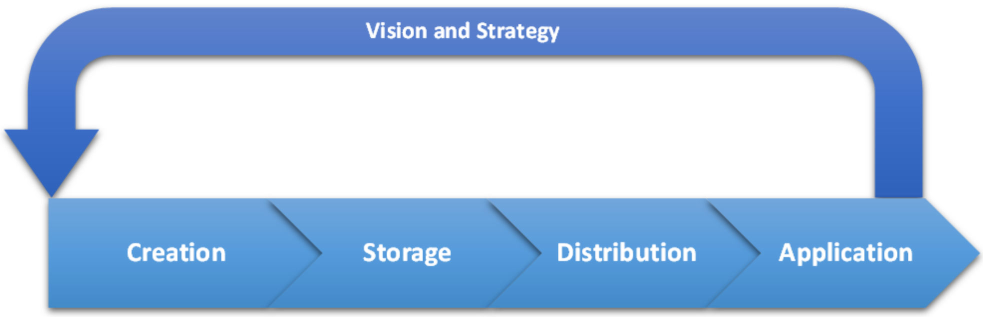

Figure 3.16 - KM value chain (adapted from Shin et al., 2001, p.341)

This cyclical KM value chain consists of an interaction procedure that links up individual knowledge to create social knowledge, and it consists of *creation* by addition or correction of existing knowledge, *storage*, which is related to individual and organizational memory, *distribution* that is the reciprocal exchange of knowledge between source and receiver and *application* by seeking to locate the source of competitive advantage (Shin et al. 2001).

The analysis of this value stream reveals five major research streams directly connected to it: culture, knowledge location, absorption, awareness and evaluation as seen in *figure 3.17*. From these five, culture has been identified as the most fundamental issue both conceptually and managerially by all KM researchers (Shin et al. 2001). This integrated model is suggested by Shin et al. (2001) as a starting point for developing an effective KM tool.

Figure 3.17 - Research streams connected to KM (adapted from Shin et al., 2001, p.349)

3.2.6 Knowledge Management lifecycle

Even though Lean Product Development and Lean Production share the same Toyota principles, these have differing views on the concepts of waste and value due to the particular characteristics of product development: creativeness, uncertainty and high variation (Swan & Furuhjelm, 2010).

Given the difficulty of evaluating whether an activity is value-adding or waste from a customer perspective in product development, Swan and Furuhjelm suggest a more operative definition of value in product development: *"Any activity that builds or creates knowledge, which is used in the current or later projects"* (Swan & Furuhjelm, 2010, p.3). According to Ward (2007) and Kennedy (2003) in Swan and Furuhjelm (2010) product development has two goals and these can be described in terms of two value streams: The *knowledge value stream* and the *product value stream* (see *figure 3.18*).

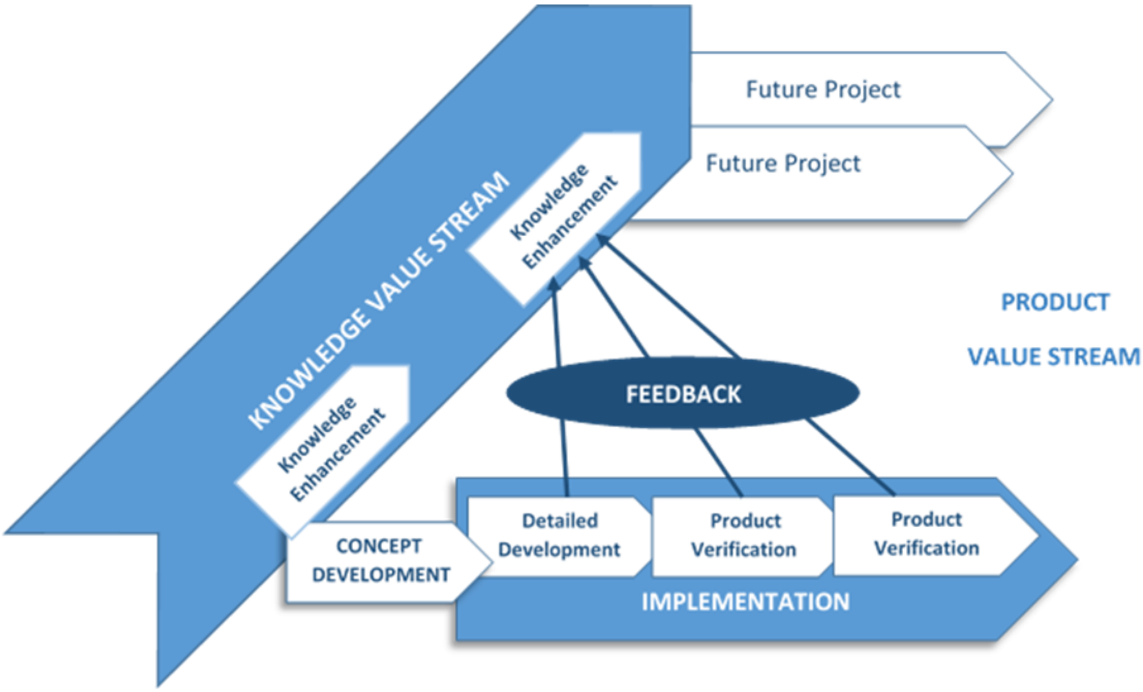

Figure 3.18 - The Knowledge Value Stream and the Product Value Stream in Lean Product Development (from Swan & Furuhjelm, 2010, p.3).

The goal of the *knowledge value stream* is to capture knowledge and to make it reusable as a way to increase organizational knowledge (Swan & Furuhjelm 2010). The *product value stream* aims to develop new products and it corresponds to the "target-focused development projects" (Swan & Furuhjelm 2010).

Companies aiming to enhance their value creation must understand that the success achieved by the companies applying Lean Product Development could be explained by their systematic way of capturing and reusing knowledge (Swan & Furuhjelm, 2010). To this effect Swan and Furuhjelm (2010) suggest a model described in a two by two matrix (see *figure 3.19*) in which the product development process is split in two phases with different characteristics: the *concept phase*, *"focused on the creation of knowledge to close knowledge gaps and minimize project risks"* (Swan & Furuhjelm, 2010, p.8), and the *implementation phase*, a process-oriented phase focused on the efficient execution of tasks (Swan & Furuhjelm, 2010).

	Concept phase	**Implementation phase**
Knowledge Value Stream	Systematic knowledge creation and generalization for reuse in future projects	Systematic problem solving to identify root causes to learn as well as to standardize into methods that prevent problems to reoccurring
Product Value Stream	Identification and closure of project-specific knowledge gaps	Efficient flow of engineering task with few interruptions since risks have been reduced in the Concept phase

Figure 3.19 - Model for the division of the product development into two phases related to the two value streams (from Swan and Furuhjelm, 2010, p.9).

3.2.7 Knowledge reuse: codification and personalization

For many organizations the return of investment on KM is certainly poor (Chua and Lam, 2005 in Liu et al., 2013) and one of the main reasons for this is their lack of knowledge reuse (Dixon, 2000; Minbaeva et al., 2003 in Liu et al., 2013). The first attempts at studying and setting up a theory for knowledge reuse were mostly focused on the design of knowledge repositories that would meet organizational needs managed by intermediaries and facilitators (Markus, 2001). However, these repositories have problems to be successfully reused by other groups for a purpose other than the originally intended because they are dependent on the distance between the original knowledge producers and the knowledge reusers (Markus, 2001). Kumar and Ganesh (2011) and Liu et al. (2013) agree that the general consensus in literature is that there are two distinct and generic strategies for managing and sharing knowledge in organizations mentioned in the literature: *codification* and *personalization* (Markus, 2001).

The *codification strategy* is a *people-to-document* approach (Liu et al., 2013) by which the knowledge is extracted from the person or persons who developed it and stored in some form of data base (Kumar & Ganesh, 2011) or electronic repository from which potential users can retrieve the information (Liu et al., 2013) and thus becomes a property of the organization (Kumar & Ganesh, 2011). Consequently, this kind of approach is heavily dependent on the information technology (Earl, 2001 in Kumar & Ganesh, 2011) and on the amount of investment that supports it (Kumar & Ganesh, 2011). In aiming for economies of scale, codification is especially suitable for mature markets and standardized settings where the same problems are repeatedly addressed (Mukherji, 2005 in Kumar & Ganesh, 2011). However, this strategy conveys a potential risk of information overload in the form of, e.g. large directories of unprocessed documents or unread mail (Kumar & Ganesh, 2011).

The *personalization strategy* is a *people-to-people* approach by which knowledge producers and users interact (Liu et al., 2013) directly in order to transfer tacit knowledge among themselves (Kumar & Ganesh, 2011). Personalization contributes to the flow of knowledge within the organization and acts as a firewall against external imitation (Kumar & Ganesh, 2011) because it is one key reason for either success or failure that cannot be clearly deciphered by our competitors (Szulanski, 1996 in Kumar & Ganesh, 2011).

Kumar and Ganesh (2011) echo the debate within the research community about how a company should balance these two strategies. Some researchers favor a biased approach in which the organization predominantly supports one of the strategies while the other strategy plays a supporting role, proposing a, e.g. 80-20 balance between them (Hansen et al., 1999). On the other hand, there is another group of researchers that support an unbiased balance (Kumar & Ganesh, 2011).

As these two strategies deliver very different costs and benefits to the organization, several authors advocate for a mixed approach that allows the usage of flexible models that can adapt to the particular characteristics of each organization (Liu et al., 2013). One such model is a comprehensive framework developed by Liu et al. (2013) that analyzes the organizational knowledge reuse processes within an organization with the goal of setting the optimum codification/personalization proportion through a KM cost-benefit analysis. The analysis evaluates the organizational knowledge reuse context through five stages (Awareness, Interest, Evaluation, Trial, Adoption) for both the codification strategy and the personalization strategy, and uses a Markov decision process model to integrate these considerations in the decision-making (Liu et al., 2013).

3.2.8 Managing lessons learned

LL can be defined as *"key project experiences which have a (...) relevance for future projects"* (Schindler & Eppler, 2003 in Goffin et al., 2010, p.40). It is important to ensure that the LL acquired through problem solving are shared at every New Product Development (NPD) as a way of improving the performance of the successive NPD teams, otherwise the teams are risking wasting time and resources, resolving previous problems (Goffin et al., 2010). Managers should take specific actions in order to transfer LL and tacit knowledge due to the inherent difficulty of capturing, expressing and sharing of this kind of knowledge, and Post-Project Reviews (PPR) are a widely recommended mechanism for identifying key LL (Goffin et al., 2010; Williams, 2008 in Goffin et al., 2010).

The study in Goffin et al. (2010) shows that NPD teams generate tacit knowledge in PPR discussions, and they identified a number of modes by which tacit knowledge may be transferred, e.g. through shared experiences, the usage of metaphors and stories to articulate stories or by the development or the usage of an existing codification scheme. Different research has shown that much of the learning generated in PPRs is lost once this knowledge is stored as part of a database because metaphors and stories usually are not part of the final reports so project-to-project learning should be supported in order for this strategy to be effective it also needs to be integrated with other mechanisms (Goffin et al., 2010).

Goffin et al. (2010) suggest five points that should be addressed by organizations seeking to tap into the knowledge that they generate through their NPD: 1) To facilitate and support PPRs with other mechanisms that support knowledge transfer, 2) To develop new codification schemas that capture knowledge, 3) To foster individual learning by promoting individual reflection, participation in communities and mentoring, 4) To designate specific team members as knowledge brokers and 5) To use kick-off meetings as an opportunity to disseminate existing knowledge. The authors make an explicit emphasis on the point that managers should not underestimate their involvement in kick-off meetings as these can boost the motivation and determination of the team (Goffin et al., 2010).

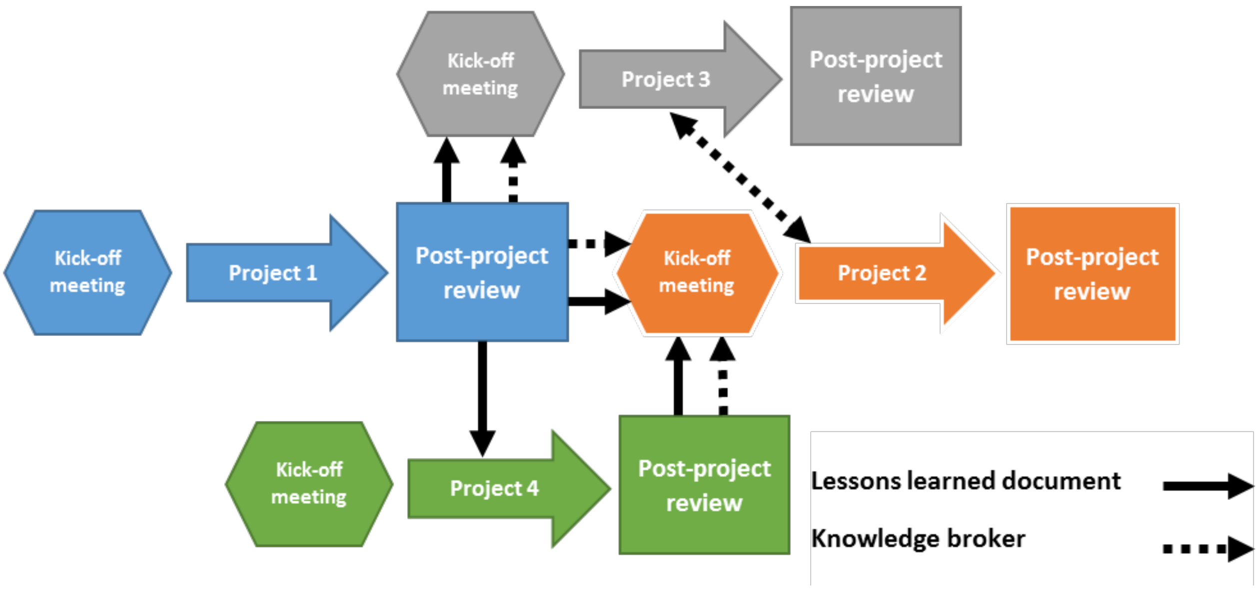

Figure 3.20 - Combined use of kick-off meetings, post-project reviews, knowledge brokers and LL documents as a way of spreading project-to-project learning (adapted from Goffin et al., 2010, p.48)

In summary, according to the method proposed by Goffin et al. (2010), PPRs contribute to NPD learning, but complementary mechanisms like kick-off meetings and knowledge brokers are needed to transfer LL from one project to another (see *figure 3.20*).

3.3 Main research areas related to project management

How top management decisions concerning team setup and how experience and LL are brought into a project are two of the factors that contribute to the successful outcome of a project. The empirical study in this research (see *chapter 4*) uncovered a series of concepts related to these topics and in this section the authors will provide a comprehensive literature review of the six main areas that are more directly linked to the scope of it.

3.3.1 Systems thinking

There is not a common understanding of what systems thinking means due to the variety of descriptions in the literature (Cabrera et al., 2008) and the term itself has been repeatedly redefined since it was coined in 1987 by Barry Richmond (Arnold & Wade, 2015). Richmond (1994, p.6) defined systems thinking as "*The art and science of making reliable inferences about behavior by developing an increasingly deep understanding of the underlying structure*".

According to Arnold and Wade (2015), systems thinking should be viewed as a system itself, a "*system of thinking about systems*" (Arnold & Wade, 2015, p.670), and thus its study should consider three major aspects: elements, interconnections and function (Meadows 2008 in Arnold & Wade, 2015). The exhaustive literature review conducted by Arnold and Wade (2015, p.675) presents the following comprehensive and updated definition: "*Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects. These skills work together as a system*".

3.3.2 Achieving cross-functional integration

Time is a critical competition element in dynamic markets and thus cross-functional integration is crucial to achieve effective product development (Wheelwright & Clark, 1992). However, just devising and implementing a framework for integration will not ensure integration by itself, since the integration takes place when individual design engineers, process engineers and marketers work together to solve problems at the development stage (Wheelwright & Clark, 1992).

In Wheelwright and Clark (1992) the PDP is explained in terms of individuals or groups tightly linked and working on closely related problems where the output of one group is the input for the other, i.e. the upstream group (design) and the downstream group (manufacturing) (Wheelwright & Clark, 1992). The pattern of communication between the upstream and the downstream group is a critical element of this interaction and it can be evaluated through four continuous dimensions: the *richness of the media* (ranging from sparse to rich), the *frequency* (ranging from low to high), the *direction* (from one-way to two-way) and the *time* (from late to early in the process) (Wheelwright & Clark, 1992).

There are four modes of upstream-downstream interaction that can be explained by the nature of the communication between the upstream and the downstream groups and how the activity of these two groups are linked together in time (Wheelwright & Clark, 1992) as seen in *figure 3.21*. The *serial mode* interaction takes place when the downstream group work starts the moment the upstream group has completed its design; it is a batch style of communication in which problem solving is not integrated (Wheelwright & Clark, 1992).

The *early start in the dark* interaction takes place when the downstream group is facing a deadline and makes an early start; however the upstream group only communicates when the design is completed, so the communication is still a batch style (Wheelwright & Clark, 1992). And even though the two groups are working in parallel, there is no interchange of information and the problem solving for each one of them are not linked (Wheelwright & Clark, 1992).

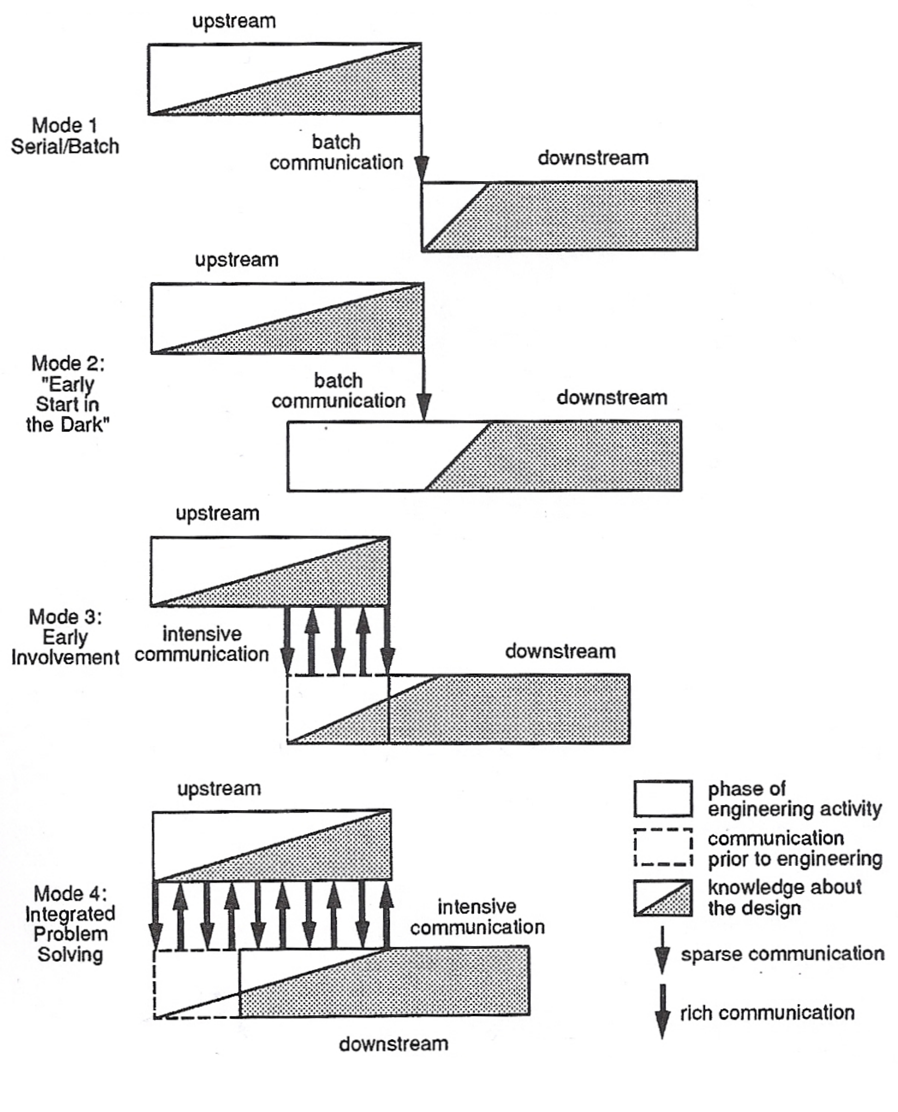

Figure 3.21 - The four modes of Upstream - Downstream interaction (Wheelwright & Clark, 1992, p.178).

In the *early involvement* mode, the upstream group also begins the design process before the downstream group begins to work (Wheelwright & Clark, 1992). Yet, at some point, the downstream group is involved in the upstream work, thus increasing its comprehension of the design and providing feedback for the upstream work with capabilities of the processes. The pattern of communication is early two-stream (Wheelwright & Clark, 1992). In the *early involvement* mode problem solving is more integrated (Wheelwright & Clark, 1992).

The *integrated problem solving* mode connects the upstream and the downstream groups in time and in pattern of communication (Wheelwright & Clark, 1992). Downstream engineers participate in preliminary design and use that information to start their own work.

The main difference between the *early involvement* and the *integrated problem solving* modes is that for the *early involvement* the content of the feedback from the downstream group is based on past experience, theoretical knowledge and engineering judgement while in the *integrated problem solving* the feedback also contains actual practice attempting to implement the design (Wheelwright & Clark, 1992).

3.3.3 Project team organization and leadership

In small, young organizations the role of the project manager and the organization structure are not major issues as efforts are mostly concentrated on a single development project and thus little energy is placed on how to organize the project and manage its execution (Wheelwright & Clark, 1992). In large, mature, organizations, however, organizing and leading development efforts is a major challenge because these organizations have established strong functional groups over time, i.e. design, manufacturing, marketing, that have their own occupations besides the development concerns.

Wheelwright & Clark (1992) identified four dominant structures of project organization, each one with an associated project leadership role as seen in *figure 3.22*. These options are based on the responsibilities of the project leader and the team members and their relationship with the functional groups and with the senior executives (Wheelwright & Clark, 1992).

The *functional team structure* is usually found in large mature firms where people are grouped around disciplines and each one of them under the direction of a functional manager. (Wheelwright & Clark, 1992). The responsibility for the process passes sequentially from one function to the next and the work for each function is agreed to by all parties at the beginning of the project (Wheelwright & Clark, 1992). According to Wheelwright and Clark (1992, p.192) this is sometimes referred to as *"the hand-off, or, less euphemistically, but probably, more accurately, as throwing it over the wall*". Some strengths of this team structure are that responsibility is aligned with authority, work is judged by the same functional managers who make the decisions about career paths and that the functions capture prior experience and become the keepers of the organizational knowledge (Wheelwright & Clark, 1992). On the other hand, functional team structures show limited coordination and integration, individuals are judged on their performance independently of the overall project success and the tendency to design considering the organizational areas of expertise rather than the system characteristics or the particular customer requirements (Wheelwright & Clark, 1992).

In the *lightweight team structure* the team members still physically reside in their functions (Wheelwright & Clark, 1992). Each function appoints a liaison person as a representative in a project coordination committee steered by a lightweight project manager that is responsible for coordinating the activities (Wheelwright & Clark, 1992). This structure is usually an add-on to the traditional functional organization as the key assets are still under control of the functional managers. The project leader therefore has a limited power and is considered to be *lightweight* (Wheelwright & Clark, 1992). The main strengths and weaknesses for this team structure are similar to the ones for the functional team structure. Yet, it contributes to an improved communication and coordination (Wheelwright & Clark, 1992).

The third approach is the *heavyweight team structure*, in which the project manager has full responsibility for all of those involved in the project (Wheelwright & Clark, 1992). They are senior managers in the organization and directly supervise the development work through key functional people on the core teams (Wheelwright & Clark, 1992). The heavyweight project leader and the core group are often co-located but the long-term career development of the individuals still rests with the respective functional managers (Wheelwright & Clark, 1992). The heavyweight project manager is key to the success of the project by managing, leading and evaluating the other members in the core team (Wheelwright & Clark, 1992). These managers are being reported to by the core team during the project duration, they are the concept champions and the ones responsible of securing the system integrity of the final product or process (Wheelwright & Clark, 1992). The five roles for a heavyweight project manager on a development project are: 1) direct interpreter of customer and market needs, 2) fluent in the language of both the market and of each one of the functions involved 3) Direct engineer manager coordinating the various engineering sub-functions 4) management "in motion" out of the office having face-to-face communication and acting as a conflict resolution manager and 5) concept champion, not only reacting to the interests of others but also seeing that the decisions are in harmony with the concept.

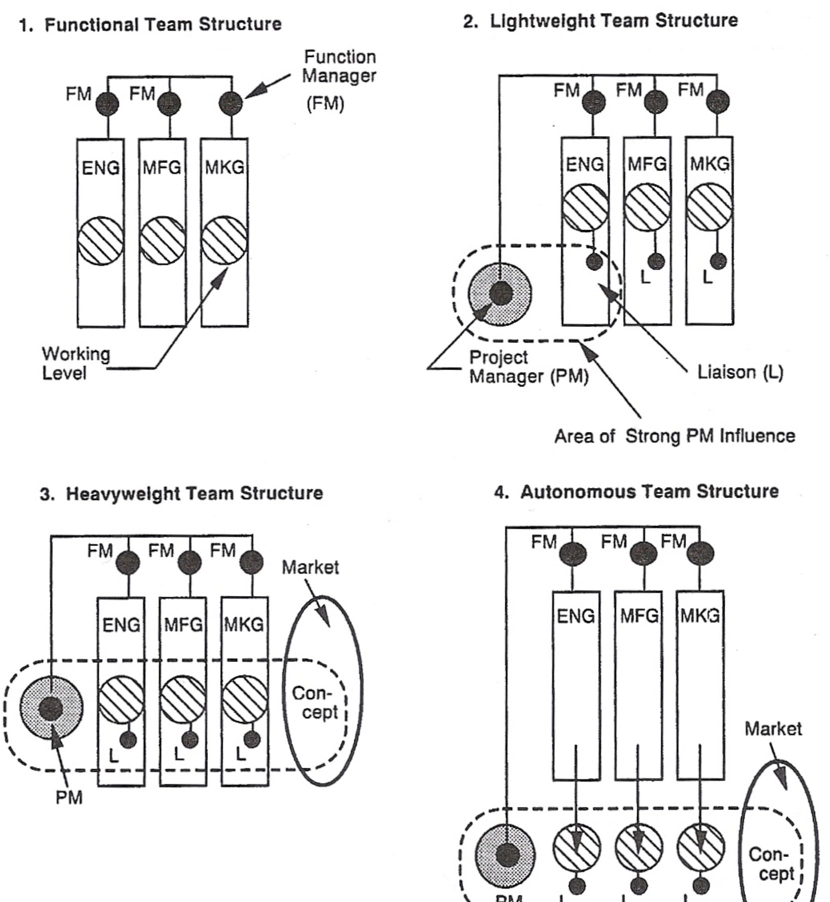

Figure 3.22 - Types of development teams (Wheelwright & Clark, 1992, p.191).

The *autonomous team structure* can also be referred to as *tiger team* (Wheelwright & Clark, 1992). The project leader has an important weight in the organization and has full control over the resources, being the single evaluator of the contributions made by every member of the team (Wheelwright & Clark, 1992). These members come from the different functions and are formally assigned and co-located to the team (Wheelwright & Clark, 1992). These teams have full autonomy to set up their own practices, systems of rewards and norms of behavior, and they will be held accountable for their results globally as a team (Wheelwright & Clark, 1992). Their main advantage is their focus, all the attention is channeled into achieving the project goals and cross-functional integration is effectively achieved (Wheelwright & Clark, 1992). However, their main con is that these teams tend to expand beyond the project definition by e.g. redesigning of a whole product instead of looking for opportunities of reusing existing organizational resources (Wheelwright & Clark, 1992).

3.3.4 KPI - Key Performance Indicators

Key Performance Indicators (KPIs) are conventionally defined as "*a quantifiable metric of performance, usually against a predetermined target for an individual, a team, or a campaign. These metrics can be both financial and non-financial and are used to track progress towards goals*" (Doyle, 2011). According to this definition, KPIs focus on the most critical aspects of organizational performance for the present and future success of the organization (Parmenter, 2015). Based on an extensive analysis conducted by Parmenter (2015) the seven characteristics of KPIs have been identified as seen in *table 3.1*

Characteristic	Description
Nonfinancial	1. Nonfinancial measures (e.g., not expressed in dollars, Yen, Pounds, Euros, etc.)
Timely	2. Measured frequently (e.g., 24/7, daily, or weekly)
CEO focus	3. Acted upon by the CEO and senior management team
Simple	4. All staff understand the measure and what corrective action is required
Team based	5. Responsibility can be tied down to a team or a cluster of teams who work closely together
Significant impact	6. Major impact on the organization (e.g., it impacts on more than one of top CSFs and more than one balanced scorecard perspective)
Limited dark side	7. They encourage appropriate action (e.g., have been tested to ensure that they have a positive impact on performance, whereas poorly thought through measures can lead to dysfunctional behavior)

Table 3.1 - The seven characteristics of a KPI (from Parmenter, 2015).

KPIs should reflect the differential characteristics of the activity that is being measured, and accordingly there should be a distinction between the KPIs for the research and for the development organization (Samsonowa et al., 2009). KPIs may differ depending on the industrial sector and they should be connected to the strategy of the organization if they want to convey some picture of its present situation (Samsonowa et al., 2009).

3.3.5 Proactivity

The adjective *proactive* is defined in the Oxford Dictionary (2016) as "*(Of a person or action) creating or controlling a situation rather than just responding to it after it has happened*". Consistent with this definition, Grant and Ashford (2008, p.4) define proactive behavior as "*anticipatory action that employees take to impact themselves and/or their environments*. A proactive behaviour is self-starting, directed towards the future and not reactive to external demands (Strauss et al., 2009). There is a general consensus in the literature that proactive behaviour is a promoter of organizational change (Strauss et al., 2009). During the eighties Keith Bloth challenged the general assumption that NPD is essentially proactive, i.e. initiated within the organization by highlighting the two main of sources of reactive NPD: the competitors and the customers (Bloth, 1985).

Responses to changes in the product mix by the competitors or the segmentation policy followed by a company regarding market segmentation are two examples of sources of reactiveness initiated by competitors, while the maintenance of customer relationships, changes in the product specifications, changes in manufacturing processes or customers' new products are sources of reactiveness initiated by the customer (Bloth, 1985). A managerial implication of a reactive approach to NPD may be that its procedures may not be completely followed due to e.g. a lack of time, while a proactive approach implies a certain control over them (Bloth, 1985).

3.3.6 CSFs – Critical Success Factors

Boynton and Zmud (1984, p.17) defined CSFs as: *"Those few things that must go well to ensure success for a manager or an organization, and, therefore, they represent those managerial or enterprise area, that must be given special and continual attention to bring about high performance. CSFs include issues vital to an organization's current operating activities and to its future success".* Product development is strongly tied to organizational results and it is critical to understand the factors that drive its performance if we want to achieve the organizational goals (Cooper and Kleinschmidt, 2007). By conducting a large study throughout 161 organizations nine key success factors that distinguish the better performing organizations were identified. These were: 1) high-quality new product process, 2) a defined new product strategy for the organization, 3) adequate resources of people and money, 4) R&D spending, 5) high quality project teams, 6) senior management commitment to product development, 7) innovative climate and culture, 8) cross-functional project teams and 9) senior management accountability (Cooper and Kleinschmidt, 2007).

Mousavi and Darvishi (2014) concluded that having both CSFs and KM influence positively NPD. Although the amount of literature on how to identify CSFs is rich, there is still a lack of studies on how to prioritize these factors as a contribution to the selection of best practices and the overall project management (Iamratanakul et al., 2014). Iamratanakul et al. (2014) developed a model with 14 CSFs, which are grouped into four categories that allow for hierarchical classification of them. These categories are dependent factors, linkage factors, independent factors and autonomous factors depending on their driving power and their dependence power.

4. Empirical study

This chapter will present the data collected from interviews conducted at GAS, and from benchmarking interviews with SCA, SKF and VCE. The two sections have the same structure as the interviews, with the first one referring to GAS and the second one to each consecutive benchmarking company.

Interview	Position	Duration (min)
1	Senior R&D Engineer	90
2	Robust Design Engineer	30
3	Process Leader	60
4	Design Leader/Definition Leader	60
5	Head of function Design and Material	60
6	Chief Manufacturing Engineer	60
7	Engineer in Charge project C	60
8	R&D Engineer	60
9	Quality Assurance Engineer	60
10	Engineer in Charge project A	60
11	Chief Design Engineer	60
12	Head of Engineering Lean and Operational Excellence	60
13	General Manager	60

Table 4.1 - Interviewees at GAS.

The empirical study consists of qualitative data collected during 13 semi-structured, face-to-face interviews with 13 different interviewees at GAS. Two interviews deviated from the goal of 60 minutes; one took 90 minutes and another took 30 minutes. These deviations were caused by the interviewees' willingness to elaborate more on some topics and by the need to shorten the interview due to urgent tasks, respectively. The interviewees were selected in order to get a wide range of views from different departments and people involved in the two main projects, but also from project B and C as well as some coming from support functions such as the quality department and engineering method specialists. Further, the number of interviews together with the varied sources allows for a more nuanced view, but also triangulation that promotes the scientific research value. A summary of the interviewees can be found in *table 4.1*.

After clearance was given from each interviewee the interviews were recorded. As a first step in organizing the findings it was decided that literal transcription of the recordings would be the most beneficial in order not to lose details. The transcription work was divided between the researchers.

After the transcriptions were finished the first iteration in retrieving information was initiated by filtering the data, but this time in the opposite way: the interviews transcribed by researcher 1 were filtered by researcher 2 and vice versa. The reason for this division was that the rich comprehension that was acquired when transcribing should be balanced between the researchers as a way of improving the understanding of all the material in the interviews. Next, two rounds of data analysis were conducted in order to reduce, condense and sort the findings into areas. These areas were formulated by the researchers and were based on a common understanding of the interview material. In total the transcription material was reduced from an initial 180 A4 sheets of plain text to a matrix that summarized the most relevant and important findings. This matrix was built on the interview template structure found in *appendix A*.

4.1 Description of a TEC

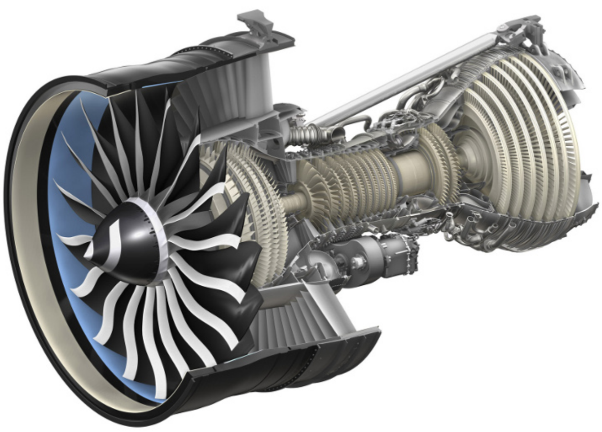

Figure 4.1 - Engine structure (General Electrics, 2016).

The two projects that are focused upon in this study are both turbine exhaust cases, TECs. A TEC is a component in a jet engine and is located in the rear part of it, which is illustrated to the right in *figure 4.1*. These components have a great level of complexity due to the high temperature differences between the entering and exiting air. Depending on the area of usage there are different requirements from the customers regarding for example temperature stress, which was also a difference between project A and project D. Because of technical differences project D had to endure higher temperature stress than project A. Historically the TEC was casted as one part, but GAS developed a new product concept where single components (e.g. hub, struts and duct plates) are welded together (see *figure 4.2)*.

Figure 4.2 - Turbine Exhaust Case.

4.2 Evolution from project A to project D

This study is built on a comparison of two projects conducted during the past 10 years that illustrate differences in performance and success. Both projects developed so called TECs, turbine exhaust cases. Within GAS there is a generally accepted view that the first project, A, was struggling with quality, cost and other performance metrics while the other, D, is de facto more successful in terms of NCRs. Project A was the first *design-to-make* (i.e. the whole process from design to manufacturing is covered in-house) TEC project that was both designed and manufactured at GAS. Previously, the product development of TECs at GAS was focused on *make-to-print* projects, where manufacturing was set up based on an existing design supplied by the customer. Prior to project A there was a preceding design-to-make project that was designed at GAS but manufactured at GAN that could contribute with valuable input to this study, although it was out of scope, and will therefore be referred to as the pre-project. The whole evolution of the projects is illustrated in *figure 4.3.*

After project A there were two new projects with a smaller type of TECs that could build on the experience from the previous projects. These projects were improvements compared to the first one, although not drastically. Next, project D was developed and the type of product was similar to the ones in project B and C, which meant a smaller TEC than in project A. The projects A, B and D are being manufactured at GAS while C is being manufactured at GAN. Despite the technical differences between project A and D, it was decided that a comparison between them would be interesting in order to identify success factors that contributed to the improvements and success in project D.

Before the pre-project similar parts were manufactured based on drawings supplied by the customer, and therefore the move towards covering the whole chain from design to manufacturing resulted in greater pressure on the internal processes. The understanding of the complexity of the move from relying on external drawings to a setup with an interaction between internal design and manufacturing is needed in order to grasp the difficulties that GAS is facing now.

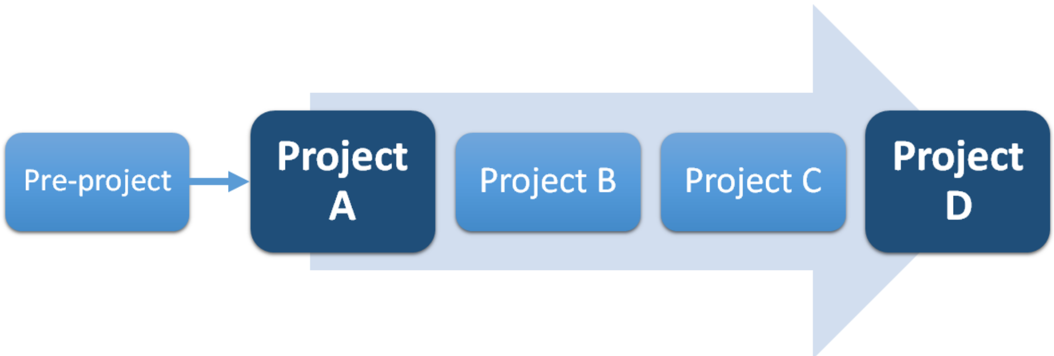

Figure 4.3 - Scope of the research

The pre-project was started in early 2000s and was already from the beginning confirmed to be designed at GAS and manufactured at GAN. Therefore, the project was set up in a way that would be possible to hand over to the separate manufacturing department in Norway. In project A, the difficulties in integrating the product development and manufacturing departments were underestimated comparing to the performance of the pre-project. One interviewee illustrates this using an example in which employees at GAS considered themselves to be superior to their colleagues at GAN: *"I told our head of design in project A* *early on that this is going to be a huge challenge to GAS, because they believe that they are better than at GAN but they don't really realize what journey they did in Norway to achieve a good result in the pre-project".*

In project A, the *communication* was mainly based on formal channels such as scheduled meetings. The product development and manufacturing departments were organized separately and few connection points between them existed. In addition to the scheduled meetings, and in order to improve the communication, the project management in project D decided to relocate representatives from the two departments into the same location to have a more informal knowledge exchange. This was described by an interviewee as: *"We put the team together in the same area, production engineering team and the design engineering team, so a lot of informal (communication) were just by sitting together, which is easier when you have a production site in Sweden at the same place as the design team but then there was also these formal meetings once a week or twice a week".* This change improved the overall communication compared to the procedure that was previously used.

Apart from the manufacturing site selection, the *pre-awareness of the future volumes* of the product being developed differed between project A and project D, and this fact affected the outcome of both programs due to importance and resource prioritization. Project A was at times deprioritized in favour of a project not addressed in this study, which lead to knowledge drain and that the project stalled. Project D was already from the start considered to be the most important high-volume product, and was therefore constantly being prioritized. One interviewee stated *"Program D when that started we knew that this is a very high volume program, like 500 TECs a year, that was the initial numbers, now even more"* and another one said *"(...) It's highly industrial and it's high volume (...) so that was important, obviously (...) we know from the start that with the volumes that we foresee with project D"* and *"The company had also a mindset that we need to do this right this time, bearing in mind the high volumes".*

The interview study showed that there was a major difference between the two projects in terms of *collaboration and integration between the product development and manufacturing departments*. In project A the two departments were separated and poorly integrated, which resulted in a low degree of collaboration and therefore poor preparations for manufacturing. In project D, on the other hand, the manufacturing and design representatives in the project development team were brought together to the same location and the integration between them was increased, with management considering them as one single team instead of the previous two separate ones. This was mentioned as an important reason for the success of the project by several of the interviewees. One interviewee stated: *"(...) We put the team together in the same area, production engineering team and the design engineering team, so a lot of informal (communication) were just by sitting together"*. Another interviewee said: *"I think we did something that we haven't done before. We as GAS do something differently. By having a team, one team, not two. There is no them in us, it was a we effort truly"* and the same person also concluded that *"I think, having the design manufacturing in the proximity is a smart thing to do".*

The previous culture at GAS was of a PDP mainly driven by the design function and with a low manufacturing representation that was not at the same level of empowerment. This was shown in project A where there was a single representative from production compared to a team of eight or nine product development engineers. One interviewee said: *"On the pre-project's time the team in my group was almost fifteen people, doing the design models, drawings, stack-up analysis and things like that. Project A was something like eight, nine* *maybe. In project D it was six people and doing the same work and even doing it better, because we had learned how to work together and that we could use it a lot since the early project".* This was changed in project D where the manufacturing representative was empowered to the same level as the other members of the project management group and was expressed like: *"(We) empowered the production facility (...) giving him the same power as a design engineer and trying to give them responsibility for the product cost, and producibility".*

Comparing the two projects, not only the *number of manufacturing representatives* was increased from one to four or five, but also the *skills*. In project A it was inexperienced and in project D they were more skilled, experienced and specialized in different fields within production. By having more than one representative the number of manufacturing competences within the group is increased, which was stated by one interviewee as: *"(...) He's not an expert in every single production. By moving in more you can have one that is good in turning, one in milling, one in welding. Suddenly you have a higher competence in the group by itself".*

An important distinction to make between the projects is that, apart from the number and skills of the production representatives, the *functional support from the manufacturing function* differed. In project A the support was low and in project D it was high, which is stated by one interviewee as: *"(...) The competence in the project D team was set up in a quite different way than the project A, and I think that the manufacturing engineering people here (in project D) they have had functional support. I think these guys here (in project A) they were quite left alone".*

Another difference worth mentioning between the two projects is the *attitude* from people within manufacturing when discussing manufacturability. In moments when people from the product development function wanted to take into consideration production details or capabilities, the response from manufacturing was an overconfident approach with a lack of self-criticism or connection to what was actually feasible according to several interviewees. At times when the manufacturing capability was not ready for a certain design, people in production had great confidence in their own ability to solve problems and assured that they would be solved. This lead to severe production issues when the serial production stage was reached. The overconfidence lead to a poor understanding of the actual manufacturing capabilities from the product development department's point of view in project A, as the people with a realistic chance to assess the manufacturability of a design assumed that they could solve more than what was actually possible. In project D the approach to what was feasible in production was more realistic, for example by conducting real-life testing and not only computer simulation. One interviewee expressed it as *"We have done more intermediate testing (in project D) (...) test pieces (...) before they relied too much on the simulation in the computers and less on the actual hardware (...) I know that project A relied a lot on the welding simulation".*

The usage of the *P-FMEA* tool differs between the two projects. In project A it was only considered lightly, as a part of a stage gate review checklist, and not in the early phases of product development. Project D, on the other hand, started to consider P-FMEAs from previous projects as a part of the work to identify risk factors that should be avoided in the design. Further, a dedicated person was assigned the responsibility to perform a P-FMEA on the new vane type selected together with the supplier, formulated by one interviewee as: *"We put a guy there, from day one and the first thing he did was a P-FMEA. His task on that was not to follow the production, it was to do a P-FMEA together with the supplier".*

One difference identified between the product development phases of the two projects is the extent to which *testing and trials* were used. In project A, intermediate testing with the purpose of improving the design based on real-life data was not used at all. One interviewee stated that: *"We are not making trials, we are assuming that we already knew everything"*. Another interviewee addressed the fact that project D got more resources for testing than any other project had gotten before: *"I think it has been a huge learning experience for us and one thing that is quite interesting is in project D because project A didn't turn out well in production the sort of engineering lead manager appointed a group of people in project D who got more material for tryouts that any TEC project ever before"*.

The cost pressure was heavy during project A and therefore there were decisions not to prioritize experiments and testing that were not considered to be fruitful. In project D testing was considered to be a vital part of the product development process, and several forerunners, intermediate tests and trials were conducted. There was an opinion from the project management that simulations and computer analyses should not have been accounted for as the ultimate truth, but that real-life tests were needed to fully comprehend the situation and define the design space in which the product could safely be designed. This was expressed as: *"They (project D) had a much stronger, both position and did a lot more of this necessary work to do a lot of testing and experiments, to evaluate different process solutions. Maybe not on the final product or final geometries, but to look for the capabilities and give that kind of input and feedback"*.

In project D the strong focus on testing was confirmed by other interviewees as well stating that *"I know that project A relied a lot on the welding simulation. We didn't, we did that but we did a test always, in reality, to prove that it was correct"* and *"We did a lot of small tests, we did a lot of small forerunners or test setups"*. Yet another interviewee confirmed this by saying: *"They (project D) have done a lot of testing and experiments and such things"*.

A differencing factor that was between project A and project D was to consider the production from a *platform perspective*. This was done by collecting data in the beginning of the project in order to create a foundation with the existing knowledge formulated in previous documentation. In project D there was a dedicated person gathering this information, which one interviewee considered to positively impact the project. This role was probably removed, according to the interviewee, who expresses it as: *"That role I was talking about previously that was responsible for our platform, that role I think that was rather important to have. That was a person that was not working directly in the programs or the project, he was founded by the organization"*.

The interviews at GAS showed that the four projects' performance rely on *specific knowledge and competence* from within individuals in the product development teams, and not only from a KM perspective. Another factor to consider was the lack of access, where personal networks within the company were necessary to get hold of the right knowledge. When an issue occurs project members are often consulting their respective personal networks within the company rather than formal function support entities. One interviewee expressed that *"75% of it is my own experience, and knowledge about it, and then I'm using the network of experts here"* and another one *"You trust those people who are involved, that they make sure that they get the right information to do the right work, so to say. It could be that the project brings in other experts as well, if they don't manage to proceed"*.

Currently the main production quality measures are non-conformances that can be corrected within production without external assistance, *Q3's*, and those that require a redesign from the design department, *Q4's*. The Q4's need to be authorized by the customer and therefore it is resource demanding and focus is set on minimizing these. A difference that came up through the interviews was that more *attention* is devoted to addressing these issues in project D than was the case with project A. One of the interviewees directly involved in project D stated: *"We looked deeply into the Q3s and the Q4s on project A, trying to find the difficulties and seeing if we had covered them. If we compare project D to project A, we now follow them in detail to see the trends"*.

In project D the Product Part Approval Process (*PPAP*) was used for the first time in a project at GAS according to one interviewee who said that *"PPAP came from automotive and that was something I was familiar with so, project D was the first program that had that requirement on it"*. This quality tool was a significant difference from the previous projects as this reduces variation in the incoming parts.

The Technology Readiness Level (*TRL*) was also used for the first time in project D which offered a measure of technology maturity preventing too immature technologies from entering the design concepts. This was expressed by an interviewee as: *"You need to meet TRL, technical readiness level, of minimum six to be allowed to use it in the designs (...) that was new (...) when we were doing project D, and that was not in place when they did project A"*.

After some time of product development in project A it was found that the *design intent* got lost, expressed by an interviewee as *"The design intent was totally lost (in project A), and there were things happening that were uncoordinated after time",* which resulted in sub-optimizations and reactive firefighting of urgent problems instead of keeping a long-term focus on where to head. One example mentioned by an interviewee was when it was decided to go for a fixed shape but with an advanced fixture. At some point the purchasing manager overruled that, concluded that it was too expensive and simply removed it from the list of project needs without considering the dependent design that relied on that fixture. This was expressed as *"(...) we decided that we would go with a net shape, but with an advanced fixture. The problem was that the purchasing manager a couple of years later, in negotiation, decided that that was way too expensive and removed that from the list"*. In project D the power balance was more even and therefore the design was optimized based on different wants and needs in the design work and this was expressed as *"If, shall we say, everyone that is influencing the design is equally unhappy then we have a perfect balance"*

A big difference between the projects was the *time pressure* that was put on them. According to one interviewee there was a clear difference between the pre-project and project A: "*So they (pre-project) were getting a lot of time to do their learning, which project A had three hardwares and they went into serial production, which was not enough for the pace of learning that we did*". Project A was run under high time pressure in parallel with another project that was given higher priority and this resulted in competition of resources, such as welding technology and was formulated by an interviewee as: *"all the laser resources, all the experts, and all the equipment and all the facilities were dedicated to the other project (...) it was decided that project A was never gonna get laser welding"*. The time pressure lead to a minimum of tests and trials and the project was instead pushed into production with limited time for project learning and reflection, which was expressed by an interviewee as: *"In my workday I don't have much time to reflect"*. Additionally, there was a passive approach from manufacturing employees in terms of learning and this was expressed by an interviewee as: *"They were waiting, learning nothing, so the learning phase was kind of lost"*.

One difference between the two projects that came up during the interviews was the *sourcing of material*. In project A the chosen material was cast, although that will always lead to cracks, pores and other quality flaws after welding according to one interviewee: *"In project A you had a lot of casting. Welding in cast material will always lead to micro features or micro cracks (...) welding in project A in the beginning caused us a lot of cracks and pores, which are mainly related to the castings, I think. So that's a big different between the two projects".* This distinction needs to be considered since welding is the most critical manufacturing method when constructing a TEC. In project D it was not possible to go with this material as it could not stand the higher temperatures that were required and therefore another more expensive material was chosen. The new material was not available as cast material, hence forging had to be used instead. Forged material has the advantage of being more suitable for welding, which results in less quality imperfections than with cast material and this contributed to less quality issues in project D when reaching the manufacturing stage.

This *change of material* was one of the reasons why this project was considered to be more conservative from a manufacturing point of view. According to one interviewee, manufacturing employees from project D had admitted that the project would have taken longer time and required more material if it had been executed with the same presets as project A and it was expressed as: *"I asked these guys who are very, very proud of what they succeeded with, zero defects, really, really good: if you would have had a casting instead of a forging, would you have pulled it off? And all the other guys who I have asked this question have responded with some hesitation that it would have taken a longer time and we would have needed more material".* Further, in project A the casting or the incoming material had lower requirements than the final part and therefore the quality had to be improved to meet tougher specifications than those of the base material, formulated by one interviewee as: *"So we just imposed all requirements that were inherited from the customer, which were quite interesting because they had tougher requirements on the end welded product than we were able to place on the casting or the incoming material which means that, after welding it all together, we had to improve quality better than the base material, after being processed, which is ridiculous of course".*

There was an evolution in how *previous knowledge* was gathered in the projects succeeding project A. In project B few documents were considered for the concept selection phase of the product development and LL were not collected actively and this was described by an interviewee as: *"Some things are at least documented (...) when we get some new people in the program, I will tell them: "Go through the technical reviews" , because we have had a lot of technical reviews and because of issues we had, problems we have had extra technical reviews, not just a gate reviews, we have had other reviews as well, and all of those reviews are very good source of knowledge I should say. And then, of course, we have the design verification report, which is also a very good source of information".* In project C, LL and some of the previous documentation were considered in the concept selection but the LL were still not collected according an interviewee stating: *"Usually we just write a report, like LL report, and there have been different formats for like writing LL. You have like a LL file, it could be an Excel file, it could be some different, so we are not very good on, like documenting LL".* In project D all previous LL documents were considered in the beginning of the project, and for the projects where no documentation could be found documentation was created in order to have a base to stand on and this was stated as: *"We took all the white books, and did a list of what's applicable to our product".*

4.3 Summary from the interviews

In the interviews it was shown that GAS is aware of the importance of bringing LL from production to product development and that some efforts are being made to this effect. However, these efforts are scattered into five loosely connected areas. The first area is the OMS where some gate reviews address the collection of LL at a certain stage. The second one is the team selection in which LL are brought to a project through the most experienced people and is considered to be the main way of addressing LL. Thirdly, internal training is being conducted as a way of standardizing the capture of LL, for example concerning the use of the P-FMEA tool. Area number four is the wrap-up meetings where it is up to the program manager to make sure that these are being held, but it also appeared that they are not conducted on a regular basis. Lastly, the responsibility of formulating white books lies on the program manager and they are not conducted on a regular basis.

The most common way of accessing previous knowledge at GAS is by having experienced members as part of the team, but the DP online system is also regularly used. The interviews showed that at one confirmed occasion in project D, there was an initial knowledge gathering where all available documentation was brought together and it was referred to as the production platform.

The interviews showed that there is a general view that the IT systems are not fully contributing to support knowledge sharing, but are rather obstacles in the daily work. The OMS is considered to be overly complex, an expression of the ideal world, a way of assuring customers that important procedures are being covered and it is not regularly used in the daily work. The SAP system is considered to be non-user friendly, difficult to retrieve information from and it has issues with data restriction and authorization. Additionally the different IT systems in place, i.e. SAP, OMS and local servers, are not integrated and thus information and documents are scattered.

Right now GAS is going through a transition from having a low awareness and a reactive approach to manufacturing issues, to a higher awareness and more proactive one by promoting a close collaboration between product development and manufacturing. An interviewee expressed it as: *"I think we did something that we haven't done before. We as Volvo Aero or GKN for that matter do something differently, by having a team, one team, not two. There is no them in us, it was a we effort truly".*

White books are not regularly formulated, nor is it standardized how these should be worked with and stored. This leads to fragmented data collection and that it takes a great effort to find relevant documents. Product development stage reviews are performed in each gate, where a specific report is issued by following a standardized process. Wrap-up meetings are done occasionally but are not addressed in the OMS. A problem that was communicated through the interviews is that there is no common practice of following a process that secures LL. The use of DPs, P-FMEAs and having the most experienced people in the startup of new projects together with the issuing of white books aims to secure that the LL can be used in future projects.

At GAS the LL are mainly captured through the DPs, analysis of quality data, P-FMEAs and by using experienced workers. By addressing the incomplete or missing DPs, especially those coming from production, it is suggested by an interviewee that the degree of proactivity in product development could be increased. Another interviewee brings up that measuring the number of *Business Process Improvements* (BPI) could be one way of measuring proactivity.

By getting the failure modes right GAS can identify what requirements are going to be non--conforming, which simplifies the management of information between product development and production. Further, one interviewee suggests that DFSS could be used as a way to become more proactive. Another suggestion is to create and implement process maps that capture manufacturing experience. Yet another suggestion is to explore the contributions of process development to enhance product development. According to the interviews GAS is currently not measuring their level of proactivity and some proposals have been provided during the interviews to this effect and they will be addressed in section 7.3 as suggestions for future research.

GAS is moving from addressing P-FMEAs on a pass/fail basis through stage gate review checklists into a more integrated and standardized approach where previous P-FMEAs are considered in the design work. Right now internal training is being conducted in order to standardize the P-FMEA work further.

Currently, GAS is not measuring the performance of their robust design work, but they have set up the Centre of Excellence Design for Robustness, focusing on risk management, Six Sigma and geometry assurance, including stack-up calculations. The producibility aspect is mainly covered by reducing the distance between product development and manufacturing, and by considering them as one unit. Right now GAS resolves non-conformances based on the data retrieved by the different *Statistical Process Control* (SPC) systems in place.

GAS has been working with Six Sigma for some years and several employees have been trained according to the methodology and are certified black belts. The company itself has also been running some projects based on a Six Sigma approach. However, the methodology has still not been established as a part of the company culture since none of the systems in place has been designed with this approach in mind.

Based on the positive experience from project D, the way the OMS addresses the team setup is in a transition from distant collaboration between product development and manufacturing, to a more integrated setup where representatives from both departments have been brought into close proximity. Without decreasing the degree of formal communication, through scheduled meetings, GAS is increasing the degree of informal communication channels within the project team, which has made the setup more agile. The main tool that is being used to enhance the collaboration and sharing of knowledge is the FMEA. Efforts on using other tools have also been conducted, like QFD, but this only resulted in occasional use of the first of the four houses of quality.

From the interviews it was retrieved that they seem to have vague notions of how the term DFM is actually defined. It has not been explicitly addressed in the OMS, but consciously or unconsciously the mindset has been adopted and is being used among people in product development.

4.4 Benchmarking study

In this section, the findings from the benchmarking interviews will be described in chronological order as they were conducted; first SCA, then SKF and last VCE. A summary of the companies with respective position and duration has been summarized in table 4.2.

Company	Position	Duration (min)
SCA	Master Coach in Design for Six Sigma	180
SKF	Manager Technical standards	60
VCE	Leader Technology Risk Analysis, Process Leader Product Risk Management	90

Table 4.2 - Summary of benchmarking interviews.

To reach the external validity mentioned in *section 2.1* a series of benchmarking interviews with stakeholders in three important, industrial corporations have been conducted. It was decided that one representative from each company would be sufficient to provide relevant input to this study, since these persons were working within similar subject areas as the one under research.

4.4.1 SCA

SCA is a global conglomerate with divisions within hygiene, forest and paper that was founded in 1929 and has approximately 44,000 employees. The focus for the comparison with GAS was the hygiene division located in Gothenburg (SCA, 2016). Representing SCA as an interviewee was the Master Coach in Design for Six Sigma, belonging to the Global Quality Hygiene Business department. It was a semi-structured, face-to-face interview of three hours conducted at SCA's headquarter in Gothenburg, Sweden, at 1 PM on December 16, 2015. Prior to the interview the interviewee was informed about the reason for the interview itself, was asked for permission to be recorded as well as given an introduction to the research area.

SCA brings LL back from manufacturing to product development by having cross-functional product teams. They use two different types of specifications; *customer requirements specification* and *finished goods specification*. According to the interview they use the finished goods specification to capture production and supply chain feedback and these specifications are linked to the customer requirements specifications through a QFD. The customer requirements specifications integrate both customer requirements and design solutions.

In the past SCA has been a company where you needed to know the actual person having specific knowledge, e.g. a glue expert, to access it. Nowadays SCA has implemented a base-QFD, which is a cause-and-effect tool used to carry knowledge. They use all the four matrices in the QFD, from customer requirements to process controls, to define the connections and understand the links but also to address gaps between requirements.

In terms of IT support functions, SCA manages incident reporting on quality in a system where you can sort incidents and make graphs and statistics. They also have a system to handle complaints as well. Further, the specification system contains the two different types of specifications, customer requirements specification and finished goods specification. The system does not support quality records, and therefore they work with QFD. Right now the top priority is to work on setting up document management and quality records.

In SCA product development works cross-functionally together with production, procurement and category. The function known as category is the owner of the brand, product ideas and concept, hence responsible for these areas. The cross-functional approach to product development is used both before and during serial production.

The project managers are responsible for writing down the LL for the product development funnel, but also for conducting a post-launch follow-up with the goal of sharing their learnings. The post-launch follow-up is a milestone in the project itself, and before the project is ended this review should be made.

SCA tries to identify relations between processes and work upstream, all the way up to the customer, and they state that this leads to proactivity. To illustrate the difficulties related to proactive work the interviewee states that *"It's very hard to be proactive if you don't know your system"*. Further, SCA uses modelling through simulation as a way of assessing performance in the product development work. When it comes to measuring proactivity, the only reply from SCA is that they are working on formulating KPIs for quality for 2016.

Currently SCA has a process to standardize FMEAs in the company's defined processes, and they also strive to reuse the FMEAs when it is considered to be possible. The interviewee also emphasizes that the process-FMEA is and should be a living document, updated whenever new knowledge is acquired or new dimensions are known.

Since SCA strives to be close to the respective markets the feedback comes directly from the customers. They have the possibility of calling directly to a dedicated telephone number where they can share complaints or opinions. These are categorized by an operator, who stores them in a database that is reviewed regularly. Further, SCA conducts market research to find out what customers want. For the company the supply chain feedback is an important area and is considered to be important both for the business results and the quality, since they do not want to ship excessive air in trucks.

SCA studies the process parameters affecting product parameters or functionalities using statistical analysis methods. This analysis is conducted in their own factories using the so called Sixpack in the Minitab software as a study tool, which has become very popular since it was launched within the company. However, only a few vital parameters are studied since it would take too much resources to focus on all possible ones. The SPC analysis in Minitab is also used to drive data-based improvement work, and this is important especially in the paper division where the margins are lower than in the hygiene division.

The approach that SCA has in terms of robustness is to start to learn what is influencing what, find the links to process parameters, and address this when the design is set. When considering robust engineering, the key is to understand how the manufacturing capabilities will be translated into product functionality, and this is done through a cause-effect analysis supported by the QFD tool.

SCA started working with DFSS in 2008 and they have internal training to spread and deepen the knowledge. The interviewee is personally responsible for the training and has led 3 classes internally during this period of time. Up until now they have 20 DFSS black belts who in turn are training green belts.

Within product development several different competences are represented, such as specialists in manufacturing, machining and so on. According to the interviewee, SCA has a tradition of being a company where people are close to the production, and it is stated that: *"SCA is more of a production company rather than an engineering company"*. Further, the interviewee stresses that SCA is mainly production oriented. To enhance the involvement and collaboration between the different functions the tools they use are primarily QFD and FMEA.

Lastly, for SCA defines DFM as what is driving cost and demand in manufacturing and how that is brought back into product development. An example is mentioned where unplanned machine stops could be avoided by changing the design in a way that prevents them from occurring. Further, they also include what problems there are in manufacturing and how those can be removed in design into the definition of DFM.

4.4.2 SKF

SKF is a global technology provider that was founded in 1907 and has about 48,000 employees. Their main focus is set mainly on bearings and units, seals, mechatronics, services and lubrication systems (SKF, 2016). Representing SKF as an interviewee was the Manager Technical standards, belonging to the Industrial Market - Technology & Solutions - Product Development department. It was a semi-structured, face-to-face interview of one hour conducted at SKF's headquarter in Gothenburg, Sweden, at 4 PM on December 17, 2015. Prior to the interview the interviewee was informed about the reason for the interview itself, was asked for permission to be recorded as well as given an introduction to the research area.

In SKF most products are incremental upgrades from existing products based on previous design experience. When developing new products they follow a defined PDP that is built on the DFSS methodology that brings together competences and input from the customer, product development and production perspectives. For SKF it takes long time to understand what the customer needs, and they start by conducting the concept design that is followed by developing it into the detailed design stage. To assess the maturity of technology used within design the TRL tool is being used. The early product development phases are about exploring and gathering competences and the later ones are about implementing competences.

SKF is setting up design rules through formulas as a way of documenting their accumulated knowledge. These formulas also include the capability in manufacturing, so they combine product development with manufacturing in order to single out what parameters are more critical. However, they require experience to be fully understood since it can be difficult to trace back where the formulas come from. Addressing this need for experience is a challenge for SKF.

The IT system at SKF is a traditional serving CAD system that is linked to a PDM system, or a widely speaking a PLM system according to the interviewee. They also have a so called research technical report that brings the technical aspects together into a single document. The weakness of this system is that you need to know what you are looking for as it does not have a good *knowledge system* that interacts with the user when searching for information.

In SKF the product development department has two explicit roles. The first role is to develop new products based on the PDP and the second one is to maintain existing products based on a daily interaction with the manufacturing department.

According to the interviewee, white books are written from time to time, but not by default on a regular basis. If an incident is reported or if new knowledge is gained they do it by the end of the project. The white book is structured in a way that it is a mixture of technical aspects and the team work experience. However, the interviewee stresses that it is not done in a normal situation. Worth mentioning is that there is an official responsibility that belongs to the sponsor of the project, but normally it is the manager leading the work that completes the white book. The interviewee states that SKF does not have a structured way of storing them. When it comes to spreading the learnings, again, it is up to the sponsor to see if these LL are unique or if they can be spread out, because often the sponsor is a member in many projects and has room to communicate certain information. However, SKF does not have a specific process for that.

When addressing how the LL could be exploited in order to achieve a higher degree of proactivity in product development, SKF believes that they could be used for setting up the teams. However, the interviewee states that on the technical level the lessons for each case are somewhat unique. SKF doubts that just documenting will contribute to proactivity, that experience is also important and that proactivity is mostly considered to avoid critical situations.

Currently SKF does not measure their performance in terms of proactivity. They argue that having a large number of KPIs turns steering into follow-up and that there should only be a small number, maximum 5-10. Although SKF considers proactivity to be important, it is not considered to be on top of the list of priorities.

SKF conducts FMEAs in what they consider to be the six sigma part of their projects. They have a template that is standardized. Right now they have developed and are implementing what is known as core-FMEAs for their processes, which is a base FMEA that can be used for each manufacturing technology in the whole company. This means that whoever wants to use a specific process can reuse this base core-FMEA as a starting point to cover the basic areas.

In SKF feedback is channeled from the customer to each product line responsible who also compiles it and then it is filtered through a process that involves application engineers. The application engineers' task is to make a difference between technical issues and business issues.

Right now SKF does not measure the robustness performance. However, the interviewee states that the robustness experience that they gain originates from what they do, including a lot of testing for the launch of a new product in the market. They especially emphasize calculations and physical testing, but they have no KPI or other ways of measuring the robustness.

When addressing how work is being improved based on data, the interviewee responded that production is managed between product engineering and process engineering and could not see that they have a lot of data stored in any database. From the service point of view the data goes directly to the factory, normally through the quality manager or engineering manager, but the product development manager does also have that information from the technical part.

In terms of the collaboration and knowledge transfer between the product development department and the manufacturing department there is a combination of push from production and pull from product development. At the same time there is a cost related aspect and there are two streams, one coming from the customer and the other from standardization. To improve the communication between the departments SKF uses two tools; FMEA on a regular basis, but QFD only occasionally. The interviewee is familiar with the term DFM but says that they are not working with it.

4.4.3 Volvo CE

VCE is a part of the Volvo Group that was founded in 1927. Today the Volvo Group employs about 100,000 employees. The main products include industrial equipment for heavy duty such as wheel loaders, crawler excavators and articulated haulers (Volvo CE, 2016). Representing VCE as an interviewee was the Leader Technology Risk Analysis, Process Leader Product Risk Management, Process Verification and Validation, belonging to the Advanced Engineering department. It was a semi-structured, face-to-face interview of one and a half hours conducted via Skype from GAS with the interviewee at VCE at 9 AM on December 18 2015. Prior to the interview the interviewee was informed about the reason for the interview itself, was asked for permission to be recorded as well as given an introduction to the research area.

In VCE the initial loop-back in product development-production is done through a Formal Design Review (FDR). Its purpose is to ensure that the design directions are consistent with achieving system's specification. As VCE does the formal design reviews, they also document and this is part of the product and process history. It is a critical evaluation of the design maturity, which means for example DFM, DFA, impact on takt, potential risks and residual risks in process FMEAs. This information follows the design over its lifecycle. VCE typically does three formal design reviews; the first one in early concept development, the second one in detailed development and third one in final development before handing it over to industrialization.

Product controlling documents such as drawings and CAD models are linked together in the so called TDM system. As a principle, when designs are updated the associated supporting documents are also updated and in that way they have traceability across the product lifecycle. According to the interviewee this is one of the tasks and deliverables for the process owner.

The OMS defines a standardized work, i.e. how to develop and who does what, from an organizational roles responsibilities perspective, supplying standardized work, methods and tools that have to be applied in an appropriate way to get the right results. However, it does not specify the product. The product is specified through a systems specification. In the TDM system VCE has full traceability of the product and the changes, but if they want to trace what happens in the field they have a separate system to do that. That system is called FRACAS and is a failure reporting and corrective actions system that records failures in the field, which helps them to monitor the corrective actions, and tracks what happens in the service phase, see *figure 1.1*.

Before releasing the product to serial production all design and production issues should be solved. VCE makes a distinction between the phases or channels in which the product is being developed and the phases when the product has entered the serial production stage. The first one is the product development and when the product is launched it goes over to product maintenance so there is a continuous flow of information. This way the product development department is aware of production issues before the product is released to serial production.

VCE uses white books in the projects and they primarily cover project knowledge, not necessarily product knowledge. According to the interviewee there are other ways to capture product knowledge, such as why a certain design was chosen or what is driving that design. One method is what VCE calls *product risk managemen*t and consists of conducting FMEA work as well conducting risk reduction work within the FMEA tool. In this way they learn the weaknesses in their designs, how they were addressed and what were the outcomes. According to VCE the D-FMEAs contain a lot of the history.

In VCE the different product development departments are officially responsible for documenting the LL and for keeping those updated. The interviewee states: *"It is part of the engineering to capture and maintain the best practice over time"*. There is a standardized approach defining who, when, how and where to store this knowledge in the OMS.

According to VCE proactivity is very difficult to measure in a standardized way. They measure the maturity of the design, so in the formal design reviews there is a requirement on maturity. Further, the interviewee says that the formal design review is the maturity measurement, and that it is also a clear indicator of the proactivity. However, it is not a KPI and VCE does not believe that a KPI is a good approach in terms of proactivity.

When discussing how P-FMEAs from previous projects are considered in the design work the interviewee states that P-FMEAs stay within manufacturing and that they are not stored in the same system. However, right now they are working on linking these P-FMEAs to the respective engineering documents in the TDM system.

VCE thinks that it is extremely difficult to measure robust design performance for several reasons. Since they have put prerequisites on maturity of FMEAs and those depend on the size of the project, the maturity outcome will vary. Therefore any measurements will be irrelevant.

When a question concerning whether VCE works with Six Sigma or DFSS, the interviewee declares that they use parts of the Six Sigma toolbox. Further, that is one of the reasons why the interviewee has been trained on Six Sigma; i.e. to understand and try to bring in relevant parts of the toolbox.

To the question regarding whether improvement work is based on data the interviewee stated that the system architecture is updated based on what VCE learns continuously throughout product development, production or any given functional system. Further, the interviewee exemplifies that when one learns from warranty data that there is a requirement on a part that is not relevant it should drive an update of the system specification, putting new requirements in place, which in turn should facilitate a design change.

In order to enhance the collaboration between the product development department and the manufacturing department, VCE manages cross-functional team setup with all the necessary interactions and interfaces. To further deepen the collaboration they use FMEA on a regular basis. QFD is being used, but only to a limited extent.

When discussing the familiarity and definition of DFM it is communicated that the interviewee is familiar with the term and it is actively considered through the implementation of a series of checklists in the formal design reviews in order to enforce it.

5 Analysis and Results

In this chapter the analysis and the results of the empirical study at GAS and each of the benchmarking companies respectively will be presented in order to lay the foundation for the conclusions and recommendations in the next chapter. The analysis of the situation at GAS was carried out using two of the seven quality tools (Bergman & Klefsjö, 2010): the affinity diagram and the interrelationship diagram and these will be addressed in section 5.1. A matrix based on the interview templates will be the foundation for the benchmarking analysis and this will be dealt with in section 5.2.

The analysis has been conducted by highlighting key ideas and concepts from the interview transcription. These key ideas have then been grouped into a list of main areas using brainstorming and affinity concepts as a first step in order to see the full picture. 17 main areas were identified and some of these also contained sub-sections, as seen in *figure 5.1*.

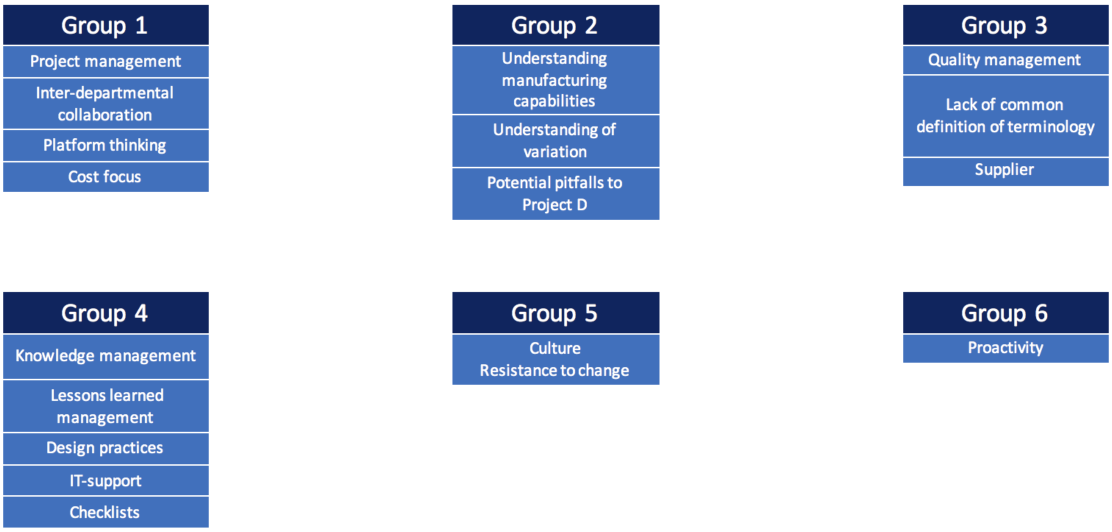

Figure 5.1 - Affinity diagram.

5.1 Analysis of GAS interview data

Based on the list of key ideas, an affinity clustering was constructed to illustrate which areas belong to which groupings. It was shown that some of the discovered main areas were more or less related to each other. In this stage no interrelationships were addressed, but rather the vicinity of the areas according to the researcher's judgement. This analysis resulted in an affinity diagram that will be further described in this section.

5.1.1 Affinity diagram

The first stage of the analysis was done using the Affinity diagram tool (Bergman & Klefsjö, 2010). The affinity grouping was initiated with the 17 main areas and was conducted using brainstorming methods, inspired by the grouping in the Affinity-Interrelationship Method (Alänge, 2009) and a guiding question was put in the top left corner to keep the focus right during the analysis session. It was decided that the affinity between the main areas was the main interest in order to find connections and patterns in the data set, and each one was considered based on the guiding question. Different possible groupings were evaluated first individually between the researchers, but later also together in order to find a consensus solution that illustrated what was seen as the best illustration of the current situation.

The affinity analysis showed that 17 main *areas* could be clustered into six *groups*. Each one of these 17 areas will be defined and described below, together with the rationale that supports the grouping.

Group 1: Project Management decisions

Area 1: Project Management

Internal leadership in the projects and factors originating from the project management itself, such as: time pressure, expectations, resource conflicts etc.

Area 2: Inter-departmental collaboration

Factors related to the integration and collaboration between different functions or departments within GAS. A special focus was set on the interface between the product development and manufacturing departments.

Area 3: Platform thinking

Factors related to a platform approach to product development as a way of increasing the commonality of different products, but also as a means of keeping focus on the high-level production platform.

Area 4: Cost focus

Defined as items specifically related to cost aspects in project management.

Rationale

When clustering group 1 the rationale was that all areas were thought to be related to the project management in some way, which was seen as the main topic and therefore the header was set to *Project Management decisions*. Interdepartmental-collaboration is seen as a result of decisions made by project owners and managers and the same logic applies with the platform thinking area that was an explicit management decision in project D

A weak voice from the manufacturing organization in project A was the result of a power imbalance due to lack of manufacturing representatives and functional support that lead to a deprioritized production focus in the product development. The pressure and focus on cost originates perhaps not from program management, but rather top management. However, the project management should have a say in the way the project is performed, and therefore stand up for the requirements of the project in case the cost pressure becomes too fierce for the project to maintain the level of performance.

Group 2: Lack of common understanding may have consequences

Area 5: Understanding manufacturing capabilities

Addresses issues related to the understanding of manufacturing capabilities in other functions of product development, and mainly within design. The logic is that the clearer the understanding of manufacturing needs are when designing, the easier is the move into serial production.

Area 6: Potential pitfalls to project D.

This area specifically addresses factors related to project D that might turn into issues when during ramp-up, but also external factors that forced the direction of the project into a more conservative path due to material requirements. There were several rapid changes done to the project compared to previous ones, and therefore there might be troubles later on since variation is not visible until 100-200 units have been produced according to one interviewee.

Area 7: Understanding of variation

Addresses issues with lack of understanding of variation throughout GAS and its implications.

Rationale

In this group the understanding of manufacturing capabilities is considered to be the ruling area of interest, and therefore this was set as the main area. The potential pitfalls to project D consists of one quote saying that although 90 percent of the non-conformances were identified before entering serial production, still 10 percent remained after the first five parts in serial production. By referring to Bohn's eight stages of process knowledge mentioned in *chapter 3*, it could be assessed that project D was in a high stage of process knowledge, but without reaching the top of the scale (stages 6-7, empirical equations or scientific models). This proves that the understanding of the manufacturing capabilities were still unclear during the product development and therefore this could be seen as a subset in this group. If this had been better known, at least in theory, all non-conformances could have been solved before the serial production. Lastly, if there is a poor integration between product development and manufacturing, the knowledge in the product development regarding what consequences occur in manufacturing, such as process variation, will likely be missing as well. However, by integrating the two departments and increasing the common understanding, also the awareness of effects later in the development chain such as variation will increase.

Group 3: Quality performance may be affected by external stakeholders and lack of common language

Area 8: Quality Management

Refers to factors connected to the use of quality tools and quality measures along with related issues.

Area 9: Lack of common definition of terminology

Consists of problems related to a lack of common understanding of concepts and tools.

Area 10: Supplier

Factors referring to the importance and influence of suppliers.

Rationale

For this group quality management was seen as the main area with two subareas. The lack of common definition of terminology belongs here since the concepts that have not been defined generally are quality related. The internal three-letter acronym for the dedicated robust design department is confusing people even more as they think it is a quality concept or tool. The supplier area fits in here since a lack of emphasis on this will mainly have quality related effects such as increased variation and this will impact quality performance such as deliverability and costs.

Group 4: Knowledge generation, transfer and support

Area 11: Knowledge Management

Summarizes the general approach to knowledge transfer and the means of doing so. The main focus is set on how knowledge is gathered, influence from project team selection, meetings, internal training and implicit knowledge and a resistance to share this.

Area 12: Lessons Learned Management

Addresses how LL and learnings in general are collected, documented and stored. The connection to the OMS is specifically addressed.

Area 13: Design practices

Factors related to the internal design practices.

Area 14: IT support

Influence from the IT support functions, such as: SAP, OMS, DP online as well as implications stemming from poor support functions.

Area 15: Checklists

Addresses the different perspectives of using checklists throughout the product development process.

Rationale

In this group the knowledge was seen as some kind of overall grouping and was therefore selected as the main area. LL management is seen as a logical subset of it since KM partly regards the LL. The design practices should also fit in here since it they are mainly seen as a way of transferring experience and knowledge from previous solutions to new ones. The IT support could fit in anywhere, but in this study it is seen from the KM point of view and should therefore be related to how knowledge is handled in general, and to what extents the IT system supports that. Checklists is considered to be an important part of knowledge assurance since it forces you to make an active consideration on whether the objectives have been fulfilled or not.

Group 5: Culture/Resistance to change

Area 16: Culture/Resistance to change

General approach to system-wise resistance to change within GAS. This area can also be seen from a company culture point of view.

Rationale

This topic is sufficiently pervasive and self-standing that it was sorted as a group on its own.

Group 6: Proactivity

Area 17: Proactivity

An area that covers the aspects of proactivity, especially in the early stages of product development.

Rationale

Just as with resistance to change, this topic is sufficiently pervasive and self-standing that it was sorted as a group on its own in order to provide a base for the interrelationship analysis later on.

5.1.2 Interrelationship diagram

The second stage of the analysis at GAS was conducted using the relations diagram or interrelationship diagram (ASQ, 2016, Bergman & Klefsjö, 2010) with the purpose of finding connections between the groups identified in the affinity section. To allow for an easier evaluation of the interrelational connections, inspiration was drawn from the corresponding step in the AIM tool and the groups were arranged in a circle according to the instructions related to the AIM tool (Alänge, 2009). By going through the areas systematically, clockwise, each possible connection was assessed. Only one-way connections were considered in order to find the strongest direction of influence. In the cases where interrelations could be drawn in both directions, only the strongest one was considered. The summary of the identified interrelations is found in *figure 5.1*.

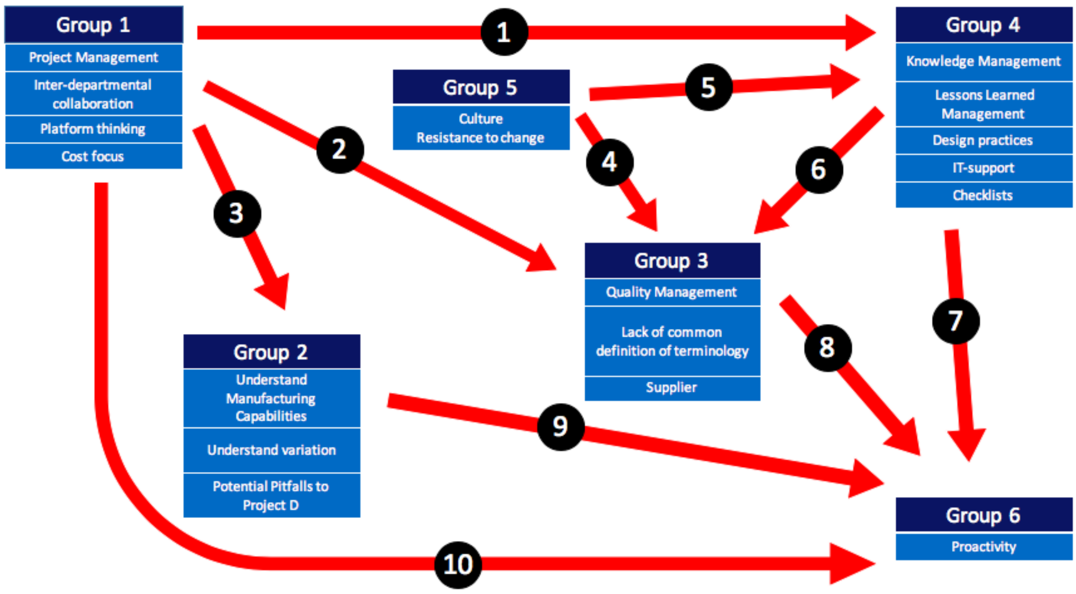

Figure 5.2 - Affinity and Interrelationship diagram.

Interrelationship 1
Project Management decisions → Knowledge generation, transfer and support

It was determined that the performance in terms of KM is a result of the way projects are being managed. Therefore, it is logical that an interrelationship arrow goes from Group 1 to Group 4. In project D a platform thinking was adopted, together with an extensive focus on intermediate trials and testing which was an active effort to increase the project learning. This means that project management had an active role and made a conscious effort in knowledge creation and distribution. In project A, on the other hand, the initial knowledge buildup was not considered to be a top priority. Goffin et al. (2010) make an explicit emphasis on management involvement as a key element supporting knowledge transfer. Koners and Goffin (2007) in Goffin et al. (2010) state that: *"Without senior management support, PPRs are often perceived as extra, unnecessary work at the end of a project. In this case, meetings will not be treated seriously and will be ineffective".*

Interrelationship 2
Project Management decisions → Quality performance may be affected by external stakeholders and lack of common language

Quality management should be considered to be a result of the project management and its approach and decision making, therefore there should be an arrow from Project management to Quality management. In project D project management established the PPAP as a quality assurance tool for the first time at GAS. The incomplete quality metrics and the potential from the quality metrics Q3's and Q4's is dependent on how the projects are being managed. Consistent with the *cornerstone model* addressed in *chapter 3*, project management sets the agenda and is therefore impacting the quality management. This is expressed in Bergman and Klefsjö (2010, p.48) as: *"It cannot be emphasized too much how important strong and committed leadership is (...) for successful and sustainable quality improvements".*

Interrelationship 3
Project Management decisions → Lack of common understanding may have consequences

The researchers found that there was a connection between project management decisions and the lack of common understanding. Since management in project D decided on a more integrated team setup, an increased understanding of manufacturing capabilities followed. In project A there was a lack of understanding and this should mainly have been a consequence of project management's acting. Further, the potential pitfalls in project D can be addressed only if the project management strives towards that. According to the cornerstone model of TQM mentioned in *chapter 3*, project management decisions have an impact on the level of team integration, formulated by Bergman and Klefsjö (2010) as: *"it is essential to create conditions for participation in the work for continuous improvement"*.

Interrelationship 4
Resistance to change → Quality performance may be affected by external stakeholders and lack of common language

The culture group has been classified as a source in the interrelationship diagram because the resistance to change is built-in into the mindset of some members and thus is present, to a minor or major extent, at every level in the organization. In this case it has consequences on the quality management since some individuals will be working against any improvement efforts and therefore hinder or hold back the change processes. An awareness of this factor is central in order to become successful. According to Bergman and Klefsjö (2010), if the companies work with Quality Management is to be successful the improvement work shall rest on a culture based on the values collected in the cornerstone model. One of these values is continuous improvement, so an organizational culture that does not have continuous improvement as one of its core values will negatively impact in its overall quality management.

Interrelationship 5
Culture / Resistance to change → Knowledge generation, transfer and support

It was found that the organizational culture and mindset influence KM. The empirical data from GAS shows that some individuals within the company have a resistance to share their knowledge in order to be unique and not to be challenged in their position and therefore major improvements in the KM area would be possible to achieve if this culture flaw would be made by nurturing a culture that promotes and encourages knowledge sharing.

According to the spiral model for knowledge creation by Nonaka (1994) mentioned in *chapter 3*, the organizational culture should encourage the interaction between individuals and individuals, and between individuals and the organization as these are the basis of knowledge generation. However, right now at GAS some individuals do not actively consider sharing their knowledge and thus the internal KM is not fully developed. One interviewee expressed it as: *"I think it is hard to get some knowledge from the engineers and I would say that it is not that it is hard to collect it, it is because they want to be unique, so they do not want to let all of their knowledge be spread because you will not be unique anymore, other people can come and challenge you in the role you have"*.

Interrelationship 6
Knowledge generation, transfer and support → Quality performance may be affected by external stakeholders and lack of common language

There is an interrelationship from KM to quality management. The reason is that by managing the knowledge in the right way it is possible to make quality improvements. There are three main reasons why this is the case. First, the main way of improving quality based on knowledge is to bring in people having tacit knowledge into the processes. The figures for project A are now being improved after bringing in experienced people into the improvement work. Second, knowledge is divided into two parts: tacit and explicit. If there is a quality issue in a process it is often that the tacit knowledge has not been converted into explicit knowledge and the way the knowledge is being managed needs to be improved. Third, the learning process is not only in the own company, but also at the supplier. By realizing the need of continuous learning work both internally and externally the quality performance can be improved. In project A there were issues with a vital supplier and when problems occurred it lead to severe issues for a long time afterwards. A more integrated approach of KM together with the supplier could overcome such difficulties. As it was already mentioned in *chapter 3*, several studies like the one by Durcikova & Gray (2009) show the contribution of KM to quality improvement initiatives. In this case KM has had an impact in both internal and external quality. Internally because the quality results have improved or are improved by bringing in experienced individuals and externally by working together with the supplier.

Interrelationship 7
Knowledge generation, transfer and support → Proactivity

The analysis showed a connection between KM and Proactivity. If knowledge is managed in the right way, it is possible to avoid repeating previous errors that have already been solved and thereby prevent problems from reappearing. Lui et al. (2013) expressed this as: *"The lack of awareness of other capabilities or the waste of resources in reinventing the wheel are potential risks of losing business opportunities"*. For apparent reasons it is preferable to reuse a solution rather than coming up with one over and over again, and therefore a structured approach to KM will lead to a more proactive process. Bringing in knowledge from experienced people into the project and allowing the project to have a learning phase were KM decisions that contributed to the proactivity of project D.

Interrelationship 8
Quality performance may be affected by external stakeholders and lack of common language → Proactivity

Since well-performing quality management should lead to fewer errors occurring and thereby fewer problems coming up, quality performance is connected to proactivity. If the number of non-conformances is reduced a more well-functioning process appears and this leads to a more proactive way of working. The PPAP is a proactive quality management tool that leads to problem solving before they appear, and by introducing this approach in project D more proactive work was done. Another reason is that the customer has reduced manpower to deal with non-conformances, hence more pressure is put on the quality management function. GAS needs to have a proactive quality management to avoid being customer dependent to solve the aforementioned non-conformances.

Lastly, incomplete quality metrics that are volume dependent, non-standardized use of Q3's and Q4's as well as a lack of system traceability where non-conformances can not be linked to specific products can lead to more proactive work if managed in the right way, but also a reactive firefighting approach if managed poorly. Quality metrics for project D were significantly better than the ones for project A partly due to a proactive approach to the quality management by using tools like the PPAP (to this respect see Hermans & Liu, 2013 in *chapter 3*) or the awareness that the customers cannot handle any non-conformances due to lack of staffing. This was stated by one interviewee as: *"You cannot send any non-conformances, because they* (customers) *have drastically minimized the personnel on their side to save money, so we know that it will take a lot of time, and it could take like up to three months if you have a very severe non-conformance. It is very expensive for us to have a lot of parts standing here, so for economical reasons you need to get rid of them"*.

Interrelationship 9
Lack of common understanding may have consequences → Proactivity

There is a connection between understanding of manufacturing capabilities and proactivity since improving the understanding of the later stages in PDP will result in a more suitable design and thereby fewer quality issues. If, on the other hand, a design is pushed out instead of pulled, and no manufacturing concerns are taken into consideration, severe difficulties will occur when reaching serial production. Therefore, the understanding should be built up by, for example, experimenting or conducting tests and trials. Project D adopted a proactive approach to understanding manufacturing capabilities by having an early involvement of manufacturing in the product development process. This corresponded to modes 3 and 4 in the model of upstream-downstream interaction described by Wheelwright and Clark (1992, p.172).

Interrelationship 10
Project Management decisions → Proactivity

The last interrelationship identified is between project management and proactivity and the reason for this is that if the proper management focus is lost, the proactivity will suffer from that. For example, if available resources are not used in the right way sub-optimizations might lead to poor performance downstream. Time pressure caused by misdirected project resources can also lead to poor proactivity. Further, if the understanding of variation is missing because of project management it may lead to increased variation related problems in production and therefore more resource demanding and reactive firefighting. Firefighting was frequent in project A, where reactive behaviour was a common approach to problems, especially after some time when the design intent got lost. This denoted a clear *single-loop* approach where problems were solved upon detection. In contrast, project D adopted a *double-loop* learning mechanism in order to be more adaptive to changes in the competitive environment (see *chapter 3*). Lastly, the analysis shows that if management does not demand something this will not be fulfilled, and that running two demanding projects in parallel will challenge the availability of resources, reducing the proactive performance.

The relationship between management, leadership and proactivity is present throughout the literature. As stated in chapter 3, the two models presented in *figure 3.21* and *figure 3.22* by Wheelwright and Clark (1992) address the four types of development teams and the interaction between product development and manufacturing. When applying the two models on Project A and Project D, it is seen that Project A had a more functional team structure with less integrated communication. The manufacturing representative had a lower functional support and experience and was under direction from the functional manager. In project D there was more of a heavyweight team structure, where the manufacturing function was empowered within the product development team. The communication was more integrated with four or five functional representatives, they were more experienced and were under direction from the project manager.

Further, in uncertain environments proactive employees think ahead and create opportunities for a more adaptive and creative organization. Therefore, proactivity is crucial to the innovation process and both team and organizational leaders play an important role in developing the proactivity of employees (Strauss et al., 2009). Team leaders have an important role in developing employees' confidence to suggest new ideas, while organizational leaders are more important in developing feelings of attachment and identity about the organization (Strauss et al., 2009).

5.2 Benchmark analysis

The benchmarking analysis was done in order to provide external aspects of the research area from large manufacturing companies present in similar contexts as GAS, but within other industries than aerospace. The three companies that were identified as suitable were SCA, SKF and VCE. A summary of the findings from the three interviews as well as the related findings from GAS have been summarized in *appendix B*. Each part of this table will be dealt with in this section.

The benchmarking matrix was constructed based on the questions addressed during the interviews and it was filled out with a summarized answer for each topic. The GAS column was completed based on the data from the interview study at GAS. As for the GAS column, it was completed based on what was brought up in the interview study at GAS and summarized with qualitative judgements by the two researchers. The last column provides the main points of the benchmark analysis based on the data retrieved from the interviews.

5.2.1 Current lessons learned practice

In the first question the interviewees were asked to describe how the *process of bringing LL from manufacturing to product development* was being managed. It was found that SCA mainly focuses on cross-functional teams and requirement specifications. They make a distinction between customer requirements specifications and finished goods specifications and the connections between these two are found by using QFD (see section 4.3.1). SKF points out that most of their products are incremental upgrades. Their product development process is based on DFSS methodology and brings together input from customers, product development and production. Further, they use TRL to examine if a design is ready to be launched for serial production. VCE emphasizes the formal design reviews and its implications on how LL are brought back from production to product development, and the influence of design maturity assessment. An important part of the development is DFM, DFA, impact on takt, potential risks and residual risks in P-FMEAs. GAS is aware of the importance of bringing LL from production to product development and some efforts are being made to this effect, but they are scattered into loosely connected areas: OMS gate reviews, standardization of P-FMEAs, wrap-up meetings and white books.

The second question addresses how the accumulated *knowledge from previous projects* is *accessed* in the product development process. SCA expresses that they used to rely heavily on internal experts. Now they have moved into using a full QFD with the four houses of quality as a carrier of knowledge, but also to address gaps between requirements. SKF on the other hand is using formulas including capability in manufacturing in combination with product development as a way of capturing knowledge and distinguish what parameters are the most important. According to Bohn's eight stage model of process knowledge described in *chapter 3*, SKF should be placed somewhere between stage 6 and 7 (empirical equations, scientific models). However, an issue with the formulas is that they require some experience to comprehend. VCE uses links between product controlling documents in a TDM system. When updating a product the corresponding support documents are also updated and thus providing traceability throughout the product life cycle. Apart from accessing knowledge through experienced project members, GAS uses DPs as a means of transferring knowledge. Occasionally data of previous knowledge is gathered in the beginning of projects, but this is not a standardized procedure. Further, there has been efforts on implementing QFD but it only lead to occasional usage of the first house of quality.

In terms of the impact of the *IT system* on how knowledge is brought into product development, SCA uses incident reporting and complaints handling systems. Further, it separates specifications as customer requirements and finished goods. Since the systems do not support quality records QFD is mentioned as the main solution to overcome that, but the main focus right now is to set up document management and quality records. SKF is using a PLM system to gather CAD documents in a PDM system. Chen et al. (2013) highlight some of the benefits in implementing a PDM system: providing single source for all design content, customer collaboration, quick response to customer queries, time to market reduction among others. There are problems, however, in the access of data in the system as you need to know what you are looking for in order to find it. For VCE the OMS defines how the work is standardized and the TDM is the main source of gathered knowledge. Events such as failures and corrective actions occurring in the field are logged in a FRACAS. In GAS there is a general view that the IT systems do not support the knowledge transfer in a satisfying way. The OMS is considered to be overly complex and somehow regarded as an idealization of the procedures actually used to provide PDP visibility to customers and auditors, and it is irregularly adopted in the daily work. The SAP serves as the main document storage, but it is hard to retrieve data and there are issues with restrictions and authorization.

When it comes to *awareness of production problems in* the *product development* work both SCA and SKF have a cross-functional approach with close interaction between different departments. Product development at SKF has the double objective of maintaining existing products and developing new ones and this approach goes for VCE as well. After product launch the responsibility is handed over to product maintenance. GAS is going through a transition from low interaction between product development and manufacturing with an "us and them" mindset into a more integrated setup with higher awareness and a more proactive approach.

The usage of white books differ between the companies. VCE has a standardized approach and uses white books in all projects, while SKF and GAS have not implemented them as a standard, but more on an occasional level. For SKF they are used when an incident has been reported and it is the responsibility of the project sponsor. In SCA it is up to the program managers to write down LL and conduct any follow-up related to this. SKF and GAS have in common that they do not have a standardized way of storing LL or white book documents.

According to VCE there are other ways to capture product knowledge than white books and they are working with product risk management by conducting FMEAs and FMEA risk reductions in order to discover weaknesses in the design, how they were addressed and what the outcomes were. Further, they argue that D-FMEAs contain a lot of the design history. All companies have in common that they follow a stage gate approach where review reports are issued in each gate. In GAS there is not a common practice of how LL are collected and secured.

As for how LL are assessed for future applicability it is up to the sponsor within projects at SKF. In VCE the it is up to each department to document LL and there is a standardized approach defining who, when, how and where to store the knowledge in the OMS. For GAS the way of assuring future applicability is through white books, DPs, P-FMEAs and by having the most experienced people involved in the start-up of new projects. As for SCA no clear data was retrieved on this topic.

SCA addresses proactivity by walking both downstream and upstream all the way between the process and the customer. Additionally, the interviewee stated that "*It is very hard to be proactive if you do not know your system*". Further, they pinpoint models to simulate and assess product performance as a possible way to become more proactive. SKF thinks that LL could have proactive effects if used in the project team selection, but the technical differences between projects make it hard to generalize based on previous learnings and doubts that documentation will lead to proactivity. GAS thinks that addressing missing or incomplete DPs could lead to improved proactivity, but also that successfully identifying the failure modes in the P-FMEA could contribute. Three additional suggestions that came up from interviews at GAS were 1) that DFSS could be used to enhance proactivity, 2) to implement process maps illustrating manufacturing capability and 3) to explore the contributions of process development to enhance product development. As for VCE no clear data was retrieved on this topic.

When it comes to measuring proactivity no company has identified a way to do this. SCA is working on formulating quality KPIs for 2016. SKF thinks there is a risk in having too many KPIs and that it should be a small number, no more than 5-10, and proactivity is not prioritized. VCE thinks it is difficult to measure in a standardized way. Instead of measuring proactivity, VCE focuses on the maturity assessment in the formal design reviews and they do not believe in KPIs for this. Currently GAS does not measure proactivity but it is an area of interest.

Some of the companies reuse FMEAs. SCA does it and also thinks the P-FMEA should be a living document. SKF uses a generic template for FMEAs, but is also developing a core FMEA to serve as a base for one manufacturing technology for the whole company, which means that anyone who wants to use a process can use that FMEA as a starting point. In VCE, P-FMEAs stay within manufacturing and are stored in a separate system. Right now they are working on linking the P-FMEAs to the other engineering documents in the TDM system. GAS is moving away from considering P-FMEAs as check/no check in a stage gate review checklist into a more integrated and standardized approach where previous P-FMEAs are considered in the design work. To manage the P-FMEA work internal training is conducted in order to standardize and align the use of these documents.

5.2.2 Robust Engineering

SKF and GAS do not measure the robust design performance at all. SCA studies the parameters affecting product characteristics or functionalities, but only a few vital parameters are followed up as it would take up too much resources to focus on all. The tool being used is the so called Sixpack in the Minitab software, which has become very popular internally since it was adopted. In VCE they think it is difficult to measure robust design performance because of the differences in FMEA maturity related to size and scope of project.

SCA strives to find the links to process parameters in order to understand what is influencing what and how manufacturing capabilities can be translated into product functionality, which is done through a QFD. For SKF robustness experience is collected by conducting extensive market testing before launching a new product. GAS has set up a dedicated robust design department focusing on geometry assurance, stack-up calculations as well as solid mechanics analysis and aerodynamics calculations with different parameters. The producibility aspect is covered by reducing the distance between product development and production together with considering them as one unit. As for VCE no clear data was retrieved on this topic.

5.2.3 Design for Six Sigma

SCA has been working with DFSS since 2008 and they train black belts internally. Right now they have about 20 black belts who in turn train green belts. When SKF develops a completely new product they have a process, PDP, which is based on DFSS. VCE states that they are using certain tools and they have black belts who are trained in order to bring in relevant parts of the toolbox. GAS has been working with six sigma for some years and several employees have been trained and certified as black belts and they have run some six sigma projects. However, it has not been established in the company culture as few processes have been built on the methodology.

In SCA improvement work based on data is driven by SPC in Minitab, and this is particularly important in the paper division where the margins are lower than in the hygiene division. SKF makes a distinction between the production and service aspects. As for the production function the degree of integration between product and process engineering is high and therefore the interviewee cannot see that there is any large database, since there is no need for it. For the service a part of the data goes directly to the factory through the quality or engineering managers, but the product development manager has the information as well. In VCE the system architecture is constantly being updated based on learnings made in production, or for example based on warranty data showing non-relevant requirements on a part. For GAS the focus is currently set on solving non-conformances by using different SPC systems, and the approach is rather reactive than proactive.

5.2.4 Collaboration between Design and Production

When asking about what the interface looks like between product development and production, but also what the level of integration is between them the replies differ. SCA says that there is a cross-functional setup of the product development teams and that they consist of for example production or machining people. Further, they argue that SCA is more of a production company than an engineering company. SKF works with a combination of push from production and pull from product development, together with a constant cost reduction focus. There are two streams of communication; one stemming from the customer and one from standardization.

VCE too has a cross-functional setup with close collaboration between product development and production. Based on the successful project D, GAS is updating the team setup and selection procedures in the OMS to a more integrated approach and a closer proximity between representatives from product development and production. Further, without decreasing the formal communication, for example scheduled meetings, this also results in GAS increasing the informal communication which makes the setup more agile.

SCA, SKF and VCE are using both QFD and FMEA as collaboration tools. GAS uses mostly FMEA. All four companies use FMEA as a collaboration tool between product development and manufacturing. However, VCE has a very limited use for QFD and for GAS, QFD is not considered at all as a collaboration tool between them.

The DFM concept is generally familiar to the interviewees in all the companies. For SCA it is about the cost and demand drivers in manufacturing and how these are brought into product development. An example is that unplanned stops need to be designed away. For SKF the concept is familiar but they are not working with it. VCE on the other hand considers it to be familiar and they are actively working with it by having implemented a number of checklists to enforce it. In GAS there is generally a vague notion of how the term is defined and it has not been explicitly addressed in the OMS, but the mindset is however adopted by people within product development.

6 Conclusions

The research questions for this study will be addressed in this chapter based on the analysis conducted in the previous sections and the answers serve as a foundation for the following recommendations in the next chapter. A summary of the conclusions from the findings have been clustered in table 6.1.

RQ1. What were the critical success factors in the evolution from a problematic project to a more successful one that contributed to proactivity?

The analysis of the evolution from project A to project D showed that there are a number of key factors that the authors consider to be of critical importance to the success, where the factors with a rating of at least eight on a one to ten scale were considered as critical success factors and these can be seen in *table 6.1*.

First, it was concluded that the requirements in project D that demanded a material that could not be cast was a coincidence that influenced the global performance of the project to a great extent since it reduced the complexity in production. If a similar approach to material selection would have been applied in project D as as the one adopted in project A, the authors believe that the outcome would have changed substantially.

It was also concluded that by solving mismatches from project A regarding the understanding of manufacturing capabilities in product development, project D was given prerequisites to achieve a vast performance improvement. Further, it was found that the emphasis on testing and trials was crucial to get applied knowledge on design concepts, without having to rely solely on simulation and computer modelling.

Rating (0-10)	Analysis area (figure 5.1)	Factor	Project A	Project D
10	Area 6	**Material selection**	Cast material	Forged material
9	Area 2	**Proximity of product development/manufacturing**	Separate buildings	Team working within close distance (implemented in OMS)
9	Area 2	**Collaboration product development/manufacturing**	Poor	Integrated
9	Area 2	**Empowerment of manufacturing**	Low	Same as others
9	Area 1	**Project Management**	Short-term focus	All team members set the balance between requirements
9	Area 5	**Awareness of manufacturing capabilities in product development**	Low	High
9	Area 5	**Testing, trials and forerunners**	Immediate jump into production	Extensive testing period
8	Area 2	**No. of manufacturing representatives in product development**	1	4-5
8	Area 1	**Pre-awareness of serial production volumes**	Poor	Detailed

Table 6.1 - Summary of identified critical success factors at GAS.

The project management was considered to be a greatly influencing, where especially the lost design focus, pre-awareness of future production volumes prior to the project, management requirements referring to that a project only reaches what the managers ask for as well as the lack of resource conflicts with other parallel projects as critical success factors in project D. One interviewee at GAS expressed this as: *"(...) managers need to ask for the right things and the right persons need to interact in order to get the results"*. Senior management commitment and accountability to product development together with a well-defined strategy, are three of the CSFs described by Cooper and Kleinschmidt (2007), see *section 3.3.6*.

Another crucial factor was the inter-departmental collaboration between the product development and manufacturing. This refers to especially the evolution from a total focus on solving daily issues and firefighting into an integrated setup together with an empowered manufacturing function with an equal balance of requirements from different competences in the team. The empowerment was done not only in terms of responsibility, but also in the number of function representatives. Further, it was concluded that the pre-awareness of the future production volumes in project D was a critical success factor that resulted in a better performing project. In project D the manufacturing site was selected early, which also impacted to performance in a significant way. Lastly, there was a key decision in project D where the product development team was co-located with the manufacturing team, which according to the researchers was a critical success factor to enhance the communication. This cross-functional way of working is consistent with one of the eight CSFs that distinguish better performing organizations identified in Cooper and Kleinschmidt (2007), see *section 3.3.6*.

RQ2. *What are the main critical success factors for a proactive product development process that are considered by large industrial manufacturing companies in Sweden?*

The benchmarking study highlighted nine areas that have been important for SCA, SKF and VCE, see *table 6.2*. The identified factors were grouped into 9 clusters depending on similarity between the procedures found in the different companies and these were colour coded to single them out as seen in the figure. It should be noted that there is no ranking between the different clusters.

One critical success factor that has been apparent in all companies, including GAS especially in project A, is a high degree of cross-functionality in the product development. The use of FMEA is also a factor that all companies have in common and that is considered to be critical in order to be proactive within product development. A difference between GAS and some of the other companies' ways of using FMEA is that they have a standardized core FMEA that can be reused, in order to to avoid repetitive work and to assure that crucial and relevant factors are included in the risk assessment.

Another difference is the way QFD is being used, where especially SCA and SKF have implemented all four houses of quality as a way of capturing the connections between customer requirements and process controls. The use of QFD is also linked to the awareness and understanding of the system, which is concluded to be of critical importance for the performance. If the system perspective is not covered, there will be sub-optimizations in the processes. It was also seen that the IT system that is considered to rather an obstacle than an asset, can be utilized differently. It was concluded that traceability of product changes is one critical feature to cover in the IT system as well as the maturity assessment of a design or technology before adopting it, for example using TRL.

According to Cooper and Kleinschmidt (2007) the first CSF that distinguishes better performing organizations is a high quality new product process, and the benchmarking companies apply QFD and FMEA together with IT-systems that support traceability as relevant elements in their respective PDP.

	SCA	SKF	VCE
Teams	Cross-functional teams	Cross-functional teams	Cross-functional teams
		Team selection for proactivity	
FMEA	FMEA	FMEA	FMEA
	Standardization and reuse of FMEA	Core FMEA	Maturity assessment of FMEA
QFD	Full QFD	Full QFD	
	Base-QFD		
IT systems	SPC	PDM IT system	TDM system
			Traceability
		Research technical report	FRACAS
			OMS
Maturity assessment		TRL	Maturity assessment of design Don't measure proactivity numerically
Integration of manufacturing and design	DFM	Design rules formulas	
	Awareness of importance of M		
Systems thinking	System awareness		System awareness
Continuous improvement cycles	DFSS	PDP based on DFSS	Formal design reviews all through the PDP
Distinction between specifications	The two types of specifications		

Table 6.2 - Summary of identified critical success factors from benchmarking.

Similarly to what was discovered at GAS, it was concluded that a deep understanding of the awareness of the importance of manufacturing, as well as an understanding of the capabilities within manufacturing are critical success factors for a proactive product development. This awareness was enhanced by a cross-functional team setup, another CSF cited in Cooper and Kleinschmidt (2007). Another way of becoming more proactive is to adopt a process based on DFSS methodology and principles (see *chapter 3*) and this is something that is commonly used among industrial companies. The researchers concluded that non-conformance challenges could be addressed by making one set of incoming specifications from customers, and one set of outgoing specifications and by comparing these quality gaps could be highlighted.

Lastly, the empirical study showed that measuring proactivity is not the ideal way of addressing the topic since the there is no common understanding of how the term is actually defined within the organization. Therefore, a unified comprehension around this concept should be established as a starting point.

RQ3. *What critical success factors in the product development process should GAS consider in order to improve its proactivity in the product development process?*

Based on the previous conclusions five critical success factors were considered to be of highest importance to GAS, and should therefore be addressed in order to achieve an improved proactivity in the product development process. It was found that FMEA is considered to be a possibility of transferring knowledge within GAS, and by adopting a more standardized approach with a core FMEA the proactivity could be improved by reusing existing knowledge. The QFD could be exploited to get a deeper understanding of the system and to connect the incoming customer requirements with process controls in order to achieve a higher degree of proactivity. In *table 6.3* a summary of the identified critical success factor gaps can be found.

	SCA	SKF	VCE	GAS
FMEA	Standardization and reuse of FMEA	Core FMEA	Maturity assessment of FMEA	Working on standardizing FMEA
QFD	Full QFD Base-QFD	Full QFD		
IT systems	SPC			
		PDM IT system	TDM system	SAP + local servers
			Traceability	
		Research technical report	FRACAS	
			OMS	OMS
Maturity assessment		TRL	Maturity assessment of design Don't measure proactivity numerically	TRL (in project D)
Integration of manufacturing and design	DFM	Design rules formulas		DPs (incomplete)
	Awareness of importance of M			
Systems thinking	System awareness		System awareness	
Continuous improvement cycles	DFSS	PDP based on DFSS	Formal design reviews all through the PDP	Formal design reviews all through the PDP
Distinction between specifications	The two types of specifications			

Table 6.3 - Summary of identified critical success factor gaps.

It was also concluded that having product specifications both before and after the manufacturing process would increase the proactivity performance since mismatches caused by the process would be highlighted. To improve from GAS current level of performance it was concluded that emphasis should be put especially on increasing the traceability of product changes and non-conformances by gathering all technical documentation in the same system, but also by analyzing production data using SPC, in order to get more support from the IT systems. As it was stated in *chapter 3*, process control triggers learnings that are the basis of process knowledge (Slack & Lewis, 2011).

7 Discussion

This chapter is structured in three main sections. In the first one the authors will deliver their recommendations for GAS based on the conclusions in the previous chapter. In the second section there is a brief, critical, discussion of the research methods employed in this study while the third section will offer a series of suggested areas and topics related to this study for future research.

7.1 Recommendations

This section has been divided into three parts, separating the recommendations based on feasibility of implementation based on technical and economical considerations into the short, medium and long term.

7.1.1 Short-term perspective (0-1 year)

In this section the recommendations that should be implemented within one year are mentioned.

1. **Standardize the team setup practices developed in project D to deal with design related failures.**

This study concluded that the critical success factors for project D could be sorted in two main groups: those that made an impact on the *design failures* in manufacturing and the ones that contributed to mitigate *robustness failures* described in Christensen (2015) (see *chapter 3*). The new team setup practices introduced in project D made a decisive contribution in solving *design* related *failures,* i.e. collaboration between manufacturing and design, co-location of team members, empowerment of the manufacturing organization and others, and accordingly GAS should capture this approach to team setup by standardizing it as an organizational practice for every new project.

2. **Structure the spread of project-to-project learning around kick-off meetings, knowledge brokers, post-project reviews and lessons learned documents.**

The cross-functional team setup that effectively contributed to the successful outcome of project D is currently being extended to new and running projects across GAS. However, the organization should consider a more structured way of tapping into the knowledge generated with each project by carefully examining the five points described in Goffin et al. (2010) (see theoretical framework section), especially the designation of specific team members as knowledge brokers and the crucial role of kick-off meetings as an opportunity to disseminate existing knowledge. Some mechanisms for an effective transfer of lessons learned from one project to another are still missing or are deficient like e.g. post-project reviews and lessons learned documents are already existing and in place but are not consistently used in a standardized way or a visible role of a knowledge broker for each project. Iamratanakul et al. (2014) find that *follow-up work* is the main critical, operational, success factor influencing the performance of a project and therefore this should be emphasized by GAS.

7.1.2 Medium-term perspective (1-3 years)

In this section a recommendation that should be applied within a time frame of one to three years is mentioned.

3. Resume the full QFD study and continue working towards a core FMEA as a way to further improve proactivity in product development

Besides their traditional engineering applications, the combined use of QFD and FMEA in product development as strategic tools positions the organization for success even before the design work has begun (Johnson, 1998). Based on the successful application of quality tools like *base-QFD* and *core-FMEA* in other major industrial companies in Sweden to acquire, spread and increase process capability knowledge, GAS should consider paying more attention to these tools and their contribution to a proactivity in product development.

GAS has already had some previous experiences with these tools, but the QFD work was left incomplete at an early stage and the FMEA is currently undergoing standardization efforts. The organization is encouraged to follow this direction towards a fully standardized FMEA that can eventually set the basis for a core-FMEA but also to support and to bring back the QFD as a way of linking product features with process capabilities and process controls.

Dikmen et al. (2005) recommend four CSFs to consider when implementing QFD in order to enhance the performance. These CSFs are: 1) employ QFD computer software and maintain QFD knowledge through e.g. training, 2) apply the tool in the early stages of projects as soon as possible in order to avoid late engineering changes, 3) great care is needed when formulating the QFD teams as subjectivity, experience and knowledge is crucial for the output and 4) use of quality tools such as affinity diagrams and tree diagrams to reduce customer needs into manageable and measureable numbers. By following these factors the implementation at GAS should be simplified.

7.1.3 Long-term perspective (5+ years)

In this section the recommendations that have a higher degree of complexity are mentioned, and these should be allowed longer time to be implemented, i.e. more than five years.

4. Explore noise factors and sources of unwanted variation to deal with robustness failures.

The main success factor was the one that contributed to solve *robustness* related *failures*, and that was the choice of material. As Christensen (2015) points out, robustness failures are more difficult to identify during the product development process and the cost to correct them is higher because they become manifest during the production ramp up (also see Siva (2013) in *chapter 3*). GAS should have a double approach to failure avoidance based not only in preventing design failures but also exploring sources of unwanted variation (see noise factors in the theoretical framework).

5. **Make upgrades to the current infrastructure of IT support systems aiming for a TDM or PDM.**

A common theme that all interviewees consistently agree upon has been the lack of support that the IT system provides to both the development and the manufacturing functions. GAS should evaluate integrating and connecting the different existing IT systems in place. One example of this is to collect the technical documents into a single system where traceability of product changes, non-conformances and upgrades could be stored. This approach is being used at VCE using a TDM system and should be assessed and considered at GAS.

A similar way of solving the documentation issue is being used at SKF where a PDM system connects different documents into a single system. In the case of GAS a first step in this direction would be to link the current OMS system with the DP online system. This is consistent with the findings by Chen el al. (2013) where they emphasize the 21 CSFs in the implementation of a PDM system in a business. Out of these 21, two of the most important are directly applicable to GAS, i.e. integration of IT systems and reinforce training, and therefore these should be addressed.

7.2 Discussion on the research methodology

The overall impression is that the present study had a series of constraints that have limited the resolution of its findings. Among others, it was conducted during a fixed period of time of four months, on a limited budget and with some access limitations due to confidentiality reasons.

Some additional research tools and methods could have contributed to a more accurate triangulation of the available data, like e.g. having an internal survey on the researched topics. Furthermore, the present study could have benefited from having more companies in the benchmarking study both as a source of data and to provide a broader picture of the Swedish manufacturing industry that allows a more detailed comparison of commonalities and differences between the practices within GAS and other organizations.

Initially the thesis was mainly focused on finding a KPI for proactivity in product development. However, the initial literature review showed that it was not feasible to aim for such a metric, and therefore the scope of the research was readjusted. Reaching these conclusions took up time resources from the project and if the final scope would have been known already in the beginning, sharper and more detailed findings could have been achieved. The topic of a KPI on proactivity was, however, addressed as a part of the interviews at GAS, and the suggestions that came up are presented in chapter 4.

One important finding in the report that needs to be noticed is the one referring to the difference in process methods used in project A and D. The findings supporting that project D was better off using forging instead of casting is mentioned by only a few interviews, as it was not covered as a topic, and should therefore be analyzed in further detail. As reflected in *section 4.2* welding in cast material will always lead to cracks, pores and other quality flaws that in turn will lead to an increased number of NCRs. On the other hand, having forged material avoids some of these shortcomings. Still, more interview data points on this topic would have increased the resolution and validity of the retrieved data.

An alternative approach to the benchmarking study would have been to involve more than one interviewee from each company. However, this was disregarded due to the fact that the interviewees were selected carefully based on the area under research. Therefore, more interviews from the same company would only have added marginal value to the study.

7.3 Suggestions for future research

Based on the findings in this thesis two main suggestions for future research were identified that could support the efforts of becoming more proactive. A key when creating suggestions is to keep them as clear as possible in order not to create too fuzzy ideas that might be disregarded due to difficulties in interpreting them. Therefore the authors believe that a direct approach on usefulness for professionals should be targeted in any work based on this thesis.

The first suggestion is to construct an implementation plan for the recommended tools in the thesis, for example a full QFD. This implementation plan should be formulated in a hands-on manner in order to provide a solid base for GAS to clearly evaluate the possibilities of implementing the tool as a way of becoming more proactive.

The second suggestion for future research would be to investigate how DFSS could be utilized as an approach of becoming more proactive. This thesis finds that DFSS has features that support a proactive mindset, but these need to be elaborated on further and could be suitable for another master's thesis.

During the interviews at GAS some suggestions for a proactivity measurement were made. One suggestion was to track how many *Business Process Improvements* (BPI) are recorded and then measure based on that. Another was to consider how many incomplete DPs there are in the system. It was also advised to consider different approaches to enhance overall proactivity within product development. For example, the adoption of DFSS methodology and tools, or the implementation of process maps illustrating manufacturing capabilities. Finally, some other interviewees suggested to explore the proactivity contributions of studying process development. Some of these suggestions could be exploited for future research studies.

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Appendix A: Interview template GKN

Ethical considerations addressed previous to the interview

- Who we are
- What and why we are researching
- Permission to record
- Anonymity in thesis
- We will be the only ones accessing the information - confidentiality

General

- For how long have you been working at Volvo Aero/GKN Aerospace?
- What is your current position at GKN?
    - What are the tasks related to that position?

Project intro

- We understand that you were involved in project X. Could you please elaborate on what your role was in it?
    - For how long did you participate in it?

Accessing previous experience (Lessons Learned)

- Were knowledge/experience back-loops actively accessed as part of the program?
- How was the accumulated knowledge coming from previous related programs accessed during the different stages of product development in project X?
    - How did you consider previously known production problems from other programs when conducting the Concept Selection?
- During your work in project X, how did you apply existing knowledge from previous programs?
    - By using some sort of formal knowledge transfer system within GKN or by some sort informal knowledge sharing within GKN?
        - Do you think it is reasonable to make a distinction between formal and informal means of transferring knowledge or experience? Why?
    - By adopting an ad-hoc or a structured approach to knowledge sharing?
    - By using existing knowledge coming from members within or outside of the the program?

    - Cross-fertilisation between projects by people transfer and recruiting
    - Could you use previous know-how directly or did you need to adjust and/or re-verify? Elaborate.
- In what way did the Informations Communications Technology infrastructure (e.g. OMS) contribute to knowledge sharing and distribution?
    - (previous, present and future)
- Were you aware of any significant production problems in program X, e.g. reworks, delays, readjustments etc?
- Were there any wrap-up meetings addressing lessons learned by the end of Program X? Why did you have those, what was the goal?
    - with the goal of securing its future availability? Elaborate.
- How did you assure that lessons learned from project X could be applied in future programs?
- How do you think that these lessons learned could be exploited in order to achieve a higher degree of proactivity in product development?

Robust Engineering – DfSS

- Have you noticed any methodology update as of lately, that has changed your way of working?
    - Were there any updates or changes to the organizational approach to robustness?
    - Were there any efforts on changing mindsets regarding robustness?
- What is your concept of robustness?
    - How do people interpret and use this term in your context?
- How could robust thinking be measured within GKN in order to become more proactive?
- Are you familiar with the term Design for Six Sigma? If so, what is your interpretation of it?
- Have you been professionally involved in any programs addressing the DfSS methodology? Please elaborate.

Collaboration between Design and Manufacturing – DfM

- Who do you think was the one leading robustness discussions in Project X? Was it Design, Manufacturing, both, neither or someone else?
    - How did they take the lead?
    - Informal or structured?

- Could you elaborate on the design-manufacturing interface today, and more specifically on robust design and manufacturing related issues?

- Are you familiar with the term Design for Manufacturing? If so, what is your interpretation of it?
- Have you been professionally involved in any programs addressing the DfM methodology? Please elaborate.
- Q3s, Q4s: What are these? How do you consider these in your design/production tasks?
    - Lina: Elaborate on how these are collected and analyzed?

Personal views

- What are your personal views on these structured, continuous improvement efforts (e.g. DFM, DfSS etc.) at GKN?
- How do you perceive that these initiatives are being received by people involved in product development at GKN?

Ending

- Is there anything that you feel hasn't been covered in this interview, or anything else that you would like to add?

Appendix B: Interview template SCA

Presentation – Ethical considerations

- Who we are
- What and why we are researching
- Permission to record
- Anonymity in thesis
- We will be the only ones accessing the information - confidentiality

General background

- What is your previous background to SCA?
- For how long have you been working at SCA?
- What is your current position at SCA?
- What are the tasks and responsibilities related to that position?

Using previous knowledge – Lessons learned

- Based on the graph (see last page), how would you describe how the process of bringing lessons learned from production to design is being managed at SCA?
- How is the accumulated knowledge from previous projects accessed during the different stages of product development?
- How is the accumulated knowledge from previous projects applied in new projects?
- In what way does the Informations Communications Technology infrastructure contribute to knowledge sharing and distribution? More specifically concerning how design can access knowledge from production.
    - (previous, present and future)
- At what point is Design aware of production problems?
    - When in relation to launch to production?
    - How are these considered during the design work?
- Are there any established practices on how to secure lessons learned at the end of any given project, i.e. white books, wrap-up meetings, reviews, reports etc.?
- How do you assure that the lessons learned can be applied in future projects?
- How do you think that these lessons learned could be exploited in order to achieve a higher degree of proactivity in product development?
- Do you measure your proactivity performance in product development?
    - If so, how?
- How do you consider P-FMEAs from previous projects when conducting the design work?
- How is SCA capturing lessons learned from the service life of their products, and feeding that back into Design?

Robust Engineering

- Do you measure your robust design performance?
    - If yes, how?
    - If no, have you considered doing it?
- How do you consider these measurements later on? Do you follow-up?

Design for Six Sigma

- What kind of approach does SCA follow in order to achieve robust performance and producibility?
    - Could you describe the structure of your development process?
- When did you start working with DfSS?
- Is it the default approach for all projects, or are there any exceptions?
- How is SCA driving improvement work based on data?
    - Design data?
    - Production data?
    - Service data?

Collaboration Design-Manufacturing

- What does the interface between the Design and Manufacturing departments look like today, more specifically on robust design and manufacturing related issues?
- What is the level of integration between these departments?
- What collaboration tools between these two is SCA using?
- Are you familiar with the term Design for Manufacturing? If so, what is your interpretation of it?

Ending

- Is there anything that you feel hasn't been covered in this interview, or anything else that you would like to add?

Appendix C: Interview template SKF

Presentation – Ethical considerations

- Who we are
- What and why we are researching
- Permission to record
- Anonymity in thesis
- We will be the only ones accessing the information - confidentiality

General background

- What is your previous background to SKF?
- For how long have you been working at SKF?
- What is your current position at SKF?
- What are the tasks and responsibilities related to that position?

Using previous knowledge – Lessons learned

- Based on the graph (see last page), how would you describe how the process of bringing lessons learned from production to design is being managed at SKF?
- How is the accumulated knowledge from previous projects accessed during the different stages of product development?
- How is the accumulated knowledge from previous projects applied in new projects?
- In what way does the Informations Communications Technology infrastructure contribute to knowledge sharing and distribution? More specifically concerning how design can access knowledge from production.
  - (previous, present and future)
- At what point is Design aware of production problems?
  - When in relation to launch to production?
  - How are these considered during the design work?
- Are there any established practices on how to secure lessons learned at the end of any given project, i.e. white books, wrap-up meetings, reviews, reports etc.?
- How do you assure that the lessons learned can be applied in future projects?
- How do you think that these lessons learned could be exploited in order to achieve a higher degree of proactivity in product development?
- Do you measure your proactivity performance in product development?
  - If so, how?
- How do you consider P-FMEAs from previous projects when conducting the design work?
- How is Volvo CE capturing lessons learned from the service life of their products, and feeding that back into Design?

Robust Engineering

- Do you measure your robust design performance?
    - If yes, how?
    - If no, have you considered doing it?
- How do you consider these measurements later on? Do you follow-up?

Design for Six Sigma

- What kind of approach does SKF follow in order to achieve robust performance and producibility?
    - Could you describe the structure of your development process?
- Are you familiar with the term Design for Six Sigma?
    - If so, what is your interpretation of it?
- Are you working with DfSS?
    - If so, is it the default approach for all projects, or are there any exceptions?
- How is Volvo CE driving improvement work based on data?
    - Design data?
    - Production data?
    - Service data?

Collaboration Design-Manufacturing

- What does the interface between the Design and Manufacturing departments look like today, more specifically on robust design and manufacturing related issues?
- What is the level of integration between these departments?
- What collaboration tools between these two is SKF using?
- Are you familiar with the term Design for Manufacturing? If so, what is your interpretation of it?

Ending

- Is there anything that you feel hasn't been covered in this interview, or anything else that you would like to add?

Appendix D: Interview template Volvo CE

Presentation – Ethical considerations

- Who we are
- What and why we are researching
- Permission to record
- Anonymity in thesis
- We will be the only ones accessing the information - confidentiality

General background

- What is your previous background to Volvo CE?
- For how long have you been working at Volvo CE?
- What is your current position at Volvo CE?
- What are the tasks and responsibilities related to that position?

Using previous knowledge – Lessons learned

- Based on the graph (see last page), how would you describe how the process of bringing lessons learned from production to design is being managed at Volvo CE?
- How is the accumulated knowledge from previous projects accessed during the different stages of product development?
- How is the accumulated knowledge from previous projects applied in new projects?
- In what way does the Informations Communications Technology infrastructure contribute to knowledge sharing and distribution? More specifically concerning how design can access knowledge from production.
    - (previous, present and future)
- At what point is Design aware of production problems?
    - When in relation to launch to production?
    - How are these considered during the design work?
- Are there any established practices on how to secure lessons learned at the end of any given project, i.e. white books, wrap-up meetings, reviews, reports etc.?
- How do you assure that the lessons learned can be applied in future projects?
- How do you think that these lessons learned could be exploited in order to achieve a higher degree of proactivity in product development?
- Do you measure your proactivity performance in product development?
    - If so, how?
- How do you consider P-FMEAs from previous projects when conducting the design work?
- How is Volvo CE capturing lessons learned from the service life of their products, and feeding that back into Design?

Robust Engineering

- Do you measure your robust design performance?
  - If yes, how?
  - If no, have you considered doing it?
- How do you consider these measurements later on? Do you follow-up?

Design for Six Sigma

- What kind of approach does Volvo CE follow in order to achieve robust performance and producibility?
  - Could you describe the structure of your development process?
- Are you familiar with the term Design for Six Sigma?
  - If so, what is your interpretation of it?
- Are you working with DfSS?
  - If so, is it the default approach for all projects, or are there any exceptions?
- How is Volvo CE driving improvement work based on data?
  - Design data?
  - Production data?
  - Service data?

Collaboration Design-Manufacturing

- What does the interface between the Design and Manufacturing departments look like today, more specifically on robust design and manufacturing related issues?
- What is the level of integration between these departments?
- What collaboration tools between these two is Volvo CE using?
- Are you familiar with the term Design for Manufacturing? If so, what is your interpretation of it?

Ending

- Is there anything that you feel hasn't been covered in this interview, or anything else that you would like to add?

Appendix E: Benchmarking comparison

			SCA
	Using previous knowledge – Lessons learned		
1	Based on the graph (see last page), how would you describe how the process of bringing lessons learned from production to design is being managed at Company X?		- Cross-functional product teams. - The finished goods specification capture production and supply chain feedback. These specifications are linked to the customer requirements specifications through a QFD. The customer requirements specifications integrate both customer requirements and design solutions.
2	How is the accumulated knowledge from previous projects accessed during the different stages of product development?		In the past SCA has been a company where you needed to know the actual person having specific knowledge (e.g. glue expert) to access it. Nowadays SCA has implemented a base-QFD as a knowledge carrying cause-and-effect. They use all the four houses of QFD from customer requirements to process controls. They use QFDs to address gaps between requirements.
	How is the accumulated knowledge from previous projects applied in new projects?		
3	In what way does the Informations Communications Technology infrastructure contribute to knowledge sharing and distribution? More specifically concerning how design can access knowledge from production. (previous, present and future)		Incident reporting on quality has a system where you can sort incidents and make graphs and statistics. Complaints handling has one system as well. The specification system contains the two different types of specifications, requirements and finished goods spec. The system

			doesn't support quality records, so they work with QFD. Top priority is working on this now, setting up document management, quality records etc.
4	At what point is Design aware of production problems?		Product development works cross-functionally together with production, material and category (brand, product ideas, concept).
		When in relation to launch to production?	Before and during serial production
		How are these considered during the design work?	
5	Are there any established practices on how to secure lessons learned at the end of any given project, i.e. white books, wrap-up meetings, reviews, reports etc.?		Project managers are responsible for writing down the LL for the PD funnel and conducting a post-launch follow-up with the goal of sharing their learnings. This post-launch follow-up is a milestone in the project itself, and before the project is ended this review should be made
6	How do you assure that the lessons learned can be applied in future projects?		
7	How do you think that these lessons learned could be exploited in order to achieve a higher degree of proactivity in product development?		- SCA tries to identify relations between processes and work upstream (all the way up to the customer) → proactivity. It's very hard to be proactive if you don't know your system. - Models: simulation as a way of assessing performance
8	Do you measure your proactivity performance in product development? If so, how?		SCA is working on formulating KPIs for quality for 2016.
9	How do you consider P-FMEAs from previous projects when conducting the design work?		SCA has a process to standardize FMEAs. SCA reuses FMEAs. The process-FMEA is a living document and should be.

10	How is Company X capturing lessons learned from the service life of their products, and feeding that back into Design?		The feedback comes directly from the customers. Customers call directly to SCA to share complaints or opinions → categorized by operator. Stored in a database and reviewed regularly. Also market research to find out what customers want. For SCA supply chain feedback is an important area → important both for the business results and the quality, don't want to ship air in trucks.
	Robust Engineering		
11	Do you measure your robust design performance?		SCA studies those process parameters affecting product parameters or functionalities. This study is conducted in their own factories using "six-packs" in Minitab as a study tool, and this tool has become very popular since it was launched within the company.
12	How do you consider these measurements later on? Do you follow-up?		Only a few vital parameters are studied since it would take too much resources to focus on all possible ones.
13	What kind of approach does Company X follow in order to achieve robustness performance and producibility?		The approach to robustness is to start to learn what is influencing what, find the links to process parameters, and address this when the design is set. The key to robust engineering is to understand how the manufacturing capabilities will be translated into product functionality, and this is done through a cause-effect analysis (QFD).
	Design for Six Sigma		
14	Do you work with Six Sigma? Do you work with Design for Six Sigma? If so, when did you start working with them?		SCA started working with DFSS in 2008. They have internal training, Katarina led 3 classes internally, and now they have 20 DFSS Black Belts who are training Green Belts.

15	How is Company X driving improvement work based on data?		By using SPC through Minitab. Especially important in the paper division where the margins are lower than in the hygiene division.
	Collaboration Design-Manufacturing		
16	What does the interface between the Design and Manufacturing departments look like today, more specifically on robust design and manufacturing related issues?		In the product development manufacturing is represented, machine people etc. People in SCA is close to the production. "SCA is more of a production company rather than an engineering company." SCA is production oriented.
17	What is the level of integration between these departments?		
18	What collaboration tools between these two is Company X using?		QFD, FMEA
19	Are you familiar with the term Design for Manufacturing? If so, what is your interpretation of it?		DFM is about what is driving cost and demand in manufacturing and how that is brought into design. Unplanned machine stops → design away. What problems are there in manufacturing and how can those be removed in design.

			SKF
	Using previous knowledge – Lessons learned		

1	Based on the graph (see last page), how would you describe how the process of bringing lessons learned from production to design is being managed at Company X?		- Most products are upgrades from existing products based on previous design experience. - SKF follows a Product Development Process (PDP) for completely new products based on DFSS. It brings competences from customer perspective, product development and production. SKF takes a long time understand what the customer needs, starting with concept design and translating that into a detailed design stage. - Technology Readiness Levels (TRL). The initial PD phases are more about exploring and gathering competences and further on the gatings are about implementing competences.
2	How is the accumulated knowledge from previous projects accessed during the different stages of product development?		SKF is setting up design rules through formulae as a way of documenting their accumulated knowledge. These also include the capability at manufacturing, so they combine design with manufacturing singling out which parameters are more critical. But they require experience to be fully understood because it can be difficult for a lot of formulae to trace back where they come from. This is still a challenge for SKF.
	How is the accumulated knowledge from previous projects applied in new projects?		
3	In what way does the Informations Communications Technology infrastructure contribute to knowledge sharing and distribution? More specifically concerning how design can access knowledge from production. (previous, present and future)		The IT system is a traditional serving CAD system, a PDM system, PLM broadly speaking. SKF also has a research technical report that brings everything together. The weakness of this system is that you need to know what you are looking for, it does not have a good "knowledge system" that interacts with the user assisting in the search for the information.
4	At what point is Design aware of production problems?		The design department has two roles: 1) to develop new products and 2) to maintain existing products based on a daily interaction with the manufacturing department.
		When in relation to launch to	

		production?	
		How are these considered during the design work?	
5	Are there any established practices on how to secure lessons learned at the end of any given project, i.e. white books, wrap-up meetings, reviews, reports etc.?		White books we are doing from time to time, but not by default. But if we have some incident or new knowledge we are exposed to then we are doing that when the projects are at the end. It is a mixture of technical aspects and the team work experience. But we do not do that in a normal situation. The responsibility is for the sponsor of the project. But normally it is the manager doing or leading the work. We do not have a structured way of storing them
6	How do you assure that the lessons learned can be applied in future projects?		That is up to the sponsor to see if these lessons learned are unique or if we can spread them out, because quite often the sponsor is a member in many projects and has room to communicate certain information. But we do not have a specific process for that.
7	How do you think that these lessons learned could be exploited in order to achieve a higher degree of proactivity in product development?		At the team level they could be used for setting up the teams, that would have proactive effects. At the technical level the lessons for each case are somewhat unique. SKF doubts that just documenting will contribute to proactivity. The experience is also important. Proactivity is mostly considered to avoid critical situations.
8	Do you measure your proactivity performance in product development? If so, how?		NO. Having a large number of KPIs turns steering into following-up. It should be a small number (max 5-10) and even proactivity is important, it is not top of the list.
9	How do you consider P-FMEAs from previous projects when conducting the		They do FMEAs in the six sigma part of their projects. SKF has a template that

	design work?		is a standard. They are now implementing core FMEAs for their processes, which is a base FMEA that can be used for one manufacturing technology for the full company. So, whoever wants to use this process they can reuse this base core FMEA as a starting point.
10	How is Company X capturing lessons learned from the service life of their products, and feeding that back into Design?		Feedback from the customer is channeled to and compiled by the responsible of the product line filtered through a process that involves the application engineers. They make a difference between technical issues and business issues.
	Robust Engineering		
11	Do you measure your robust design performance?		No
12	How do you consider these measurements later on? Do you follow-up?		-
13	What kind of approach does Company X follow in order to achieve robustness performance and producibility?		So the robustness experience that we have is that we are doing a lot of testing for the launch of a new product in the market. Both calculations and physical testing, but we have no KPI or another way to measure the robustness.
	Design for Six Sigma		
14	Do you work with Six Sigma? Do you work with Design for Six Sigma? If so, when did you start working with them?		But when we create a completely new product we have one design route for that, a process for that, called Product Development Process (PDP) and it is based on DfSS

15	How is Company X driving improvement work based on data?		- The production is going very much between product engineering and the process engineering function in the factory. So I cannot see that we have a lot of data, a huge database. - From the service part part of the data goes directly to the factory, normally the quality manager or engineering manager. But also the product development manager has that information from the technical part.
	Collaboration Design-Manufacturing		
16	What does the interface between the Design and Manufacturing departments look like today, more specifically on robust design and manufacturing related issues?		There is a combination of push from production and pull from design. At the same time there is more a cost reduction aspect. There are two streams, one coming from the customer and the other from standardization
17	What is the level of integration between these departments?		
18	What collaboration tools between these two is Company X using?		QFD, FMEA
19	Are you familiar with the term Design for Manufacturing? If so, what is your interpretation of it?		They are familiar with the term but they are not working with it

			Volvo CE
	Using previous knowledge – Lessons learned		

1	Based on the graph (see last page), how would you describe how the process of bringing lessons learned from production to design is being managed at Company X?		The intitial loop-back in design-production is through a formal design review (FDR). Its purpose is to ensure that the design directions are consistent with achieving system's specification. As Volvo CE does the formal design reviews, they also document and this is part of the product and process history. It's a critical evaluation of the design maturity: that means design for manufacturing, design for assembly, impact on takt, potential risks, residual risks in process FMEAs etc. This information follows the design over its lifecycle. Volvo CE typically does three formal design reviews: one in early concept development, one in detailed development and one in final development before handing over to industrialization.
2	How is the accumulated knowledge from previous projects accessed during the different stages of product development?		Product controlling documents (drawings and CAD models) are linked together in the TDM system. As a principle, when they do design updates they also update the supporting documents. That way they have traceablity across the product life cycle. This is one of the tasks and deliverables for the process owner.
	How is the accumulated knowledge from previous projects applied in new projects?		
3	In what way does the Informations Communications Technology infrastructure contribute to knowledge sharing and distribution? More specifically concerning how design can access knowledge from production. (previous, present and future)		The OMS (operational management system) defines a standardized work: how to develop and who does what, from organizational roles responsibilities perspective, supplying standardized work, methods and tools that have to be applied in an appropriate way to get the right results. But it doesn't specify the product. The product is specified through a systems specification. A TDM (Technical Document Management) system provides full traceability of the product and the changes. To trace what happens in the field, there is a FRACAS (failure reporting and corrective actions system) that records failures in the field and helps us to monitor corrective actions.

4	At what point is Design aware of production problems?		Before releasing the product for serial production all design and production issues should be solved. After the product is launched it goes over to product maintenance so there is a continuous flow of information, but through two different channels. One is product development and the other is product maintenance.
		When in relation to launch to production?	Before release to serial production.
		How are these considered during the design work?	
5	Are there any established practices on how to secure lessons learned at the end of any given project, i.e. white books, wrap-up meetings, reviews, reports etc.?		In the projects VCE runs white books. White books primarily cover project knowledge, not necessarily product knowledge. There are other ways to capture product knowledge (why a certain design was chosen, what is driving that design, etc.). One method is what VCE calls product risk management. It consists of doing their FMEAs and doing the risk reduction of the FMEAs. This way they learn the weaknesses in their designs, how they were addressed and what were the outcomes. Design FMEAs contain a lot of the history.
6	How do you assure that the lessons learned can be applied in future projects?		The different design departments are responsible for documenting the lessons learned and for keeping those updated. "It is part of the engineering capturing the best practice and maintaining them over time". There is a standardized approach defining who, when, how and where to store this knowledge in the operational management system.

7	How do you think that these lessons learned could be exploited in order to achieve a higher degree of proactivity in product development?		-
8	Do you measure your proactivity performance in product development? If so, how?		Proactivity is very difficult to measure in a standardized way. They measure formal design reviews, the maturity of the design, so in the formal design reviews there is a requirement on maturity. The formal design review for us is the maturity measurement, and it's also a clear indicator of the proactivity. It's not a KPI. We don't believe in KPIs in this case.
9	How do you consider P-FMEAs from previous projects when conducting the design work?		P-FMEAs stay within manufacturing and are not stored in the same system. They are working on linking these P-FMEAs to the engineering documents.
10	How is Company X capturing lessons learned from the service life of their products, and feeding that back into Design?		In the Technical Document Management system (TDM) we have full traceability of the product and the changes, but if we want to trace what happens in the field, we have a failure reporting and corrective actions system that records failures in the field and that helps us to monitor corrective actions.
	Robust Engineering		
11	Do you measure your robust design performance?		It's extremely difficult for several reasons. we have put prerequisites on maturity of FMEAs, and depending on the size of the project, scope of the project, you will have different maturity.

12	How do you consider these measurements later on? Do you follow-up?		-
13	What kind of approach does Company X follow in order to achieve robustness performance and producibility?		-
	Design for Six Sigma		
14	Do you work with Six Sigma? Do you work with Design for Six Sigma? If so, when did you start working with them?		We are using parts of the toolbox, and that's one of the reasons why I'm trained on six sigma, to understand and try to bring in the relevant parts of the toolbox.
15	How is Company X driving improvement work based on data?		The system architecture is updated based on what Volvo CE learns continuously throughout production, design or any given functional system. If you for instance learn from warranty data that you have a requirement on a part that's not relevant. That should drive update of your system specification, putting new requirements in place, then driving design change.
	Collaboration Design-Manufacturing		
16	What does the interface between the Design and Manufacturing departments look like today, more specifically on robust design and manufacturing related issues?		We have a cross-functional setup. The project manager has a cross-functional team where we have the interactions and the interfaces.
17	What is the level of integration between these departments?		

18	What collaboration tools between these two is Company X using?		(QFD), FMEA
19	Are you familiar with the term Design for Manufacturing? If so, what is your interpretation of it?		They are familiar with the term and they actively consider it by having implemented a series of checklists to enforce it

			GAS
	Using previous knowledge – Lessons learned		
1	Based on the graph (see last page), how would you describe how the process of bringing lessons learned from production to design is being managed at Company X?		GAS is aware of the importance of bringing lessons learned from production to design and some efforts are being made to this effect. However, these efforts are scattered in loosely connected areas: - OMS: some gate reviews address the collection of lessons learned a certain stage. - Team selection: lessons learned are brought to a project through the most experienced people. - Internal training: as a way of standardizing the capture of lessons learned, e.g. P-FMEA. - Wrap-up meetings: up to the program manager and not conducted on a regular basis. - White books: up to the program manager and not conducted on a regular basis.
2	How is the accumulated knowledge from previous projects accessed during the different stages of product development?		On a regular basis the accumulated knowledge from previous project is accessed through the design practices. Exceptionally, there has been initial knowledge gathering for certain projects (production platform). The most common way, however, of accessing accumulated knowledge is by having an experienced member as part of the team. At GAS they made an effort with the QFD but then it ended up with just one house.
	How is the accumulated knowledge from previous projects applied in new		

	projects?		
3	In what way does the Informations Communications Technology infrastructure contribute to knowledge sharing and distribution? More specifically concerning how design can access knowledge from production. (previous, present and future)		There is a general view that the IT systems are not fully contributing to support knowledge sharing, but rather as an obstacle in the daily work. The OMS is considered to be overly complex and an expression of the ideal world, and is irregularly used in the daily work, but rather considered to be a way of assuring customers that important procedures are being covered. The SAP system is considered to be non-user friendly, it's difficult to retrieve information from it and has issues with data restriction/authorization.
4	At what point is Design aware of production problems?		GAS is going through a transition from low awareness and a reactive approach to manufacturing issues, to a higher awareness and more proactive one by having a close collaboration between design and manufacturing.
		When in relation to launch to production?	
		How are these considered during the design work?	
5	Are there any established practices on how to secure lessons learned at the end of any given project, i.e. white books, wrap-up meetings, reviews, reports etc.?		White books not regularly performed, nor is it standardized how these are stored. Reviews are performed in each stage gate, where a stage gate report is issued and this is part of a standardized process. Wrap-up meetings are done now and then, but is not addressed in the OMS. There is not a common practice of following a process that secures lessons learned.
6	How do you assure that the lessons learned can be applied in future projects?		Through white books, design practices, P-FMEAs and by having the most experienced people in the start-up of new projects.

7	How do you think that these lessons learned could be exploited in order to achieve a higher degree of proactivity in product development?		Lessons learned are mainly captured through the DPs, analysis of quality data, P-FMEAs and by experienced workers. By addressing the incomplete/missing DPs, especially those coming from production, the degree of proactivity in product development could be increase. By getting the failure modes right GAS identifies what requirements are going to be non-conforming and then it is easier to manage the information between design and production. One interviewee suggests DfSS as a way to become more proactive. Another suggestion is to implement/create process maps that capture manufacturing experience. Yet another suggestion is to explore the contributions of process development to enhance product development.
8	Do you measure your proactivity performance in product development? If so, how?		Currently, no. Some suggestions have been provided during the interviews but they need to be further reviewed.
9	How do you consider P-FMEAs from previous projects when conducting the design work?		GAS is moving from addressing P-FMEAs on a pass/fail basis through stage gate review checklists into a more integrated and standardized approach where previous P-FMEAs are considered in the design work. Internal training is being performed in order to standardize the P-FMEA work further.
10	How is Company X capturing lessons learned from the service life of their products, and feeding that back into Design?		-
	Robust Engineering		
11	Do you measure your robust design performance?	No	
12	How do you consider these measurements later on? Do you follow-up?		-

13	What kind of approach does Company X follow in order to achieve robustness performance and producibility?		GAS has set up a dedicated department (DfR) focusing on geometry assurance, stack-up calculations, stress analysis with different parameters and air calculations with different parameters. The producibility aspect is mainly covered by reducing the distance between the design and manufacturing departments, and by considering them as one unit.
	Design for Six Sigma		
14	Do you work with Six Sigma? Do you work with Design for Six Sigma? If so, when did you start working with them?		GAS has been working with Six Sigma for some years. Several employees are certified Black Belts and the company itself has been running some projects based on a six sigma approach. Still, it has not been established as a part of the company culture, since none of the systems in place has been designed with this approach in mind.
15	How is Company X driving improvement work based on data?		Right now the focus is mainly set on solving nonconformances based on the data retrieved by the different SPC systems in place. The approach is rather reactive than proactive.
	Collaboration Design-Manufacturing		
16	What does the interface between the Design and Manufacturing departments look like today, more specifically on robust design and manufacturing related issues?		Based on the "successful" experience from the 30K program, the way the OMS addresses the team setup is in a transition from distant collaboration between design and manufacturing to a more integrated setup where representatives from both departments have been brought into close proximity. Without decreasing the degree of formal communication (meetings), GAS is increasing the degree of informal communication channels, which has made the setup more agile.
17	What is the level of integration between these departments?		
18	What collaboration tools between		FMEA

	these two is Company X using?		
19	Are you familiar with the term Design for Manufacturing? If so, what is your interpretation of it?		Vague notions of how the term is actually defined. The term itself has not been explicitly addressed in the OMS, but the mindset is used among people in product development.