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SUPPORTING PRE-DEVELOPMENT OF NEW MANUFACTURING TECHNOLOGIES

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ABSTRACT

In today's tough industrial environment, efficient development of new products and new manufacturing solutions is necessary to stay competitive on a global market. Manufacturing companies use substantial money and development resources to develop new products. However, the resources spent on finding and implementing emerging manufacturing technologies are much more limited. This is often the case even though it is well known that a way of competing on a global market is through the introduction of new manufacturing technologies that can improve product quality as well as contribute to reducing manufacturing time, resulting in reduced product price and in the end increased profit.

When introducing new manufacturing technologies, different challenges arise such as lack of knowledge, involvement of an external equipment supplier, etc. In addition, time-to-volume is critical when introducing new manufacturing technologies in a manufacturing context. To be able to have a fast ramp-up, manufacturing technology needs to be mature enough and at the same time meet all requirements. Efficient introduction of new manufacturing technologies requires that pre-development activities have been performed in advance.

Previous research in this area highlights a lack of knowledge and solutions regarding pre-development of new manufacturing technologies. Such pre-development is important in order to have a successful introduction, fast time-to-volume and production system development. Based on these challenges, the objective of the research presented in this thesis is to develop support for pre-development of new manufacturing technologies.

The research is based on literature reviews and three empirical case studies, carried out over a two-year period of time. The first empirical case study was an exploratory case study in the manufacturing industry. The purpose of that research study was to identify critical factors forcing manufacturing companies to improve the development of manufacturing technologies.

The second study was a longitudinal embedded case study in the manufacturing industry with the purpose of identifying factors that affect evaluation of new manufacturing technologies during new product development. Particular attention was given to the product development process and how it has affected the evaluation of new manufacturing technologies.

Finally, the third study was a single case study in the manufacturing industry with the purpose of analysing and discussing the assessment of the maturity level of a manufacturing technology.

SAMMANFATTNING

I dagens tuffa industrimiljö är effektiv utveckling av nya produkter och nya tillverkningslösningar nödvändig för att förbli konkurrenskraftig på en global marknad. Tillverkande företag använder stora pengar och utvecklingsresurser för att utveckla nya produkter. Men resurserna som satsas på att hitta och införa nya tillverkningstekniker är mycket mindre. Detta är ofta fallet trots att det är välkänt att ett sätt att konkurrera på en global marknad är att införa nya tillverkningstekniker som både kan förbättra produktkvaliteten och bidra till att minska tillverkningstiden, vilket resulterar i minskat produktpris som till slut ger ökade vinster.

Införandet av nya tillverkningstekniker medför olika utmaningar som brist på kunskap, medverkan av extern utrustningsleverantör, etc. Dessutom är tid till volym kritisk vid införandet av nya tillverkningstekniker i ett tillverkningssammanhang. För att kunna ha en snabb igångkörning måste tillverkningstekniken vara mogen nog och samtidigt uppfylla alla krav som fastställts. Effektiv introduktion av nya tillverkningstekniker kräver att förutveckling har skett.

Tidigare forskning inom detta område belyser att det finns brist på kunskap och lösningar avseende utveckling av nya tillverkningstekniker. En sådan utveckling är viktig för att få en lyckad introduktion, snabb tid till volym och produktionssystemutveckling. Baserat på dessa utmaningar är syftet med forskningen som presenteras i denna avhandling att utveckla stöd för framtagning av nya tillverkningstekniker.

Forskningen bygger på litteraturstudier och tre empiriska fallstudier, utförda under två års tid. Den första empiriska fallstudien var en explorativ fallstudie inom tillverkningsindustrin. Syftet med denna studie var att identifiera kritiska faktorer som tvingar tillverkande företag att förbättra utvecklingen av ny tillverkningsteknik.

Den andra studien var en longitudinell inbäddad fallstudie inom tillverkningsindustrin med syftet att identifiera faktorer som påverkar utvärderingen av nya tillverkningstekniker under utveckling av nya produkter. Särskild uppmärksamhet ägnades produktutvecklingsprocessen och hur den har påverkat utvärderingen av nya tillverkningstekniker.

Den tredje studien var en enfallsstudie inom tillverkningsindustrin med syftet att analysera och diskutera bedömning av en tillverkningsteknisk mognadsgrad.

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Further, I would like to thank all my colleagues in the INNOFACTURE Research School for interesting conversations and collaboration. A great advantage of this research school is that we started at the same time and we were facing the same type of problems in the research process that had to be discussed and solved.

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PUBLICATIONS

APPENDED PAPERS IN THE THESIS

Paper I

Ahlskog et al. (2014) "Factors affecting development of production technologies in a machining environment" in *Proceedings of the Tenth International Symposium on Tools and Methods of Competitive Engineering, TMCE 2014*, 19-23 May 2014, Budapest, Hungary

Paper II

Ahlskog and Bruch (2014). "Evaluation of Advanced Manufacturing Technology during New Product Development". Paper presented at the *21st EurOMA Conference, Operations Management in an Innovation Economy*, 20-25 June 2014, Palermo, Italy. The paper is not printed in the book, only an abstract.

Paper III

Ahlskog et al. (2015). "Manufacturing Technology Readiness Assessment". Paper accepted for the POMS 26th Annual Conference, Production and Operations Management Society, 8-11 May 2015, Washington, DC, USA.

ABBREVIATIONS

DoD (Department of Defense)

NASA (National Aeronautics and Space Agency)

NPD (New Product Development)

MRL (Manufacturing Readiness Level): A ten-grade scale with predefined readiness levels that offers a measurement scale and vocabulary for assessing and discussing manufacturing maturity and risk. MRL should be used in conducting assessments of manufacturing maturity and suggests how such assessments should be carried out (DoD, 2012).

TRL (Technology Readiness Level): A nine-grade scale with predefined readiness levels. Technology Readiness Levels is a systematic metric measurement system that supports assessments of the maturity of a particular technology and a consistent comparison of maturity between different types of technology (Mankins, 1995).

TTM (Time-to-market): Time-to-market is associated with development and introduction of new products. This means that activities during the product development process, methods, planning of production processes, etc., precede the actual start-up (Bellgran and Säfsten, 2010, p. 244).

TTV (Time-to-volume): The last phase of both the product and production development process and the product introduction process constitutes the production ramp-up: start of commercial production and increase of production rate until planned volume, quality, etc., are achieved. The main difference between time-to-market and time-to-volume is that the former ends when commercial production has started, whereas the latter continues during the production ramp-up phase (Fjällström, 2007).

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1 INTRODUCTION

This chapter introduces and describes the context and background of the research area. The problem statement is described leading to the formulated objective of the thesis as well as two specified research questions. Further, the scope and delimitations are discussed. The chapter ends with a presentation of the outline of the thesis.

1.1 RESEARCH BACKGROUND

Global competition in the manufacturing industry is very tough and Asia, the USA and Europe are currently making large investments in industrial and academic research connected manufacturing industry to attain competitive advantages (Teknikföretagen, 2008). Much research work in this area has concentrated on product development processes, whereas manufacturing technology development has been largely neglected despite its importance (Frishammar et al., 2012; Frishammar et al., 2013; Kurkkio et al., 2011).

However, there is a close link between manufacturing technology development and product development, and these two areas must be developed in parallel to be able to attain short lead time for products being developed (Cooper, 1994; Cooper, 2011; Bellgran and Säfsten, 2010). Bellgran and Säfsten (2010) emphasise that the prerequisites of the manufacturing process must be taken into account in the early stages when developing new products. At the same time adjustments have to be made in the production system already during the product development process. Changes in the production system that are initiated too late could be devastating to profitability (Teknikföretagen, 2008; Ulrich and Eppinger, 2008).

A rapid market introduction of new products is critical for competitiveness, and a short time-to-market (from concept to new products on the market) will increasingly be relevant in manufacturing industries (Teknikföretagen, 2013; European Union, 2010; Cooper, 2011; Tidd et al., 2005; Trott, 2012). One industrial trend is that the development time for new products becomes shorter, and more development work for the product is performed in earlier phases (Tidd et al., 2005; Trott, 2012). From a manufacturing perspective this trend also has an impact on the development of production systems. Development of new products often causes a need for investments in new production equipment, and time-to-volume is crucial when introducing new manufacturing technologies in the production system (Bellgran and Säfsten, 2010; Fjällström et al., 2009). In order to have a fast ramp-up and short time-to-volume, new manufacturing technologies need to be evaluated and verified in early phases (Bellgran and Säfsten, 2010; Trott, 2012). Further, new manufacturing technologies should be evaluated to find out if they are mature enough for implementation in the production system (DoD, 2012; Homeland Security, 2009; Drejer and Riis, 1999).

Evaluation and work with new manufacturing technologies is thus an important successes factor for competitiveness. Leif Johansson, former CEO of AB Volvo, states: "*The renewal of production technologies and innovative cost control are key areas to strengthen the competitiveness of Swedish industry. Perhaps even the most important areas to further develop the country's all immature products*" (Ahlbom (2013)). Further, Phaal et al. (2001) and Monge et al. (2006) also argue that managing the renewal of new manufacturing technologies is a vital issue to become competitive on a global market. New manufacturing methods and processes can create new possibilities that may make it necessary to change the whole production chain (Pisano, 1997). This can affect both product design and the production system and thereby give significant productivity improvements (Teknikföretagen, 2008). Trott (2012) states that development of new products and manufacturing processes has enabled many firms to continue to grow. By quickly taking advantage of new manufacturing technologies, manufacturing companies can meet customer and market requirements and thereby create competitive advantages (Ordoobadi, 2009; Goyal and Grover, 2012). Therefore, to obtain the benefits from new manufacturing technologies and have a short time-to-volume, pre-development of new manufacturing technologies is needed. In this thesis pre-development refers to early investigations of the maturity level of new manufacturing technologies in order to find out when these can be implemented in the production system.

In summary, building knowledge about new manufacturing technologies is a major key for competitiveness, because knowledge is difficult to observe and imitate by competitors (Hayes et al., 2005; Drejer and Riis, 1999), and acquiring knowledge about new manufacturing technologies takes time, involves people and experiments and requires learning (Trott, 2012).

1.2 PROBLEM STATEMENT

As stated in the background section, introduction of new manufacturing technologies is a vital issue in order to stay competitive on a global market. Trott (2012) argues that very often manufacturing competences are the missing element in corporate strategy. Manufacturing competences are not viewed as an integral part of the strategic planning process and they are seen as something to be acquired if required. Also, Frishammar et al. (2012) emphasise that more research is needed in the early phases of manufacturing technology development projects, because prior research has concentrated on product development, and pre-development of new manufacturing technologies has attracted relatively little attention.

Pre-development of new manufacturing technologies requires a structured way of working and a process to evaluate these technologies. In this thesis, evaluation is defined as a methodical process of investigating and judging a manufacturing technology in the light of certain criteria, or the result of that process (adapted from Säfsten (2002)). However, the trend of reduced development time for new products will be challenging for manufacturing companies without a structured way of working and a process for evaluating new manufacturing technologies. As

Gupta et al. (1997) and Gouvea Da Costa et al. (2006) conclude, despite the potential benefits of new manufacturing technologies, many manufacturing companies are still struggling with evaluation of new manufacturing technology during new product development.

Evaluation of new manufacturing technologies is a time-consuming process (DoD, 2012). Without pre-development resources there is a large risk that the same type of manufacturing technologies is invested in over and over again, and thus there is no production system development. Bellgran and Säfsten (2010) argue that evaluation constitutes an important part of the work in production system development, but evaluation is often a neglected activity among manufacturing companies because of lack of time and knowledge of how to perform an evaluation. Hayes et al. (2005) point out that the resources spent on finding and assessing new emerging manufacturing technologies are often very scarce, and Trott (2012) argues that acquiring knowledge about manufacturing technologies takes time, involves people and experiments and requires learning. Further, Hubka and Eder (1988) argue that a working process is subject to change with time, depending on the progress of the acquisition of insight and knowledge. Furthermore, there exist different approaches to evaluate manufacturing technologies. Hynek and Janeček (2009) claim that investments in new manufacturing technology are often difficult to evaluate on the basis of traditional analytical techniques such as pay pack, return of investment, net present value and internal rate of return, because they require quantifiable numbers and many of the benefits of new manufacturing technologies are hard to quantify.

Another challenge is to assess the maturity level of a new manufacturing technology and to decide when a technology is ready for introduction into the production system (Hayes et al., 2005). For this reason manufacturing companies have to develop resources, capabilities and core competencies for the evaluation of new manufacturing technologies (Greitemann et al., 2014; DoD, 2012; Joint Defense, 2007). Greitemann et al. (2014) argue that establishing and extending core competencies is a key success factor for manufacturing companies. For this purpose, manufacturing companies must be aware of the current maturity stage of their core competencies.

Development of new products often requires new investments in the form of new production equipment, and problems often arise due to the need to integrate an external equipment supplier (Abd Rahman et al., 2009; Ordoobadi, 2009; Chan et al., 2001). Abd Rahman and Bennett (2009) show that companies with a closer relationship with their equipment supplier are more likely to achieve higher levels of technology and implementation performance than those that lack such relationship. Abd Rahman and Bennett (2009) also argue that equipment supplier relationship represents one of the most important attributes for manufacturing technology acquisition. Further, Kotabe et al. (2003) have found that manufacturing technology transfer becomes beneficial if the buyer and equipment supplier have interacted long enough. Also, Rönnberg Sjödin (2013) emphasises the importance of selecting the right partners to cooperate with in joint manufacturing technology development projects.

To summarise, pre-development of new manufacturing technologies is challenging for many manufacturing companies and pre-development is often not considered as a competitive weapon, despite its importance. Further, when evaluating new manufacturing technologies, an external equipment supplier often becomes involved and the manufacturing technology needs to be evaluated against specified assessment criteria. To be able to perform the assessment, resources and manufacturing competence are required.

1.3 OBJECTIVE AND RESEARCH QUESTIONS

As said in the problem statement section, pre-development of new manufacturing technologies has attracted relatively little attention in manufacturing industry despite the potential benefits. Against this background more understanding and knowledge are needed about how new manufacturing technologies can be pre-developed and introduced into the production system. Therefore, the following research objective has been formulated:

> *"*The objective of this thesis is to develop support for pre-development of new manufacturing technologies.*"*

Support in this thesis refers to a process that gives support to pre-development of new manufacturing technologies. That is what this research aims to do, and it has therefore been conducted in close collaboration with manufacturing engineers in industry. The purpose of the studies was to find out what factors influence the introduction of new manufacturing technologies during product development and how new manufacturing technologies can be evaluated by different approaches.

To be able to meet the objective of this research, two research questions are proposed below.

> **RQ1:** What factors have an impact on the successful introduction of new manufacturing technologies?

The first research question is posed to investigate what factors influence the introduction of new manufacturing technologies during product development. Success factors and challenges in the interfaces between the product development and production equipment acquisition processes that impact on the introduction of new manufacturing technologies have been investigated. This research question was also formulated to create a broader understanding of the way of working in these development processes. Especially the collaboration and involvement of external equipment suppliers during new product development has been studied.

RQ2: How can the maturity level of new manufacturing technologies be evaluated?

The second research question aims at analysing how the maturity level of new manufacturing technologies can be evaluated and assessed. This research question was also formulated to create a broader understanding of different evaluation approaches and their limitations and challenges as well as to find out what factors impact the evaluation of the maturity level of new manufacturing technologies.

1.4 DELIMITATIONS

The case studies in this licentiate thesis have only been performed at one large Swedish company in the manufacturing industry. The limitations to manufacturing industries have arisen from the fact that many manufacturing companies are struggling with manufacturing technology evaluation and introduction of new manufacturing technologies into the production system (Gouvea Da Costa et al., 2006; Gupta et al., 1997).

This thesis was written from a manufacturing perspective, where the focus is on pre-development of new manufacturing technologies. The lack of real pre-development projects in manufacturing in industry implies that nearby contexts for research studies have been chosen. In this research, the product development and production equipment acquisition processes have been studied as well as the interfaces between these two processes. A product development project and two related acquisition projects of new manufacturing technology have been followed in real time in order to find out what factors influence the introduction of new manufacturing technologies as well as to find out how new manufacturing technologies are evaluated.

In the frame of reference, market and strategy (Section 3.2.1) are included from a theoretical perspective but has not been the unit of analysis in the studies performed. These areas are included because they are relevant for pre-development of new manufacturing technologies and for setting the research in a context. Finally, the support for pre-development of new manufacturing technologies has not been implemented and verified.

1.5 OUTLINE OF THE THESIS

Chapter 2 presents the research methodology employed in this research. In Chapter 3, the theoretical frame of reference is presented followed by the empirical findings in Chapter 4. In Chapter 5, a support for pre-development of new manufacturing technologies is presented**.** Finally, Chapter 6 presents conclusions, contribution and suggestions for future research.

2 RESEARCH METHODOLOGY

This chapter presents the research methodology. It starts with a discussion about the scientific approach. After that the research design is described followed by the corresponding research process, discussing the studies performed. Then the data analysis is reviewed. Finally, the chapter ends with a discussion concerning the quality of the research.

2.1 SCIENTIFIC APPROACH

Research can be performed using different methodological approaches (Alvesson and Sköldberg, 2008; Arbnor and Bjerke, 1994), and the choice of methodology depends to a large extent on the researcher's view of knowledge but also the nature of the research questions. The three main approaches, as described by Arbnor and Bjerke (1994), are the analytical approach, the actors approach and the system approach (Hubka and Eder, 1988).

Pre-development of new manufacturing technologies is a complex process that requires input from various internal functions and product development projects. The involvement of external equipment suppliers during product development increases also the complexity. This makes it difficult to explicitly isolate the process of pre-development from its surroundings. Therefore, the research problem has been approached from the system perspective, which means that the pre-development process, where the evaluation of the new manufacturing technology maturity level is performed, is thought of as a system.

The objective of this thesis is to develop a support for pre-development of new manufacturing technologies. Therefore, the object of analysis has been development processes (product and manufacturing technology) and the internal/external interfaces connected to these development processes in different settings. Finally, since pre-development of new manufacturing technologies is a complex phenomenon interacting with multiple areas, a suitable approach is the system approach.

2.2 RESEARCH DESIGN

The use of qualitative and quantitative data is fundamental in research design and both types of data can be utilised for generating and testing theories (Saunders et al., 2003). Qualitative data are more suitable for studying complex phenomena (Alvesson and Sköldberg, 2008). Mainly qualitative data have been used to fulfil the research objective; the design of this research has been adapted from the Design Research Methodology (DRM) framework presented by Blessing and Chakrabarti (2009). The DRM framework was chosen to create new knowledge by iterating between the different stages in the framework; the framework used consists of four stages (Blessing and Chakrabarti, 2009):

- Research clarification
- Descriptive study 1
- Prescriptive study
- Descriptive study 2

The first two stages, research clarification and descriptive study 1, have been covered in this thesis by reviewing the literature and performing an analysis of collected empirical data after each research study carried out. First, in the research clarification stage, the research objective and research questions were defined. In the descriptive study stage, the pre-designed research studies were conducted and empirical data were collected. By iterating between these two stages, deeper understanding and knowledge were gained of the phenomenon studied.

A case study method (Yin, 2009) was chosen as the method for collecting empirical data in this research. A case study method provides the opportunity to use multiple sources of data and different techniques for data collection (Yin, 2009) offering the ability to gather a rich set of data from observation, interviews and documents and to study the phenomenon that is not completely understood (Voss et al., 2002; Yin, 2009; Meredith, 1998; Eisenhardt, 1989). Also, the case study method allows proximity to the empirical data, enabling a rich analysis of the phenomenon studied (Yin, 2009). Further, the case study method also allows various designs of studies, e.g., single, embedded and longitudinal case studies, for data collection.

To be able to address the research questions and objective, the research strategy has been to find a suitable context for data collection and study the phenomenon impacting on pre-development of new manufacturing technologies. Development of new products often causes a need for investment in new manufacturing technologies. Therefore, a new product development project and two related acquisition projects of new manufacturing technology have been followed in real time. Also, an assessment of an assembly system maturity level has been studied in order to find out how manufacturing technologies can be assessed. The units of analysis in the three case studies performed were (see Figure 1):

- Case study 1: Project models for product development and production equipment acquisition and their relationship as well as organisational structure and decision making in these processes.

- Case study 2: The application of those project models and involvement of external equipment suppliers during new product development.

- Case study 3: The assessment of development project results.

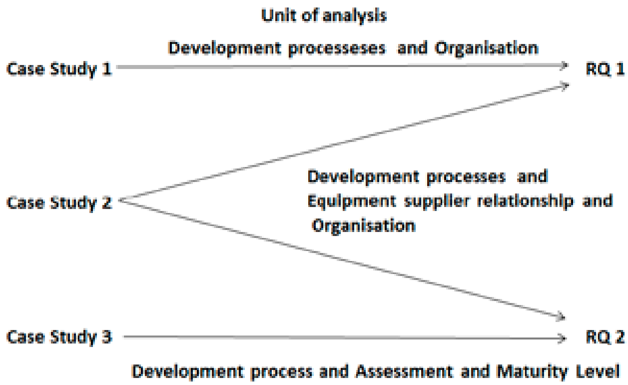

Figure 1 - Unit of analysis in the case studies performed.

2.3 RESEARCH PROCESS

The research process has been an iterative process between theory and case studies, and the process has not been a straight path forward (see Table 1) (Blessing and Chakrabarti, 2009). The research started in an exploratory manner before a clearer focus, research questions and objective had been specified.

Table 1 - The actual research process

Start date	End date	Research process	Literature review	RQ	Paper
Nov 2012	Dec 2012	Research clarification			
Dec 2012	Mar 2013	Single Case Study 1	Literature review 1	1	Paper I Dec 2012 to Mar 2013
Jun 2013	Aug 2013	Updated research clarification			
Sep 2013	On-going	Longitudinal Embedded Case Study 2	Literature review 2	1, 2	Paper II Oct 2013 to Feb 2014
Aug 2014	Aug 2014	Updated research clarification			
Jun 2014	Dec 2104	Single Case Study 3	Literature review 3	2	Paper III Sep 2014 to Jan 2015
April 2015		Licentiate Thesis			

The problem statement was based on industrial problems identified; the research process and data collection methodology of each case study are discussed in more detail below.

Research clarification (November 2012 to December 2012)

In November 2012, the first research proposal was written clarifying the research objectives and research questions. The title for the research project was "Industrialisation of new products in a machining environment" with the objective to "develop a model for efficient industrialisation of new products in a machining environment which will enable an adaptive and sustainable production system responding to high value requirements from customers".

Single Case Study 1 (December 2012 to March 2013)

The purpose of this initial single case study was to identify critical factors and success factors as well as existing challenges when introducing new products in a machining environment. Particular attention was given to the product development process and the production equipment acquisition process. The study started with a literature review regarding existing methods and models of working during product introduction. Main areas for the literature review were new product development, production system development, engineering design and concurrent engineering. Factors found during the literature review were compared with the way of working when developing new products at the case company.

The company studied had a global industrial footprint and the production site where the case study was conducted is characterised by advanced production technology, high mechanisation and a high level of automation. Development of new products in the company involves the areas of production equipment acquisition and production system development and is an ongoing process in the company involving different functions. Production equipment acquisition is common when developing new products, which makes this case suitable for identification of critical factors, success factors and challenges when introducing new products in a machining environment.

Data were collected from internal handbooks, observations and the company's intranet management system and databases with full access to documents. Semi-structured interviews were conducted with project managers in both product and production equipment acquisition projects and department managers in order to find out the challenges of the current way of working. The interviews focused on project models that were used in the company in order to learn more about what has and has not worked during the product development project and how these challenges were handled. Also, daily conversations with staff from different functions in the organisation presented a broad picture of the current situation and challenges. Passive observations at meetings gave an understanding of how decisions are taken by managers and the steering committee. Further, the observations gave insight into what types of problems have occurred and how they were handled by managers. This first research study resulted in Paper I. When collected data were analysed, a new picture and point of view appeared. This resulted in an updated research clarification.

Updated research clarification (June 2013 to August 2013)

The title, objective and research questions were reformulated; also the project scope was narrowed down. The title of the research project was changed to "Evaluation of new production technology during new product development" with the objective to "develop a process for evaluation and introduction of new production technology in a machining environment during new product development".

Longitudinal Embedded Case Study 2 (September 2013 and ongoing)

In this longitudinal embedded case study a new product development project and two production equipment acquisition projects have been followed. This new product development project started in 2012 and will end in January 2016. The purpose of this study is to identify factors that impact on the introduction and evaluation of new manufacturing technology during new product development. Particular attention has been given to the new product development process and how it has affected the acquisition and evaluation of new manufacturing technology. Main areas for the literature review were advanced manufacturing technology (AMT), production equipment acquisition and buyer-supplier relationship.

Further, this new product development project caused the need for investment in new manufacturing technologies. Therefore it was suitable to follow and observe, in order to identify what factors influence the evaluation of new manufacturing technology. To increase the internal validity of this research study (Voss et al., 2002; Yin, 2009), two different manufacturing technology development projects were selected. The two manufacturing technologies had various requirements that had to be met. These requirements came from the product being developed in the form of product drawings and technical specifications. In this study the two projects are called Case A and Case B, and they have been followed in real time at the case company.

Data have been collected weekly from new product development meetings (60-90 min/week) with participants from quality, logistics, project management, production engineering (assembly and manufacturing) and finance since September 2013 and the project will be followed until start of production. During those meetings written notes were taken. With full access to databases, qualitative data were also collected from project documents (risk analyses, meeting notes from other meetings related to the project, etc.). A review of whiteboards that monitored progress and status of all ongoing development projects at the company added empirical data.

Further, semi-structured interviews were held with project members and project managers in Case A and Case B. These semi-structured interviews were not recorded and transcribed; only written notes were taken during these interviews.

Pre-defined questions were used during the interviews; they applied to project status and progress as well as equipment supplier involvement. Furthermore, informal conversation with project members from the different cases added valuable empirical data from various perspectives. The different data collection techniques gave a broad picture of ongoing activities and showed what factors impact on the introduction and evaluation of new manufacturing technologies during this product development project. Data collected were stored in a case study database, and a case study protocol has been used to filter data and put events in chronological order (Voss et al., 2002; Yin, 2009). The first part of this longitudinal embedded case study resulted in Paper II.

Updated research clarification (June 2013 to August 2013)

In June 2013, title, objective and research questions were slightly reformulated, because investments in new production equipment or manufacturing technologies are not only limited to development of new products. There can also be other reasons causing the need for investment in new production equipment, such as the need of increasing capacity in the plant or replacement of production equipment, etc. The title of the research project was adjusted to "Supporting pre-development of new manufacturing technologies" and the objective was to "develop a support for pre-development of new manufacturing technologies".

Single Case Study 3 (June 2014 to December 2014)

This single case study was conducted in the manufacturing industry, and the practical use of an MRL (Manufacturing Readiness Level) scale was observed. The purpose of this study was to analyse the assessment of the maturity level of a manufacturing technology. An assessment of MRL 4 (capability to produce the technology in a laboratory environment) has been studied and the framework used in the assessment originates from the U.S. Department of Defense (DoD, 2012).

In this study different frameworks and concepts used to assess maturity level of technologies have been reviewed. In particular, the Manufacturing Readiness Level (MRL) and Technology Readiness Level (TRL) scales have been studied. The literature review also aimed to find out the relationship between the MRL and TRL scales and how these concepts have been developed over time, as well as their challenges and limitations. However, the main focus has been on the MRL scale developed by the U.S. Department of Defense, and the MRL scale was also used by the case company in this study.

Data were collected through two formal one-hour meetings during the MRL 4 assessment of the assembly system. At the first meeting the production development project with associated project documentation was presented to the assessors, as well as the areas in the MRL 4 framework that would be assessed. One week later, a follow-up meeting was held with the assessors, in which the comments were reviewed and documented as an input to a coming (MRL4) gate presentation to the steering committee of the project. During these two meetings written notes were taken. The notes from the meetings and the assessors' written comments were analysed by consulting the MRL framework on how to perform a Manufacturing Readiness Assessment (MRA). This single case study resulted in Paper III.

Literature review

The books and articles used for the theory were found mainly by using the Mälardalen University library directory and databases: Diva, Scopus, Science Direct, Discovery, Web of Science and Google Scholar. The distribution of unique and overlapping citations in Google Scholar, Web of Science and Scopus reveals a more comprehensive and accurate image of the extent of scholarly relationship (Meho and Yang, 2007). Although Google Scholar unique citations are not of the same quality or weight as those found in Web of Science or Scopus, they could be very useful in showing evidence of broader international impact than could be possibly done through using only Web of Science and Scopus (Meho and Yang, 2007). Further, Web of Science was used for searching for similar journal papers and research if a journal paper was found in the area of interest. By using the citation function back and forward in time, similar work could be found and thereby cover a larger research area and research studies performed.

The following keywords and Boolean operators OR, NOT, and AND were used when searching in databases: acquisition, advanced, assessment, buyer, concurrent, cultural, cycle, design, development, differences, evaluation, engineering, equipment, framework, industrialisation, industry, innovation, lean, level, life, machining, management, manufacturing, matrix, maturity, model, operation, organisation, process, product, production, project, proximity, readiness, relationship, risk, stage-gate, strategy, supplier, system, technology, transfer, world class.

2.4 DATA ANALYSIS

All case studies have begun with a literature review and the conclusions have been drawn from collected empirical data and literature reviewed. The analysis of the collected data has been performed in three steps and has been an interplay between theory and data (Miles and Huberman, 1994).

1. First the reviewed literature was stored and categorised in a database based on the unit of analysis. Then key findings from the literature were derived and stored in a database.

2. During the case studies data were documented and coded in a case study database. A case study protocol was also used for filtering the data and arranging occurrences in chronological order (Voss et al., 2002; Yin, 2009).

3. In the third step, the qualitative data collected were analysed. This step aimed at identifying unique patterns for each case, and key findings from the literature were compared with the empirical data collected (Eisenhardt, 1989).

Based on the emerging pattern in the data analysis phase, new cases studies were designed and initiated. This has been an iterative process as is described in Section 2.2.

2.5 THE QUALITY OF THE RESEARCH

Academic research is measured in several ways, and it is imperative that the research conducted reflects quality when seen from those aspects. In general, research results are measured in terms of validity and reliability. When it comes to case studies, Yin (2009) argues that criteria for judging the quality of research design are construct validity, internal validity, external validity and reliability. These quality measurements are discussed below.

Construct validity

Construct validity refers to the process of making generalisations about higher-order concepts or constructs from the findings that have been measured (Blessing and Chakrabarti, 2009). According to Yin (2009), construct validity refers to design of real operational measures for the concepts being studied. Tactics that can be used are, for instance, using multiple sources of evidence and having key informants reviewing draft case study reports (Yin, 2009).

- Multiple data sources have been used for data collection in the case studies performed. The results have also been derived by triangulating empirical data from different data sources.

Internal validity

Internal validity seeks to establish a causal relationship, whereby certain conditions are believed to lead to other conditions, as distinguished from superior relationships (Blessing and Chakrabarti, 2009; Yin, 2009). Tools that can be used are pattern matching, explanation building, addressing rival explanations and using logical models. These tools can be used in the data analysis phase (Yin, 2009).

- Pattern matching was used in the data analysis phase. The factors derived from prior research were used as a predicted pattern when analysing the empirical data.

- Also, in Case Study 2, two production equipment acquisition projects with different prerequisites were selected in order to strengthen the internal validity.

External validity

External validation concerns the extent to which the findings of a study can be generalised. According to Blessing and Chakrabarti (2009), generalisation can be applied to particular target persons, settings and times and across these. Further, Yin (2009) argues that external validity concerns delimitation of the area to which the study's result can be generalised.

- The results are drawn from limited empirical studies, thus affecting the possibility to generalise from them. Further, the results are also limited to a manufacturing context in the automotive industry.

Reliability

Reliability concerns reproducibility, the certainty that a researcher can independently repeat the research of another and achieve the same results. Yin (2009) requires it to be the same case, not a similar one, which can be problematic when looking for similar results from another researcher, because qualitative research also relates to people.

- The research process has been documented and a case study protocol has been used, arranging occurrences in time and place. The result of the research studies conducted would probably not be the same if another researcher repeated the same studies. The problem of verifying the reliability is that these cases only occur once and it is impossible to repeat these studies with the same conditions. It is up to the researcher to demonstrate good research morality.

Role of the researcher

The research started in November 2012. The researcher's background is in the manufacturing industry where he has worked in different positions and functions at the same company since September 1997. Before becoming a PhD student, the researcher worked as a production engineer with work tasks such as work package leader in new product development projects, production equipment acquisition, design of forging blanks and collaboration with the forging suppliers, documentation, preparation of new products into the production system, etc.

Against this background, manufacturing research is well suited. The researcher has acquired considerable experience from introduction of new products in a manufacturing context, but there is also a risk of being biased. Challenges met have been to remain unbiased and not make own assumptions from previous experience and not to ask misleading questions or influence persons during the daily discussions regarding the phenomenon that has been studied. Also, the change of focus from a very detailed level to a more holistic perspective has been a challenge. The strengths have been easy access and the rich amount of qualitative and quantitative data as well as the proximity to the phenomenon observed in its natural environment. Furthermore, the researcher's background has given knowledge about which persons to contact for various questions.

3 FRAME OF REFERENCE

The theoretical frame of reference is based on literature studies performed during the research process and is a summary of knowledge found in relevant books and scientific articles. The chapter is divided into three major areas in the frame of reference; the overlapping areas in Figure 2 are the areas of interest.

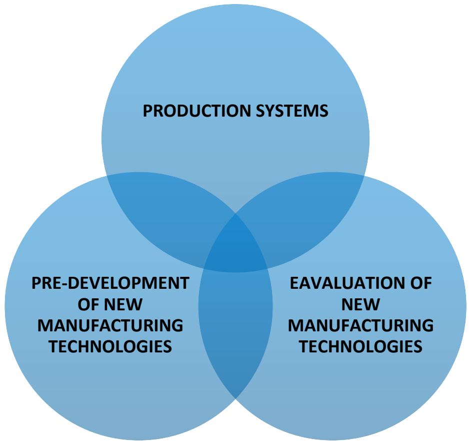

Figure 2 – The research area in focus.

The area of interest for this research comes from breaking down the objective and research questions into different theoretical areas. The area of Production Systems intends to set the research in a context and define key concepts for this thesis. The area of Pre-Development of new manufacturing technologies has been divided into three relevant subareas: market and strategy, development processes and organisation. The interactions between these areas have an impact one pre-development work and are important to discuss in order to address the research questions and achieve the objective. The area of Evaluation of new manufacturing technologies intends to provide an understanding of different approaches used to evaluate the maturity level of new manufacturing technologies.

3.1 PRODUCTION SYSTEMS

3.1.1 DEFINITION OF PRODUCTION SYSTEMS

A production system can be described in different ways depending on the perspectives of observers. Bellgran and Säfsten (2010) define the production system as a transformation of input to output, i.e., transformation of raw material to finished product. The transformation from raw materials to products requires technology, humans, energy and information that is organised and controlled in the best way (Bellgran and Säfsten, 2010). The production system thus represents the company's ability to manufacture a product and includes not only physical artefacts of manufacturing technology and manufacturing techniques but also operational routines and processes required to manufacture the product (Pisano, 1997).

Rösiö (2012, p. 14) characterises the constituent parts of a production system as five subsystems that affect a transformation process from raw materials to products: (1) the technical system, (2) the material handling system, (3) the computer and information system, (4) the human system and (5) building and premises. These five subsystems are understood as follows:

- Technical system: hardware directly related to the production process, e.g., tools, machines, fixtures, etc.

- Material handling system: hardware related to operations at or between stations, e.g., pallet, forklift, transport line, etc.

- Computer and information system: hardware and software to be used to communicate information, e.g., work instructions, software programs, etc.

- Human system: direct and indirect labour, e.g., operators, administrators, etc.

- Building and premises: buildings and their premises, e.g., floor, walls, ceiling, etc.

All these five subsystems are interrelated with each other when transforming material constituents to final products. Therefore, in this research, a **production system** is defined as (Chapanis, 1996, p. 22)

> "an interacting combination at any level of complexity, of people, material, tools, machines, software facilities, and procedures designed to work together for some common purpose".

3.1.2 DEFINITION OF MANUFACTURING TECHNOLOGIES

Hubka and Eder (1988) describe a transformation system as the sum of all elements and influences (and the relationship among them and to their environment) that participate in a transformation. Each transformation system has a fairly well defined purpose, namely to perform the intended transformations on the appropriate operand and thus fulfil the stated and implied needs. Further, the technical process (TP) is an element of the transformation system. A specification of a technical process describes the complete transformation of the operand from "what" (entry state) to "what" (exit state) through "what" (intermediate state), see Figure 3 (Hubka and Eder, 1988).

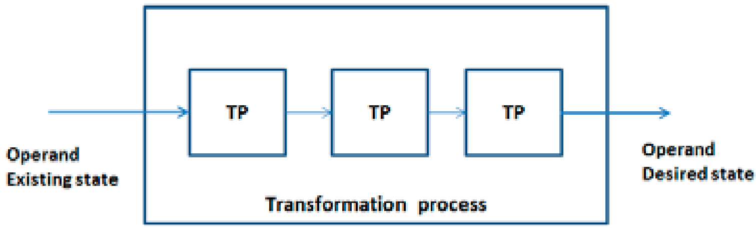

Figure 3 - Model of a transformation process consisting of technical processes. Based on Hubka and Eder (1988).

Based on Hubka and Eder (1988, pp. 35-36) description of a transformation process, **manufacturing technology** is in this thesis defined as

> "the act or process (or connected series of acts or processes) of actually physically making a product from its material constituents".

There are many definitions of "technology" in the literature (Phaal et al., 2004; Drejer and Riis, 1999; Roussel et al., 1991; Trott, 2012). Technology is a commonly used word not yet fully understood by all those who use it. Spiegler (2003) also argues that much confusion exists about the relationship between technology and knowledge. Hickman (1990) offers a comprehensive classification of technology used to describe both products and processes. Roussel et al. (1991) define technology as the application of knowledge to achieve a practical result. Drejer and Riis (1999) state that technology is defined rather broadly in the literature sometimes to represent every capability of an organisational unit or system. Also, the broad definition of technology often imposes some difficulties with respect to assessing the role of technology in industrial enterprises.

Also the term advanced manufacturing technology (AMT) has been defined and grouped in different ways in the literature (Abd Rahman et al., 2009; Chan et al., 2001; Goyal and Grover, 2012; Abd Rahman and Bennett, 2009). Goyal and Grover (2012) have listed different definitions and classifications of AMT that have been made by other researchers. A common denominator when defining AMT is that the technology contains both soft- and hardware. Today, nearly all manufacturing equipment incorporates some electronic elements and thus fits the definitions of AMT.

In this thesis, production technology, advanced manufacturing technology and manufacturing technology are treated as synonyms, and a **new manufacturing technology** is defined as

> "a manufacturing technology that is new or advanced for a company compared to its previous or current manufacturing technology".

3.2 PRE-DEVELOPMENT OF NEW MANUFACTURING TECHNOLOGIES

The focus in this research is pre-development of new manufacturing technologies. Three areas are important when introducing new manufacturing technologies: market and strategy, development processes and organisation.

Development of new products often starts with a market need or changed market demands (Cooper, 2011). From these needs and demands manufacturing companies adapt their product strategy and thereby market and product strategy are closely linked. Further, development of new products usually starts with some R&D based on the market needs before it turns into a formal product development project (Pisano, 1996). However, a product development project often causes a need for investment in new manufacturing technology when an external equipment supplier becomes involved (Abd Rahman and Bennett, 2009; Kotabe et al., 2003). The type of manufacturing technology to be acquired is based on the information from the product being developed such as drawings, technical specifications, etc. Thus, manufacturing companies need to find and evaluate manufacturing technologies found on the market, to see if they can fulfil the manufacturing requirements from the product being developed. However, product development and acquisition of new manufacturing technology are two different processes, but they are dependent on each other.

The different interfaces between strategy and market, development processes and organisation have impact on the efficient introduction of new manufacturing technologies will be covered and discussed in the following sections.

3.2.1 MARKET AND STRATEGY

As stated in the introduction, development of new products is a very important industrial activity (Cooper, 2011). In this work several activities are necessary, e.g., timing of product introduction, development of technology readiness, market readiness and competition analysis (Ulrich and Eppinger, 2008). Cooper (2011) argues that building the voice of the customer through a market-driven and customer-focused new product development process is critical to success. Iterative development including building, testing, getting feedback and updating will put something in front of the customer early and often gets the product right (Cooper, 2011). However, a precondition to achieve and retain a market position is the ability to not only develop products in the most effective way but also to introduce the right products on the market at the right time (time-to-market, TTM) and in the right volume (time-to-volume, TTV) (Bellgran and Säfsten, 2010; Fjällström, 2007). In order to introduce the product on the market at the right time, several functions in the company need to be involved. Ulrich and Eppinger (2008) declare that development of new products involves several functions in the company, three of which have been identified as central to a product development project: marketing, design and manufacturing (Ulrich and Eppinger, 2008; Frishammar et al., 2013).

Often the production system needs to be renewed or modified when developing new products. It can also be necessary to invest in new manufacturing technologies in order to meet the requirements from the product being developed. Trott (2012) states that development of new products and new manufacturing technologies has enabled many firms to continue to grow. However, there is a wide range of alternative strategies they may follow, depending on their resources, their heritage, their capabilities and their aspirations. Collectively these factors should contribute to the direction that the corporate strategy takes (Trott, 2012).

Manufacturing strategy and R&D for manufacturing are important factors to become competitive at a global market and has attracted serious research attention in the recent past (see e.g. Dangayach and Deshmukh, 2001; Skinner, 1969; Hill, 2000; Voss, 2005a; Voss, 2005b; Hayes et al., 2005; Trott, 2012; Pisano, 1996). Skinner (1969) maintained already in the 1960s that manufacturing is a missing link in corporate strategy. Too often management overlooks manufacturing's potential to strengthen or weaken a company's ability. Skinner (1969) also proposed a top-down approach starting with the company and its competitive strategy; its goal was to define manufacturing policy. This was earlier managed from a bottom-up approach and top executives tended to avoid involvement in manufacturing policy making (Skinner, 1969). Hill (2000) argues that in the majority of cases, manufacturing is simply not geared to a business's corporate objective and most companies share access to the same manufacturing technology, and thus technology is not inherently different.

In the last decades, countries such as Japan, Germany and Italy as well as emerging industrial nations such as South Korea and Taiwan have gained competitive advantage through manufacturing (Hill, 2000). Also, in the manufacturing strategy research area different streams have appeared. Dangayach and Deshmukh (2001) reviewed a total of 260 papers (from 31 refereed journals and international conferences) on manufacturing strategy, and process research (including design, development and implementation of manufacturing strategy) has received less attention. It seems that a majority of the researchers have worked in manufacturing capabilities and strategic choices. According to Voss (2005b), three manufacturing strategy paradigms have emerged in the last decades competing through manufacturing, strategic choices in manufacturing and best practice. Hill (2000, p. 13) states that there are two important roles that manufacturing can play as part of the strategic strengths of a company:

- to provide manufacturing processes that give the business a distinct advantage in the marketplace. In this way, manufacturing will provide market-unique technological developments in its process and manufacturing operations that competitors are unable to match.

- to provide coordinated manufacturing support for the essential ways in which products win orders in the marketplace that is better than such support provided by the manufacturing functions of its competitors.

Further, Pisano (1996) found that vertical integration of new manufacturing technologies and in-house manufacturing is important. The trend is that companies utilise outside partners or contractors for manufacturing and such manufacturing strategy could be costly. Tracey et al. (1999) argue that there is a positive relationship between new manufacturing technologies and competitive capabilities and between manufacturing managers' participation in strategy formulation and competitive capabilities.

3.2.2 DEVELOPMENT PROCESSES

Development of new products usually starts with some sort of research and development (R&D); the term R&D is used both by academics and in the manufacturing industry. It is sometimes difficult to determine when research ends and development begins (Trott, 2012). There is no clear boundary between these two areas, but one important factor that combines these two words is knowledge. Roussel et al. (1991) define R&D as developing new knowledge and applying scientific or engineering knowledge to connect the knowledge in one field to that in others.

Trott (2012) states that traditional industrial research has focused on a variety of research activities performed in the organisation and the main activities of industrial R&D have included the following:

- Discovering and developing new technologies.
- Improving understanding of the technology in existing products.
- Improving and strengthening of technologies in manufacturing.
- Understanding research results from universities and other research institutions.

However, to ensure successful product introduction, most manufacturing companies follow a formalised cross-functional new product development process (often called stage-gate process) in which the project members carry out a number of activities for moving the product development project from idea to launch (Griffin, 1997; Cooper, 2008). Cooper (2008) describes the stage-gate process as a process consisting of a series of phases that are followed by go/no go decision points (see Figure 4).

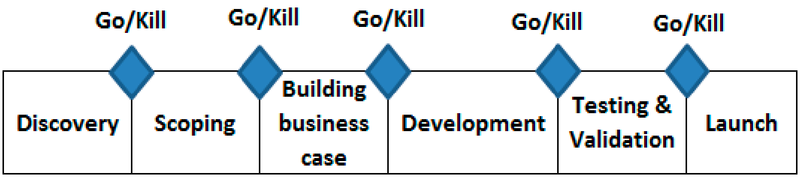

Figure 4 - Stage-gate processes adapted from Cooper (2008).

A well-defined development process is useful for quality assurance, coordination, planning, management and improvement (Ulrich and Eppinger, 2008). Phillips et al. (1999) made a comparative study of six different companies' product development approaches. The number of phases ranged from four to ten. Although the number and description of the phases may have varied between the organisations, they all had the same underlying objective, to provide a means to monitor and execute projects efficiently and effectively (Phillips et al., 1999). Further, Elfving (2007, p. 68) summarises different authors' product development approaches: "there are no clear boundaries between the different approaches, processes and models. Many of them merge. They have much in common. All include variants of the following phases: recognition of need, planning, concept development, detail design, testing and validation, production preparation, and launch". Also, in new product development literature different approaches to make the new product adapted for production can be found, such as design-for-manufacturing (DFM) or design-for-assembly (DFA) (Bellgran and Säfsten, 2010; Pahl et al., 2007; Ulrich and Eppinger, 2008). Further, overlapping activities are used, such as concurrent or simultaneous engineering. Pahl et al. (2007) point out that simultaneous engineering can reduce development times, achieve faster product realisation, reduce product and product development costs and improve product quality (Pahl et al., 2007; Prasad, 2000; Hu et al., 2003; Liker et al., 1996; Xu et al., 2007).

In earlier studies on new product development and product introduction the importance of having a structured process has been highlighted (Bellgran and Säfsten, 2010; Bruch and Bellgran, 2013; Cooper, 2011; Pahl et al., 2007; Ulrich and Eppinger, 2008). However, despite the advances made, product introduction is still a highly challenging endeavour for many manufacturing companies. One explanation for the difficulties might be that although production system development issues are considered in the stage-gate model, the model has mainly been created from a product perspective (Bruch, 2012; Bruch and Bellgran, 2012). As a result, the focus in the stage-gate model is on product design activities, thereby excluding many necessary production system development activities, e.g., pre-development of new manufacturing technologies, production equipment acquisition, etc.

Development of production systems is often connected to the development of new products. The process of developing products has become a central contributor to companies' competitiveness and is extensively described in the literature (see e.g. Cooper, 2011; Pahl et al., 2007; Ulrich and Eppinger, 2008; Tidd et al., 2005). Renewal or modification of production systems is often connected to new product development projects. The type of manufacturing technologies and production equipment to be used for transforming raw material into a final product is based on information about the new product. For example, previous research points to a general reluctance among engineers to release early information on the one hand and to use incomplete information on the other hand (Clark and Fujimoto, 1991; Hauptman and Hirji, 1996). The information on how to design the production system comes from the product development process; Cooper (2011) argues that it is important to get sharp and early product and project definitions, and avoiding scope creep and unstable specification means higher success rates and faster to market. Unstable product and project definitions, which keep changing as the project moves along, are the number one of delays later in the project (Cooper, 1994; Cooper, 2011).

Also, Bellgran and Säfsten (2010) emphasise that an unstable product definition increases the risk of disturbances in the production system in the form of cassation and reduced quality when running in the product. Further, in production system literature, characteristics facilitating an effective management of information when developing a production system have been found. Bruch and Bellgran (2013) highlight the importance of considering the management of information as a multidimensional construct of three dimensions, the acquiring, sharing and using of information. The acquiring, sharing and using of information has to be performed continuously through the production system development process, i.e., in each phase of the production system development process relevant and necessary information needs to be acquired and used among the project members (Bruch and Bellgran, 2013; Xu et al., 2007; Terwiesch et al., 2002).

The importance of investing in new manufacturing technologies has been highlighted in previous research (see e.g. Chan et al., 2001; Ordoobadi, 2009; Goyal and Grover, 2012; Abd Rahman and Bennett, 2009). Still, evaluation and introduction of new manufacturing technologies are challenging. Chan et al. (2001) categorise adoption of new manufacturing technologies into following major steps. The steps in a typical technological adaption process are identified as the generation/identification of technology alternatives, assessment of technology alternatives, ranking of alternatives, emergence of champions, resource allocation and implementation of the selected technology. Goyal and Grover (2012) found that very few implementation models have been built for measuring the effectiveness of manufacturing technologies. Pisano (1997) emphasises that investments in manufacturing technologies have a large impact on the way manufacturing is done, i.e., the manufacturing process. Investments in new production equipment often involve an external equipment supplier that is responsible for the design and subsequent building of the production equipment. As a result, manufacturing companies become dependent on the equipment supplier's capabilities to develop production equipment that ensures high operation performance (Lager and Frishammar, 2010).

Also, Abd Rahman and Bennett (2009) have shown that to be able to understand and utilise the capabilities of equipment suppliers, manufacturing companies need to closely work with the equipment suppliers (Lee et al., 2009; Abd Rahman and Bennett, 2009). To be able to integrate the equipment supplier in product development requires that the equipment supplier gets access to relevant and necessary information from the manufacturing company (Bruch, 2012; Abd Rahman and Bennett, 2009). Similar results are found by Rönnberg Sjödin (2013), who emphasises that a key problem in interorganisational development is related to information not being shared or jointly understood by the partners. Further, the study by Abd Rahman et al. (2009) shows that higher implementation performance is achieved when stronger relationships between the manufacturing companies and the equipment supplier are developed. Also, Rönnberg Sjödin (2013) emphasises the importance of selecting the right partners to cooperate with in joint manufacturing technology development projects in order to have a successful introduction of new manufacturing technologies.

Another challenge is the geographical distance between buyer and equipment supplier. Gertler (1995) found that geographical distance and location affects communication and different time zones reduce the number of hours of the day during which both buyer and equipment supplier are operating. Kotabe et al. (2003) found that technology transfer becomes beneficial if the buyer and supplier have interacted long enough. Further, Cannon et al. (2010) suggest that understanding cultural norms and values that emphasise supplier performance and/or trusting relationship may help both buyers and equipment suppliers to develop and improve their buyer-supplier relationship strategies, thereby increasing the likelihood of a relatively successful buyer-supplier relationship.

Finally, in the literature the expression “process development” is used when it concerns manufacturing technology development. This expression is often used when the research is performed in a process industry context. Process industries span several industrial sectors such as minerals and metals, pulp, paper, food and chemicals (Lager and Storm, 2013). Lager and Storm (2013) declare that process development generally refers to the development of a firm’s manufacturing processes and process development often takes place in collaboration with manufacturers of process equipment and suppliers of raw material.

According to Lager and Hörte (2005), a simplified process development process in the process industry can be described by the following phases: 1) identifying internal production, 2) process development in laboratories, pilot plants and production plants, 3) transferring development results to production. Kurkkio et al. (2011), describe the pre-development in process development as four different phases: 1) informal start-up, 2) formal idea study, 3) formal pre-study and 4) formal pre-project. Further, Lu and Botha (2006) have developed a theoretical framework with twelve enablers supporting process development divided into the following areas: intra-functional enablers in the process development function, inter-functional enablers through interacting with related functions and learning enablers (aligning experiments and learning with timing and stages of knowledge). Hayes et al. (2005) argue that deciding when a process technology is ready to be transferred into operations is a subject of great debate in many organisations and there is no right answer to this debate. A model commonly used when describing the life cycle of a product is the S-curve, from basic research to applied technology (Drejer and Riis, 1999). Further, Hayes et al. (2005) describe the transfer of process technologies into operations as a link between knowledge and learning strategy as learning before doing and/or learning by doing.

3.2.3 ORGANISATION

In agreement with product development theories and production system development literature, studies about product introduction reveal that lacking the right skills, knowledge and cross-functional teams to undertake the project is crucial (Bellgran and Säfsten, 2010; Cooper, 1994; Cooper, 2011). The lack of true cross-functional teams is a major fail point in many projects according to Cooper (2011) and Zirger and Hartley (1996). Zirger and Hartley (1996) have investigated acceleration techniques in order to reduce development time, and the team structure and management variables appear to have the greatest impact on product development time. Further, Da Rosa Cardoso et al. (2012) highlight the importance of appointing a coordination group to manage the whole process of new manufacturing technology evaluation, adaption and implementation. Gupta et al. (1997) found that smaller firms with a leaner organisation got better performance from new manufacturing technology implementation. A successful implementation of new manufacturing technology could be achieved with a careful focus on organisational size.

Product development is an interdisciplinary activity requiring contributions from nearly all functions of a firm (Ulrich and Eppinger, 2008; Prasad, 2000). Ulrich and Eppinger (2008) found that many organisations take on too many projects without regard for the limited availability of development resources. As a result, skilled engineers and managers are assigned to more and more projects, productivity drops off dramatically, projects take longer to complete, products come later to the market and profits are lower. Cooper (2011) also argues that one of the greatest failures in product and production system development is senior management issues, namely overloading the development pipeline. Far too many projects are approved at the Go/Kill gates before considering the resources available. Bellgran and Säfsten (2010) point out that it is relevant to consider how resources are spread between the functions production engineering/production development and manufacturing technology development and construction. Resource allocation in production engineering affects the development of the production system.

One way to monitor development projects and resources is aggregate planning. Aggregate planning helps an organisation make efficient use of its resources by pursuing only those projects that can reasonably be completed with the budgeted resources (Ulrich and Eppinger, 2008). In the aggregate planning process, an organisation may find that it is in danger of over-committing resources. Therefore the organisation must decide at the planning stage which projects are more important to the success of the firm and pursue those with adequate resources. Other projects may need to be eliminated from the plan or shifted in time (Ulrich and Eppinger, 2008).

In development projects different types of knowledge are needed, and in the literature the word “knowledge” has been defined in various ways. Spiegler (2003) argues that the difficulty of defining knowledge is due to the paradox that knowledge resides in a person's mind and at the same time has to be captured, stored and reported. Spiegler (2003) maintains that any definition of knowledge must start from data and information. If data become information when they add value, then information becomes knowledge when it adds insight, abstraction and better understanding. Knowledge can also be divided into explicit and tacit knowledge. According to Phaal et al. (2004), technological knowledge is that which can be articulated (for example in a report, procedure or user guide) together with the physical manifestations of technology (equipment). Tacit technological knowledge is that which cannot be easily articulated and which relies on training and experience (Phaal et al., 2004; Drejer and Riis, 1999). Acquiring new knowledge takes time and needs to be built over time. Trott (2012) says that acquiring knowledge about technology takes time, involves people and experiments and requires learning. To exploit technological opportunities, a firm needs to be on the "technology escalator" (Trott, 2012). Building new knowledge is also a competitive weapon and should be part of the company's strategy. Drejer and Riis (1999) argue that key competencies essential for competitive strength in an industrial enterprise hold substantial elements of tacit knowledge that are difficult to identify and describe.

In development projects different types of knowledge are needed to cover different aspects. Bellgran and Säfsten (2010) maintain that the team members in development projects should represent different functions and disciplines, in order to provide enough knowledge and cover different aspects. Pahl et al. (2007) state that project leaders must have good knowledge of the relevant technology and be good problem solvers. Only then are they able to manage a team of experts from different fields to achieve the project goals and to cope with the task assigned to them (Pahl et al., 2007). In acquisition projects of new manufacturing technologies the knowledge needs to be shared with an external partner and both partners need to be ready and willing to share information and understanding with each other. Mortara and Ford (2012) point out that this can be particularly challenging if the companies are significantly different in size. Knoben and Oerlemans (2006) argue that technology proximity is based on shared technology experiences and knowledge bases and define technology proximity as those tools, devices and knowledge that mediate between inputs and outputs and/or that create new products or services. Further, Knoben and Oerlemans (2006) assert that the match between organisations in terms of strategy, structure and culture is an important aspect but only facilitates the exchange of technological knowledge. A certain amount of technological proximity is also required in order to be able to use the knowledge and capabilities of the other actor (Knoben and Oerlemans, 2006).

3.2.4 FACTORS AFFECTING THE SUCCESSFUL INTRODUCTION OF NEW MANUFACTURING TECHNOLOGIES

In the literature many aspects impacting on the successful introduction of new manufacturing technologies can be found. From the literature reviewed, the following factors with an impact on the successful introduction of new manufacturing technologies can be summarised (see Table 2):

Table 2 – Factors impacting on the successful introduction of new manufacturing technologies

Key Factors	Introduction of new manufacturing technologies
Market and Strategy	• Discovery • Equipment supplier relationship • Company size • Geographical location • Language • Culture • Technology readiness • Manufacturing strategy
Development processes	• R&D • Pre-development • Development model • Aggregate planning • Project definitions • Development time • TTV • Information sharing
Organisation	• Organisation size • Cross-functional teams • Development resources • Right knowledge

3.3 EVALUATION OF NEW MANUFACTURING TECHNOLOGIES

As presented in Section 3.2, different factors impact on the introduction of new manufacturing technologies. In this section, the words evaluation and assessment will be defined and different approaches used for assessing the maturity level of new manufacturing technologies will be discussed.

3.3.1 EVALUATION AND ASSESSMENT

In order to evaluate new manufacturing technologies, the words "evaluation" and "assessment" need to be defined.

Pahl et al. (2007, p. 110) state that an evaluation is to determine the "value", "usefulness" or "strength" of a solution with respect to a given objective. An objective is indispensable since the value of a solution is not absolute but must be gauged in terms of certain requirements. An evaluation involves a comparison of concept variants or, in the case of comparison with imaginary ideal solutions, a "rating" or degree of approximation to that ideal (Pahl et al., 2007). Derelöv (2009) argues that evaluation is the activity which, in most cases, precedes a decision. The objective of an evaluation is to collect and compare information from different alternatives. Further, Säfsten (2002, p. 228) defines evaluation as the system and methodical process of investigating and judging an assembly system in the light of certain criteria, or the result of that process.

Derelöv (2009) describes an evaluation process consisting of three steps/activities: define goal, collect information and assess information (see Figure 5).

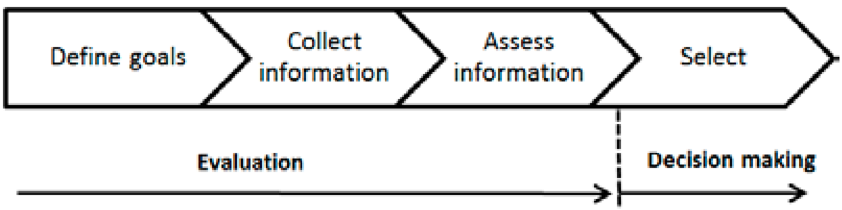

Figure 5 - A basic outline of the evaluation and decision making process. Adapted from Derelöv (2009).

As the expression indicates, evaluation and decision making are two separate parts: one evaluation part and one decision making part. Even if evaluation and decision making are often closely associated with each other when discussing design issues, it is important to keep in mind that they are, in theory, two widely different activities (Derelöv, 2009).

In this thesis, **assessment** is defined as (based on Säfsten, 2002)

> "points during the manufacturing technology development cycle when the manufacturing technology is assessed in the light of certain criteria, and the result of that assessment".

An assessment of a manufacturing technology is performed in order to define current maturity level and identify maturity shortfalls and associated costs and risks.

3.3.2 EVALUATION MODELS AND APPROACHES

In the literature different models for evaluation can be found and with different objectives. Säfsten (2002) argues that an evaluation model can be described as an approach or a way of action in order to carry out an evaluation. The role of evaluation has either been to control the degree of goal fulfilment or to identify potentials for improvement. Evaluation concerns examination and judgement of a system in terms of its relative worth, quality of performance, degree of effectiveness, anticipated cost and so on (Säfsten, 2002). Säfsten (2002) also claims that evaluation deals with three main issues, knowledge, judging and use of result.

Further, there are several approaches for evaluating investment in new manufacturing technologies; they can be classified into three groups, strategic evaluation, economic evaluation and analytic evaluation (Chan et al., 2001; Small, 2006; Goyal and Grover, 2012). Orr and Sohal (1999) and Hynek and Janeček (2009) claim that investing in new manufacturing technology is often difficult to evaluate on the basis of traditional analytical techniques such as pay pack, return on investment, net present value and internal rate of return, because they require quantifiable numbers and many of the benefits of new manufacturing technologies are hard to quantify.

Small (2006) investigated the relationship between the type of technology portfolio being used and the justification approaches and evaluation techniques that were utilised to justify the investment. The results indicate that the majority of the 82 responding plants had a hybrid approach to justifying the manufacturing technology (Small, 2006). Chan et al. (2001) found when reviewing the literature that most companies only use one or two hybrid evaluation approaches (e.g., strategic and economic or economic and analytic) to decide on manufacturing technology investment. Da Rosa Cardoso et al. (2012) recommend that new manufacturing technology to be introduced should be selected according to strategic criteria and its implementation planned according to a set of organisational design recommendations. There are also challenges when evaluating new manufacturing technologies. Ordoobadi (2013) summarises barriers when evaluating new manufacturing technology: uncertainty, lack of resources, perception of payback, priority scheme, time constraints to make a decision, resistance to change, issues regarding the champion for the cause, success rate in past technology introduction and current perceived need of the company for a new technology.

In the literature, various ways of measuring the maturity level[1] of a technology can be found (Mortara and Ford, 2012). One commonly used scale in R&D projects mostly applied to the development of new products is the Technology Readiness Level (TRL) scale, developed by the National Aeronautics and Space Administration (NASA) in the 1970s (Mankins, 2002; Mankins, 2009b). Mankins (2009b) declares that the TRL has proved to be highly effective in communicating the status of new technologies among sometimes diverse organisations. However, an alternative metric is provided by the STAM (Scientific, Technology, Application, Market) model. Mortara and Ford (2012) explain the STAM model as follows: a technology starts with its scientific underpinnings, then develops into a technology, leading to an application and finally to the market.

In the manufacturing area there are also some examples of how to assess and develop knowledge about new manufacturing technologies, e.g., the Manufacturing Readiness Level (MRL) developed by the U.S. Department of Defense (DoD, 2012). MRLs and related assessments of manufacturing readiness have been designed to manage manufacturing risk in acquisition projects and increase the ability of the technology development projects to transition new technology to weapon system applications. According to DoD (2012), Homeland Security (2009) and Sauser et al. (2006), the MRL scale was created from a manufacturing perspective to evaluate manufacturing readiness helping program managers assess manufacturing risks.

However, numerous types of readiness levels have been created since the inception of TRL (Homeland Security, 2009; Azizian et al., 2009; Sauser et al., 2009; Fernandez, 2010). As an example, Ramirez-Marquez and Sauser (2009) propose a System Readiness Level (SRL) index that incorporates both the current TRL scale and the concept of an Integration Readiness Level (IRL) for determining current and future readiness of systems. Tao et al. (2010) have developed an Innovation Readiness Level (IRL) framework for managing the process of incremental innovation. Further, Islam (2010) has developed a method for understanding and/or assessing the maturity of micro and nanomanufacturing technologies using a readiness matrix called Innovative Manufacturing Readiness Levels (IMRLs). Fernandez (2010) summarises commonly used readiness levels for the assessment of maturity into Human Readiness Levels, Logistics Readiness Levels, Operational Readiness Levels, Programmatic Readiness Levels, Capability Readiness Levels, Design Readiness Levels, Software Readiness Levels, etc. Moreover, Fernandez (2010) divides these different readiness levels into qualitative and quantitative techniques for assessment of maturity levels. There are many different readiness levels and scales. They are all dependent on what context they will be used in and they have their limitations and challenges.

[1] In this thesis, readiness level and maturity level are considered as synonyms.

Mankins (2009a) argues that the challenge for technology managers is to be able to make clear, well-documented assessments of technology readiness and risks, and to do so at key points in the development life cycle. Moreover, TRLs do not address the problem of difficulty in R&D progress, i.e., how hard it will be to move from one TRL to the next for a given set of R&D objectives (Mankins, 2009a). Further, Sauser et al. (2006) and Magnaye et al. (2010) assert that the TRL does not take into account the integration of two technologies and TRLs do not provide a full assessment of the difficulty of integrating technology into an operational system. The TRL scale, however, only provides a snapshot of the maturity of a technology or system at a given point in time and TRLs by themselves do not provide a full picture of risk associated with a project or the difficultly required to advance a project (Homeland Security, 2009). Fernandez (2010) argues that TRLs have limitations especially with regard to integration of complex systems.

To summarise, there are different models used for evaluation and three commonly used are strategic, economic and analytic evaluation; many manufacturing companies use a hybrid approach to justifying the manufacturing technology. Further, there also exist different scales for assessing the maturity level of various technologies; that evaluation deals with three main questions, knowledge, judging and use of result.

4 EMPIRICAL FINDINGS

This chapter summarises the most important findings and conclusions from the empirical studies conducted as a part of this research. Table 3 shows how the case studies are related to the research questions. The empirical part of this research comprises three studies, Studies 1 to 3. The studies, their objective and the course of action are presented in detail in Section 2.3. In the following sections the most important findings from each study are presented. Each section ends with a summary of the study.

Table 3 - The relationship between research questions and cases studies performed

Research question	Case Study 1	Case Study 2	Case Study 3
What factors have an impact on the successful introduction of new manufacturing technologies?	✓	✓✓	(✓)
How can the maturity level of new manufacturing technologies be evaluated?	(✓)	✓	✓✓

✓✓ = Strong relationship, ✓ = Medium relationship, (✓) = Weak relationship

The case studies were conducted at one company in the manufacturing industry at two different plants. The company had a global industrial footprint, and the production sites were characterised by advanced production technology, high mechanisation and a high level of automation.

4.1 SINGLE CASE STUDY 1

This study was initiated by the research clarification and is connected with RQ 1. The study aimed to identify critical factors forcing manufacturing companies to improve the development of manufacturing technologies. Particular attention was given to the product development process and the production equipment acquisition process. Further, this study was an explorative single case study; the results are presented in Paper I.

4.1.1 RESULTS

At the case company development of new products started with R&D, developing technical solutions and concepts up to an acceptable technical readiness level. When new concepts and solutions were ready for implementation in new products, they were transformed into product development projects and were developed further. R&D of products and the product design department were located in the same city, while the manufacturing plant was located in another city. At the company there was no pre-development of new manufacturing technologies; all manufacturing technology development took place during new product development projects. However, development of new products required an interaction between engineers at the product design department and the production engineers at the manufacturing plant. Engineers at the design department developed the product into an implementation-ready product and production engineers at the manufacturing site were involved in, among other things, giving feedback on the product design, manufacturability and design changes of the product.

If new production equipment had to be acquired because of the design or technical specification of the product, production equipment acquisition projects were initiated concurrent with the new product development project (see Figure 6). In production equipment acquisition projects also materials handling, automation, machine layout and workplace design were done by the project team. New investments included purchasing of new production equipment from an external equipment supplier who was responsible for the design and subsequent building of the production equipment. The responsibility for the investments had been at the manufacturing plant during product development projects. The production equipment acquisition process was affected by an increasing capacity in production and also by the technical requirements or geometrical design of the new products. The type of manufacturing technology to be acquired was based on information about the new product such as drawings and technical specifications, i.e., all information needed for evaluating suitable manufacturing processes.

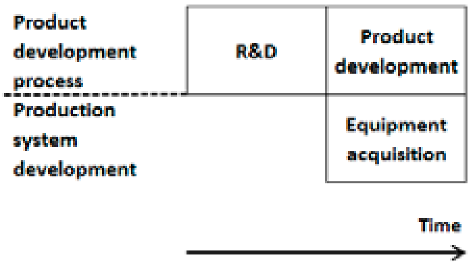

Figure 6 – Product and production system development processes

The production equipment acquisition process started after the product development project had been defined and set in motion. Both models were stage-gate based and used for following-up progress of projects. The project models had different checklists for each project phase, with criteria that had to be fulfilled before each decision gate.

When a production equipment acquisition project was initiated at the manufacturing plant, a project manager was appointed by a steering committee. The project manager required resources from functions needed to undertake the investment project and managers for each function assigned available resources. The project manager was responsible for coordinating the project and reported the progress of the project to a local steering committee at the manufacturing plant. Functions commonly involved in production equipment acquisition projects were production engineering, production (production managers and machine operators), maintenance and purchasing. Production engineers were often involved in both product and production equipment acquisition projects, which increased their workload depending on how many projects they were involved in. Project managers for production equipment acquisition projects did not participate as project members in new product development projects.

New product development projects had a team structure similar to that for production equipment acquisition projects. When a new product development project was initiated, a project manager was appointed at the manufacturing plant. This project leader reported the progress of the project to a main project leader located in another city. The main project leader coordinated all the functions that were involved in the new product development project such as design and manufacturing. The project manager at the manufacturing plant used resources in the form of work package leaders from functions needed to undertake the new product development project.

Managers for each function assigned available resources to the product development project. Functions commonly involved in product development projects were logistics, production engineering, quality and finance. Work package leaders required resources from functions such as production, e.g., machine operators, thereby creating a cross-functional team with members from different functions. The project manager was responsible for coordinating the product development project at the manufacturing plant and reported deliverables before every gate. When a gate was passed, the project manager gave new tasks to the work package leaders to be investigated during the next project phase.

Further, there was no overall planning and follow-up of available resources at the company. Sometimes resources were involved in several product development projects, production equipment acquisition projects or other projects concerning production system improvements or the daily production. This resulted in available resources being involved in many different projects with a high workload as a result. Thus, allocation of production engineers to different types of development projects was a problem at the company.

The information that was used to evaluate suitable manufacturing technology came from the early phases in the new product development project. At a certain point in the production equipment acquisition model, the project team was supposed to recommend an equipment supplier to a steering committee at the manufacturing plant. If the recommended equipment supplier was approved by the steering committee, a final negotiation was held with the equipment supplier. After the final negotiation the equipment supplier could start to design and build the production equipment. However, constant changes of information during the early product development phases were common in product development projects. This made evaluation of suitable manufacturing technology difficult. Changes in information after the contract with the equipment supplier had been signed meant that the new information also needed to be sent to the equipment supplier. This caused extra work and cost. In addition, it also the increased the risk that old and incorrect information was used during the design of the production equipment.

Both project models were under continuous development and the new product development model was going to be changed. The main goals were to reduce TTM and to reduce cost in product development projects. Activities to achieve these goals were

- more front-end loading in new product development projects
- more simulation and calculation in early development stages
- stable releases of drawings and specifications

The goal of reducing TTM affected the production equipment acquisition process as time allocated for evaluation of new manufacturing technology needed to be reduced. Further, the delivery time of production equipment in this type of industry was between 12 and 18 months and the lead time was dependent on the external equipment supplier. Investment in new production equipment ranged from a single machine to a complete production line consisting of six to seven machines including automation solutions like robot cells for loading/unloading the machines and conveyors between the machines for transportation of material. Investment in a complete production line involved several equipment suppliers with different time plans for designing and building the production equipment, which complicated coordination. Coordination of information and requirements on the production equipment between the company and the production equipment supplier was handled by the project leader responsible for the production equipment acquisition project at the manufacturing plant. Finally, the company had great knowledge and experience of their existing production equipment but a lack of experience concerning new manufacturing technologies.

From this study, the following factors can be summarised affecting the successful introduction of new manufacturing technologies and evaluation of maturity level (see Table 4):

Table 4 – Summary of factors affecting the successful introduction of new manufacturing technologies and evaluation of maturity level from Case Study 1

Key factors	Introduction of new manufacturing technologies	Evaluation of maturity level
Market and Strategy	• Equipment supplier relationship • Lead time for production equipment • R&D	• Equipment supplier relationship • Lead time for production equipment • R&D
Development processes	• Development model • Aggregate planning • Project definitions • Development time • Information sharing • Decision making	• Development model • Project definitions • Development time • Decision making • Future goals
Organisation	• Cross-functional teams • Development resources • Workload • Technical knowledge	• Cross-functional teams • Development resources • Workload • Technical knowledge

4.2 LONGITUDINAL EMBEDDED CASE STUDY 2

This study was initiated after Case Study 1 and an updated research clarification; the study is connected with RQ 1 and RQ 2. The study aimed to identify factors affecting the introduction and evaluation of new manufacturing technologies during new product development. Paper II is based on the first part of this study. A new product development project and two related acquisition projects of new manufacturing technologies were studied in real time at a company in the manufacturing industry. These two acquisition projects will be referred to as Case A and Case B.

4.2.1 RESULTS

This new product development project started in 2012. The product that was being developed had several new technical solutions consisting of several components, which caused the need for investments in new manufacturing technology. Monitoring and follow-up of projects were done with stage-gate models, one for the new product development project and one for the acquisition of production equipment. If a new manufacturing technology had to be acquired because of the geometrical design or technical specification of the component, a production equipment acquisition project was initiated. Initiation of projects at the company was done by a steering committee that appointed a project leader. The project leader appointed was often an experienced production engineer from the company. The project leader also participated in the new product development project as responsible for the evaluation and acquisition of manufacturing technologies. During the new product development project a decision was made to increase the capacity in the plant, which required coordination of the new product development project and a capacity project. A decision on what type of manufacturing technologies had to be invested in needed to be synchronised between these two projects, as well as allocation of staff resources.

The results will be presented separately, starting with Case A.

Case A

In Case A, due to the complex design of one of the components being developed, a new manufacturing technology had to be acquired. Initiation and startup of the acquisition project was delayed, because no approval to start up the project was given by the steering committee at the company. The production engineer responsible for this category of components and manufacturing processes took the initiative and contacted several equipment suppliers before the acquisition project was initiated. This early initiative was taken since the time for evaluating and deciding what type of manufacturing technology to be used was critical. Also, the production engineer's previous experience from acquisition and evaluation of new manufacturing technologies influenced the decision. All the equipment suppliers contacted were given the necessary information and were asked to suggest a suitable manufacturing technology.

All the equipment suppliers contacted were European-based suppliers known from previous collaboration and investment in manufacturing technology. These equipment suppliers were also familiar with the acquisition process of the company. One equipment supplier responded with a proposal of a suitable manufacturing technology. A meeting was held at the case company and manufacturability was discussed with the equipment supplier. The supplier's proposal required a minor design change of the component that was to be manufactured. The proposal would be sent to the product designer to ascertain whether the design change was possible. If it was possible to change the product design it would in return provide improved manufacturability and a stable manufacturing process, which would have resulted in improved product quality and reduced cycle time. This new manufacturing technology would also have an impact on the production system. There were plans at the company to redesign one manufacturing line and replace some of the production equipment by which this new component would be manufactured. The introduction of this manufacturing technology meant that one step in the manufacturing line could be removed. Thus, the new manufacturing technology also reduced investment cost by reducing the number of manufacturing steps. However, the new technology had to fulfil the requirements from older products that were going to be made in the manufacturing line.

According to the equipment supplier, this was their first delivery of this type of manufacturing technology to Sweden. This new technology had not been verified or tested with prototypes by the company. The manufacturing technology had existed on the market for a couple of years and the case company relied on the equipment supplier. A reason that was given for not performing some type of verification was the lack of time and resources. The new manufacturing technology might have a high maturity level and should be able to be introduced in the production system at the case company. However, there must be some in-house knowledge regarding limitations and challenges of the new technology. In this case the new knowledge was built through an external equipment supplier and no prototyping was performed. Also, a manufacturing technology can be mature in one context and not in another.

Finally, during a function test of the product the new technical solution, which also the component was a part of, failed. It was decided in the new product development project to replace the new technical solution with an old verified solution. The new technical solution was excluded from the product development project and was put on hold and thereby excluded from further development. No decisions were taken about its future development. However, the company did make a decision to invest in the new manufacturing technology that was meant to produce the new component. The main reason for that was the reduced number of manufacturing steps in the manufacturing line that would be reconfigured. Also, if a new decision were taken to resume the development of the technical solution that had failed, a suitable manufacturing technology would be available.

From this study, the following factors can be summarised affecting the successful introduction of new manufacturing technologies and evaluation of maturity level (see Table 5):

Table 5 - Summary of factors affecting the successful introduction of new manufacturing technologies and evaluation of maturity level from Case A

Key factors	Introduction of new manufacturing technologies	Evaluation of maturity level
Market and Strategy	• Equipment supplier relationship • Geographical location • Language	• Equipment supplier relationship • Geographical location • Language
Development processes	• Development model • Project definitions • Development time • Information sharing	• Project definitions • Development time • Information sharing
Organisation	• Development resources • Own initiative • Technical knowledge	• Development resources • Technical knowledge

Case B

In Case B, a new external equipment supplier was involved during the new product development project. This new manufacturing technology was discovered by a business unit in the company that informed the design department regarding its potential benefits. A project team was put together at the company, with team members from manufacturing, product design and materials laboratory, who started investigating this new manufacturing technology. The main purpose of the new technology was to change some material characteristics in some of the components in the product being developed. If the manufacturing technology were not successfully introduced into the production system, one of the consequences would be that a new material had to be used in these components. A change of material would have an impact on the existing production system, because the production system was optimised for another type of material. A change of material would have demanded a great deal of verification of existing production processes. On the other hand, if the manufacturing technology were successfully introduced in the production system, it would have an impact on other products and components. These wanted material characteristics could be applied to other components in other products as well. Furthermore, this manufacturing technology would also allow new design of other products manufactured by the company. Therefore the evaluation of the new manufacturing technology was highly prioritised at the company.

The equipment supplier was located on another continent than the case company. The long distance between the equipment supplier and the company made travels and communication more difficult. Further, the case company started to evaluate the new manufacturing technology before the product development project started in 2012. In the early stages this project was considered as an R&D project for manufacturing. The team included experts from manufacturing, product development and materials laboratory. However, the team composition and the participants from manufacturing changed over time. Project members at the manufacturing plant were replaced by others due to organisational changes, new work tasks, other projects, etc.

In the early phases of the evaluation of the new manufacturing technology, subject matter experts such as manufacturing technology experts, product designers and materials experts visited the production equipment supplier. An interpreter from the equipment supplier company was present during meetings and conversations. Discussions regarding the new manufacturing technology were held and prototypes were produced by the equipment supplier. These prototypes were then analysed by the case company in its laboratory and other tests were performed as well, such as fatigue tests. The prototypes showed the desired characteristics and a decision was taken to go on working with the new equipment supplier. Also, other possible concepts and equipment suppliers were evaluated, but none of them were considered to be at the same level as the manufacturing technology supplier chosen. Further, when the new manufacturing technology was regarded as evaluated and verified, it was handed over to the product development project.

When the new manufacturing technology had been handed over to the product development project, new production engineers started to work with it at the manufacturing plant. They discovered that the new manufacturing technology had negative consequences for one of the dimensions of the component. This had not been investigated in the early evaluation of the manufacturing technology and this discovery was crucial for the whole product development project. A joint collaboration with the equipment supplier was initiated to try to solve the problem. Project members from the company visited the equipment supplier and discussions were held regarding what caused the dimension change. The root cause was found but the equipment supplier could not guarantee that this would not happen in full production. This resulted in problems regarding process stability that had to be solved.

To solve this problem the project members at the company started to discuss it on their return home. They came up with three different proposals for change that were discussed with the equipment supplier. These proposals needed to be verified and therefore new prototype series were initiated and manufactured at the equipment supplier. This was an iterative process and the evaluation of the proposed changes took much time and was therefore time-critical in the product development project.

From this study, the following factors can be summarised affecting the successful introduction of new manufacturing technologies and evaluation of maturity level (see Table 6):

Table 6 - Summary of factors affecting the successful introduction of new manufacturing technologies and evaluation of maturity level from Case B

Key factors	Introduction of new manufacturing technologies	Evaluation of maturity level
Market and strategy	• Discovery • Equipment supplier relationship • Company size • Geographical location • Language • Culture • Technology readiness • Manufacturing strategy	• Equipment supplier relationship • Geographical location • Language • Culture
Development processes	• Early investigation • Development model • Project definitions • Development time • Information sharing • Decision making	• Project definitions • Development model • Development time • Information sharing • Prototyping
Organisation	• Cross-functional teams • Development resources • Technical knowledge	• Cross-functional teams • Development resources • Technical knowledge

4.3 SINGLE CASE STUDY 3

This study is connected with RQ 2 and aimed to analyse how the MRL scale can support the assessment of the maturity level of a manufacturing technology. A single case study in the manufacturing industry was conducted investigating the use of an MRL scale. This study was performed at another business unit than Case Study 1 and Case Study 2. The MRL scale was used for the first time at the company and one specific assessment of MRL 4 was studied in connection with a case of development of an assembly system. The result from this study is presented in Paper III.

4.3.1 RESULTS

In a development project of an assembly system the case company tried to combine four different product platforms so that they could be assembled in one assembly system. The development project focused on the design of a large-scale mixed-product assembly concept and attempted to find solutions to achieve assembly of very different products from different manufacturing sites in the same main assembly flow (assembly line). This includes overcoming challenges of handling different product design, length and weight in the same assembly flow. The project was global with representatives/representative factories from different sites around the world, e.g., Korea, the USA, Germany, Poland and Sweden with knowledge of their products, assembly processes and methods. Further, the development project was divided into four development areas, (1) the development of a main assembly line concept, (2) the development of a materials handling/logistics solution connected with assembly and the proposed assembly concept, (3) investigations into a possible application and implementation of the concept in a specific factory and (4) the specification of flexible requirements on product development.

A first analysis of current products in the corporation resulted in a first proposal for the grouping of products. For this, aspects such as size and weight, product design, assembly process, sequence and tooling, volumes and assembly times were considered. This grouping exercise was used to select a first group of products to start the detailed assembly system development. The detailed development of the main line concept continued towards a layout/process proposal with the main principles of

- having a generic assembly sequence
- using generic assembly zones – a clear zone/station for defined major product modules
- using standardised and common interfaces towards subassemblies/product modules
- common tooling/equipment in each zone

Based on this a first line concept and layout were generated. More data were collected regarding, e.g., detailed work content for each product in each zone. A specific analysis was also done regarding necessary tooling and equipment. In order to increase the maturity of the concept, a prototyping of the concept was done during the fall of 2014. Different products were assembled together to test manufacturing technology challenges in, e.g., tooling and equipment. The objective of the prototyping was also to identify product design characteristics necessary to be changed in order to make the assembly concept feasible and competitive. The goal of the prototyping was to achieve MRL 4 and the main idea behind that assessment was to apply the TRL concept in a manufacturing context.

To determine the maturity level of the assembly system, an MRL framework was used that was based on the framework developed by the U.S. Department of Defense. The MRL framework and assessment were used for the first time at the case company and provided a case for further production system development and process development. Further, the two external auditors came from two different functions in the company with experience of pre-development of products and technology readiness assessment of products. The two external auditors made individual assessments of the assembly system. Their background has made them familiar with the TRL scale and how to carry out an assessment of a technical solution for a product. The normal procedure at the company performing a technology readiness assessment for new product solutions is that the product development team gathers and presents data and external assessors review the material to see if the project fulfils the objectives as an input to a later gate meeting review and approval. The assessment of MRL 4 was performed at two formal one-hour meetings, first a start-up meeting and one week later a follow-up meeting.

The two meetings were held on the internet since project members and the assessors were global participants. The development project had been documented with regard to project criteria to meet and activities performed during the development project. Project leaders in the development project had stored all project documents in a project folder at the company server. This documentation was used in the assessment of MRL 4 in the following areas: 1) Technology & Industrial Base, 2) Design, 3) Cost & Funding, 4) Materials, 5) Process Capability and Control, 6) Quality Management, 7) Manufacturing Workforce, 8) Facilities and 9) Industrial Management.

At Meeting 1, the production development project with associated project documentation was presented to the auditors, as well as the areas in the MRL 4 framework that would be assessed. The assessors were given access to the project folder and the project documents to be assessed.

At Meeting 2, the comments and written notes from the assessors were reviewed and discussed. The notes were used as an input to a coming (MRL4) gate presentation to the steering committee for the project. There was one area that was considered as not fulfilling the MRL 4 level and that was the Cost & Funding area. In order to reach MRL 4 there needs to be a plan on how to achieve MRL 6 and funding for further development. This had not been defined from the beginning in the project scope. Thus, this area was excluded from the assessment.

From this study, the following factors can be summarised affecting the successful introduction of new manufacturing technologies and evaluation of maturity level (see Table 7):

Table 7 - Summary of factors affecting the successful introduction of new manufacturing technologies and evaluation of maturity level from Case Study 3

Key factors	Introduction of new manufacturing technologies	Evaluation of maturity level
Market and Strategy		
Development processes	• Development model	• Development model • MRL • Prototyping • Information sharing
Organisation	• Cross-functional teams • Development resources	• External assessors • Technical knowledge

4.4 SUMMARY OF EMPIRICAL FINDINGS

This section summarises the most important conclusions from the empirical findings.

The conclusions from Case Study 1 are that the technical solutions and concepts for products were further developed in product development projects, information from product development projects was used in the evaluation of new production equipment and all evaluation of suitable manufacturing technology was performed during the early phases in product development projects.

The conclusions from Case Study 2, Case A are that the late initiation of the production equipment acquisition project caused that no evaluation of the new manufacturing technology was performed. Also, other reasons given for not performing any evaluation were the lack of time and resources. The own initiative and earlier collaboration with equipment suppliers highlights the importance of a good equipment supplier relationship. The discussed proposal with the equipment supplier would have provided an improved manufacturability of the component being manufactured.

The conclusions from Case B are that early investigation of a new manufacturing technology was performed before it was handed over to the product development project, cross-functional teams were used in the evaluation, prototyping was used for test and verification of the new manufacturing technology, team members changed over time in the project and the long distance between company and equipment supplier affected communication and travels.

The conclusions from Case Study 3 are that prototyping in a production environment was used, assessment of a production system maturity level was made with the help of an MRL scale and external assessors and a global development project was implemented.

From all studies conducted the following factors can be summarised affecting the successful introduction of new manufacturing technologies and evaluation of maturity level (see Table 8):

Table 8 - Summary of factors affecting the successful introduction of new manufacturing technologies and evaluation of maturity level

Key factors	Introduction of new manufacturing technologies	Evaluation of maturity level
Market and Strategy	• Equipment supplier relationship • Lead time for production equipment • Discovery • Company size • Geographical location • Language • Culture • Technology readiness • R&D • Manufacturing strategy	• Equipment supplier relationship • Lead time for production equipment • Geographical location • Language • Culture • R&D
Development processes	• Development model • Aggregate planning • Project definitions • Development time • Information sharing • Decision making • Early investigation	• Development model • Project definitions • Development time • Decision making • Future goals • MRL • Prototyping • Information sharing
Organisation	• Cross-functional teams • Development resources • Workload • Technical knowledge • Own initiative	• Cross-functional teams • Development resources • Workload • Technical knowledge • External assessors

5 SUPPORTING PRE-DEVELOPMENT OF NEW MANUFACTURING TECHNOLOGIES

This chapter analyses the findings of the research and their implications for the research objective and questions. Factors for achieving a successful introduction of new manufacturing technologies are proposed, as well as a way to evaluate the maturity level of such technologies.

In order to achieve the expected aim of developing support of pre-development of new manufacturing technologies, several aspects need to be addressed and discussed. Based on the theoretical review and the empirical results, the following areas where identified as important and relevant and should be discussed in relation to the stated objective and research questions:

- Factors affecting the successful introduction of new manufacturing technologies:
    - Market and strategy
    - Development processes
    - Organisation

- The maturity levels of manufacturing technologies.

These areas are discussed and dealt with in the following sections.

5.1 FACTORS AFFECTING THE SUCCESSFUL INTRODUCTION OF NEW MANUFACTURING TECHNOLOGIES

Market and strategy

From a company perspective, knowledge of market needs is important in two different perspectives. This has great impact on success when developing products as well as on finding and evaluating new manufacturing technologies available on the market. To find new manufacturing technologies, an active scan of the market is needed including the evaluation of a good equipment supplier relationship.

In Study 4.2, Case A, the equipment suppliers contacted were already known from previous collaboration. The case company knew which equipment suppliers to contact when problems occurred and help was needed. This shows the importance of long-term collaboration and trust, information and knowledge sharing between buyer and equipment supplier. The importance of a good equipment supplier relationship has been shown in prior research, e.g., Abd Rahman and Bennett (2009), Kotabe et al. (2003).

In Study 4.2, Case B, both the equipment supplier and the manufacturing technology were new to the company. The geographical distance between the company and the equipment supplier had an effect on travels and communication.

Also, language differences and cultural differences affected the communication. During project meetings with the equipment supplier, English was used for communication and an interpreter from the supplier company was present. To use an interpreter increases the risk of misunderstanding when no direct communication is possible. Also, the cultural differences may have had an impact on how things were interpreted and understood during the conversations. Furthermore, a different standard was used to build the production equipment than was usually used at the company. Gertler (1995) found that closeness between buyer and equipment supplier is important for the successful introduction of new manufacturing technologies. Cannon et al. (2010) found that few research studies have examined the buyer and equipment supplier relationship in the context of different cultures.

A manufacturing company's product strategy is often linked to market needs and demands. As stated in Section 3.2.2, the development of new products often creates a need for investment in new manufacturing technology. Investments in new manufacturing technologies should be coordinated with plans for future products. In order to have a fast ramp-up and minimise risks when running in new manufacturing technologies, pre-development of such technologies is needed. A substantial amount of money and development resources is spent on the development of new products, while manufacturing technology development seems neglected despite its importance. Fewer development resources are used to investigate and evaluate new manufacturing technologies. Knowledge regarding new manufacturing technologies has been seen as something that can be acquired when needed. These dilemmas have also been highlighted in prior studies, e.g., Hill (2000), Bellgran and Säfsten (2010), Trott (2012) and Pisano (1996).

In Study 4.1, the findings reveal that the case company did not have any pre-development of new manufacturing technologies, which caused all manufacturing technology development to be performed during product development projects. In Paper I a model for improved production system development and manufacturing technology development is proposed. This model proposes and highlights a separate R&D function for manufacturing.

With a separate R&D function for manufacturing, pre-development of new manufacturing technologies can be evaluated separately from the product development process. First, when new manufacturing technologies have reached an acceptable degree of maturity, they can be implemented in the production system. This way of working becomes more proactive and would lead to faster product introduction and improved production system development. As presented in Study 4.2, Case B, the evaluation and introduction of this new manufacturing technology was highly prioritised in the company. It was a strategic decision to evaluate this new manufacturing technology due to its potential benefits to future products. However, the evaluation and introduction of this new manufacturing technology can be time-critical in the product development project. Despite the early investigations and evaluation of the new manufacturing technology, the maturity level was too low before it was handed over to the product development project. This shows that support for pre-development is needed and that new manufacturing technologies should be assessed against some maturity scale like, for example, the MRL scale.

Development processes

In Paper I the findings reveal that two different project models and time plans need to be synchronised. Delays in either product development or production equipment acquisition projects could cause delays in both directions. Further, both these project models were well defined, with clear goals of what to be achieved for each gate in order to minimise risks. This is line with studies by Cooper (2011), Pahl et al. (2007), Ulrich and Eppinger (2008) and Bellgran and Säfsten (2010).

If evaluation of new manufacturing technologies is performed only during product development projects, the time that can be used for evaluation is limited to development time for new products. As presented in Study 4.1, the goal was to reduce development time for new products, which will also affect the time to evaluate new manufacturing technologies. Without pre-development of new manufacturing technologies, evaluation and introduction of such technologies will be challenging. The trend of reduced development time for new products in manufacturing industries has also been highlighted as a challenge in research reports and studies like, among others, Teknikföretagen (2013), European Union (2010) and Tidd et al. (2005).

Also in Study 4.1, product design changes in product development projects made it necessary for new information to be sent to the equipment supplier. Further, product design changes could also have consequences for the choice of manufacturing method when evaluating a suitable manufacturing technology. Especially late design changes in a product development project can be devastating when evaluating a suitable manufacturing technology. As Cooper (2011) argues, design changes are the most common reason for delays in development projects.

In Study 4.1, a TRL scale was used for defining the maturity level of new products, but the company did not use any readiness scale or metric that described maturity levels of new manufacturing technologies. This implies that it is difficult to know when a new manufacturing technology is ready for implementation in the production system. Further, in Study 4.2, Case A, the technical solution for the product might have had too low a TRL before it was transferred to the product development project. This technical solution was excluded from the product development project and replaced by another old and verified technical solution. As presented in Section 3.3.2, this could be due to the fact that the TRL does not take into account the integration of two technologies.

Pre-development of new manufacturing technologies is common in process industries as presented in Section 3.2.2. Pre-development is performed in laboratories or pilot plants before transferring development results to manufacturing. The differences between process and manufacturing industries are in different manufacturing processes and manufactured products, which may be the reason that pre-development is more common in process industry than in manufacturing industry. In Study 4.3, a first attempt to use an MRL scale in a manufacturing context was made. An MRL 4 assessment corresponds to a laboratory environment, and prototyping was also used for verifying the assembly system. This approach is not common in the manufacturing industry and could be compared with the pre-development phases used in the process industry.

Organisation

In Study 4.1 and Study 4.2, cross-functional teams were used in both product development and production equipment acquisition projects. Project members in these cross-functional teams gave input from different perspectives and thereby increased the chances of finding an optimal solution and minimising risks in various issues. However, the lack of resources caused a high workload for project members in development projects. This meant that less time was used for evaluating new manufacturing technologies. According to Cooper (2011) and Zirger and Hartley (1996), the lack of true cross-functional teams is a major fail point in many development projects.

In Section 3.2 different types of knowledge are discussed. Tacit knowledge is an important factor and is something that needs to be developed in order to become and stay competitive on the global market. Tacit knowledge is often seen as difficult to copy, because it relies on experience and training. As presented in Paper II, the production engineers had great experience and knowledge about current manufacturing technology used in the production system. But knowledge about emerging manufacturing technologies was limited. Knowledge regarding new manufacturing technologies was transferred through external equipment suppliers, because no pre-development activities were performed. Also, at visits at international fairs new manufacturing technologies could be discovered. Development of new knowledge is important in order to have an efficient introduction of new manufacturing technologies. In Section 3.3.1 evaluation is defined as “the methodical process of investigating and judging a manufacturing technology in the light of certain criteria, or the result of that process”. Emerging manufacturing technologies need to be assessed throughout their development cycle, which requires knowledge and experiments.

In Study 4.2, Case B, new knowledge about the new manufacturing technology had to be gained. This was achieved through prototyping at the equipment supplier and discussions with the new equipment supplier. Further, in Study 4.3, the objective of the prototyping in the development project was to identify product design characteristics that needed to be changed in order to make the assembly concept feasible and competitive. The new knowledge in this case was gained through in-house prototyping.

To summarise the most important factors affecting the introducing of new manufacturing technologies can be concluded, they are the following:

- Pre-development process
- Project definitions
- Equipment supplier relationship
- Geographical location
- Knowledge and knowledge building
- Development resources
- Cross-functional teams
- Defined maturity levels for new manufacturing technologies
- Development time for new products

5.2 EVALUATION OF THE MATURITY LEVEL OF NEW MANUFACTURING TECHNOLOGIES

Evaluation of new manufacturing technologies can be performed in different ways. As Säfsten (2002) states, evaluation deals with three main questions, knowledge, judging and use of result. In Study 4.1 prototyping was used to evaluate both product and manufacturing processes. However, only the manufacturing processes in the existing production system were verified by these prototypes. All evaluation and verification of new manufacturing technologies was performed at external equipment suppliers as in Study 4.2, Case A and Case B.

In Case A, a production engineer contacted several equipment suppliers before the acquisition project was initiated. This decision was based on previous experience from acquisition and evaluation of new manufacturing technologies. Evaluation of new manufacturing technologies is time-consuming and requires knowledge, people, experiments and learning. Also, in Case A, the new manufacturing technology was not evaluated with prototypes or with any other type of verification before it was acquired. The reasons given for not conducting any verification were lack of time and resources, which is in line with prior studies by Ulrich and Eppinger (2008) and Cooper (2011). Further, the company considered the new manufacturing technology as known and verified because it had existed on the market for a couple of years and therefore no verification would be needed. However, new knowledge needs to be built regarding the challenges and limitations of manufacturing technologies. Also, the maturity level of new manufacturing technologies is context-dependent. A manufacturing technology can be mature in one context and not in another. One way to evaluate and assess the maturity level of new manufacturing technologies could, for example, be to use an MRL scale or similar framework.

In Case B, several prototype series were initiated to evaluate the new manufacturing technology and to verify that process stability could be achieved. Through these prototype series new knowledge was built at the company. But the evaluation also required the involvement of an external equipment supplier in addition to own development resources. The evaluation of the new manufacturing technology took much time and became in the end time-critical in the product development project. Hayes et al. (2005) argue that an optimum of knowledge building is somewhere between learning before doing and learning by doing and that learning by doing is costly and unnecessarily time-consuming. Further, the maturity level of the new manufacturing technology was never assessed against a readiness scale like the MRL scale before it was handed over to the product development project, as in Study 4.3.

In Study 4.3, an MRL scale was used for the first time at the case company and in a manufacturing context. In prior research, the focus has been on product development and maturity levels of products, such as indicated by the TRL scale and further development of the TRL scale (see e.g. Mankins, 2002; Mankins, 2009b; Mankins, 2009a; Sauser et al., 2006; Tan et al., 2011; Azizian et al., 2009). An assessment of MRL 4 requires the capability to produce prototypes in a "laboratory environment". In this case, prototyping was used in the evaluation and different products were assembled together to test manufacturing technology challenges in, e.g., tooling and equipment. However, this evaluation was performed in a modified and further developed production system and so the environment may have corresponded to MRL 5 or MRL 6 in the MRL scale, which demands prototyping in a "production-relevant environment". As presented in Paper III, the definitions in the MRL framework can be interpreted in many ways, and this framework was used for the first time at the company. However, the assessment of the assembly system is an unusual activity, because many production systems go into full production directly, without being assessed regarding their degree of maturity.

In Section 3.3.2 different scales for measuring maturity levels are discussed. There are different scales for measuring the maturity level of different technologies. An assessment of a manufacturing technology is only a snapshot of its maturity level (Homeland Security, 2009). Also, these scales do not address the problem of difficulty in the R&D progress, i.e., how hard it will be to move from one maturity level to the next for a given set of R&D objectives (Mankins, 2009a).

If a new manufacturing technology is evaluated during a product development project and a TRL scale is used for the product and an MRL scale for the new manufacturing technology, it is still challenging. The development time and the maturity level of these two different technologies are most likely different and should therefore be evaluated separately. Only after they have reached readiness level 6 should they be implemented in product development and manufacturing technology development projects.

Also in Section 3.3.2 different approaches used to evaluate new manufacturing technologies are discussed. Orr and Sohal (1999) and Hynek and Janeček (2009) point out that the benefits of a new manufacturing technology are often hard to quantify with traditional analytical methods. In Case B, the new manufacturing technology was considered as strategically important in the company. This new technology would allow new product designs and better product performance if it was successfully implemented in the production system. This shows the importance of evaluating new manufacturing technologies. New manufacturing technologies can create competitive advantages if they are successfully implemented in the production system.

From the three studies the following factors affecting the evaluation can be summarised (see Table 9):

Table 9 – Factors affecting the evaluation of maturity levels in Case A, Case B and Case 3

	Case A	**Case B**	**Case 3**
Development project	NPD	NPD	Production system
Time-critical	Yes (early phase in NPD)	Yes (late phase in NPD)	No
Prototyping	No	Yes	Yes
Previous collaboration with equipment supplier	Yes	No	-
Knowledge building through	Equipment supplier	Equipment supplier/Prototyping	In-house/Prototyping
Assessment of maturity level	No	No	Yes (first attempt)
Cross-functional teams	No	Yes	Yes
Dedicated resources	No	Yes	Yes

To summarise, the main conclusions regarding evaluation of the maturity level of new manufacturing technologies are the following:

- Knowledge needs to be built both through experiments in-house and through external equipment suppliers.
- The degree of maturity of new manufacturing technologies should be assessed through their whole development cycle.
- A manufacturing technology can be mature in one context but not in another.
- When assessing the maturity level of a new a manufacturing technology, predefined maturity levels should be available.
- A new manufacturing technology should have reached a certain degree of maturity before it is implemented in the production system.

5.3 SUMMARY

The main objective of this thesis has been to develop a support for pre-development of new manufacturing technologies. In Figure 7, a support for such pre-development is proposed. This support aims both to put the research in a context and propose a process that supports introduction and evaluation of new manufacturing technologies. The area marked in red is the area of interest for this research. Further, the red points indicate points at different interfaces where the factors affect the pre-development of new manufacturing technologies.

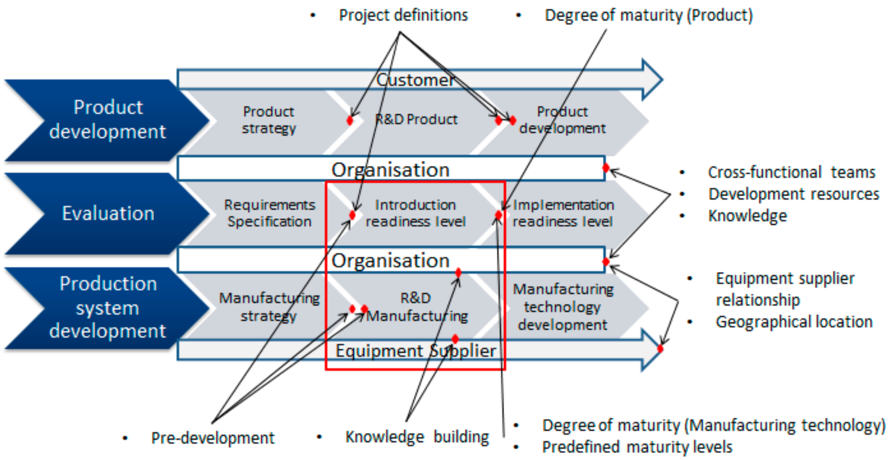

Figure 7 – A support for pre-development of new manufacturing technologies.

In this research the interaction between product development and manufacturing technology development has been studied. Also, the involvement of external equipment suppliers during product development has been studied, as well as how the maturity of new manufacturing technologies has been evaluated.

Different factors affecting the successful introduction and evaluation of new manufacturing technologies have been discussed. Based on the discussions in Sections 5.1 and 5.2, the maturity level of new manufacturing technologies should be evaluated stepwise during their development cycle. The proposed support highlights the most important factors in the different interfaces between market (equipment supplier), strategy, development processes and organisation. Further, this support intends to show that knowledge needs to be built over time through an R&D function for manufacturing, which is often missing in the strategy of manufacturing companies (Trott, 2012; Skinner, 1969). In order to achieve a successful introduction of new manufacturing technologies, a proactive way of working is needed. The maturity level of new manufacturing technologies needs to be evaluated before they are implemented in the production system. Only when they have reached an acceptable maturity level should they be implemented in the production system.

6 DISCUSSION AND CONCLUSION

This chapter starts with a discussion regarding the main conclusions and the fulfilment of the research objective and the questions. The research contribution is then presented followed by an assessment of the quality of the research. The chapter ends by proposing topics for future research.

6.1 CONCLUSION

The main objective of this thesis was to develop support for pre-development of new manufacturing technologies. A theoretical frame of reference has been presented in order to provide a theoretical foundation for the research. Further, three empirical studies have been conducted investigating what factors affect the successful introduction of new manufacturing technologies. The empirical studies also aimed at identifying how the maturity level of new manufacturing technologies can be evaluated.

Throughout the research, pre-development of new manufacturing technologies has been seen as a necessary activity with the main purpose to enable efficient introduction of new technologies and production system development. The research conducted describes and analyses various areas affecting pre-development of new technologies. Thus, this research does not develop any new theories but rather combines different interacting theoretical areas affecting pre-development of new manufacturing technologies.

The theoretical frame of reference has been divided into three main areas, production systems, pre-development of new manufacturing technologies and evaluation of new manufacturing technologies. These areas were important to analyse and discuss in order to develop support for pre-development of new manufacturing technologies. Also, from the theoretical review, production systems, new manufacturing technology, evaluation and assessment were presented and defined. Further, pre-development of new manufacturing technologies has been divided into three areas, market and strategy, development processes and organisation. From these areas factors affecting a successful introduction were derived and summarised (see Section 3.2.4). The theoretical frame of reference concludes with a presentation of different approaches and models used to evaluate new manufacturing technologies.

The first research question was

> **RQ1:** What factors have an impact on the successful introduction of new manufacturing technologies?

The first research question was formulated to develop an understanding of what factors affect the successful introduction of new manufacturing technologies.

This research question has been answered through literature reviews and empirical studies. In Section 3.2.4, factors from the literature are summarised, and Section 4.4 presents factors found from the empirical studies.

In Study 1 (Section 4.1), critical factors forcing manufacturing companies to improve their development of manufacturing technologies were identified. Based on the empirical findings and the literature review, it became evident that pre-development of new manufacturing technologies is necessary, and therefore Study 2 was initiated. In Study 2 (Section 4.2), a product development project and two related acquisition projects of new manufacturing technologies were studied, from which factors could be derived.

The second research question was

> **RQ2:** How can the maturity level of new manufacturing technologies be evaluated?

The second research question was formulated to analyse how the maturity level of new manufacturing technologies can be evaluated and assessed. In Section 3.3.2, different evaluation models and approaches from the literature are presented. In Study 3 (Section 4.3), the assessment of a manufacturing technology maturity level was studied. Also, in Study 2 (Section 4.2), factors that affect the evaluation of the maturity level of new manufacturing technologies were found.

Different factors affecting the successful introduction and evaluation of new manufacturing technologies have been found during the empirical studies and theoretical reviews. In Sections 5.1 and 5.2, these factors are analysed; based on the discussions, the maturity level of new manufacturing technologies should be evaluated stepwise during their development cycle. The maturity level of new manufacturing technologies needs to be evaluated before they are implemented in the production system. Only when they have reached an acceptable maturity level should they be implemented in the production system, and to achieve a successful implementation, pre-development is needed.

One way to evaluate maturity level is with the help of the MRL scale developed by the U.S. Department of Defense. However, the definitions for each level are quite subjective and can be interpreted in various ways. These maturity levels must be further clarified and defined in order to assess the maturity level of new manufacturing technologies.

The support proposed in Section 5.3 highlights the most important factors in the different interfaces; one important factor is knowledge and knowledge building. New knowledge needs to be built over time and requires assigned staff working with pre-development. To achieve this, an R&D function for manufacturing is needed, which is often missing in the strategy of manufacturing companies.

To sum up, the objective of this research can be considered fulfilled when the research questions posed in Section 1.3 have been answered. Both research questions have been answered in Section 5.1 and Section 5.2, where the empirical findings are analysed and compared with the theoretical frame of reference. This discussion supports pre-development of new manufacturing technologies, as presented and summarised in Section 5.3.

The support proposed is a first step and needs to be further developed in order to achieve successful introduction of new manufacturing technologies. Still more knowledge needs to be gained; proposals for future research that can add value to this support are presented in Section 6.4.

6.2 RESEARCH CONTRIBUTION

The research presented has generated both scientific and industrial contributions. During the empirical studies, factors affecting the successful introduction and evaluation of new manufacturing technologies have been found. The main scientific contribution is in the interfaces between product development, manufacturing technology development and equipment supplier relationship.

Pre-development of new manufacturing technologies is not a well-explored research area. This research offers new insights into how such pre-development can be performed. Further, the use of an MRL scale in a manufacturing industry context adds scientific value to how new manufacturing technologies can be evaluated and assessed.

The industrial contribution is a support for pre-development of new manufacturing technologies. Figure 7 shows the most important factors affecting the successful introduction and evaluation of new manufacturing technologies. These factors need to be considered when working with pre-development of new manufacturing technologies.

The support has been of interest for manufacturing companies; as discussed in Section 5.3, many manufacturing companies are struggling with the introduction of new manufacturing technologies. This support requires a strategic decision to establish an R&D function for manufacturing with dedicated development resources. Therefore, this support should be used by site managers, management teams, project managers, etc., in decision-making positions.

6.3 QUALITY OF THE RESEARCH

Common criteria for assessing and evaluating research in terms of quality are validity and reliability, as described in Chapter 2.5. Further, it is difficult to state that the research conducted is fully repeatable. The reason is that the empirical studies were conducted in a manufacturing industry with constant and rapid changes. During the empirical studies there were changes such as new project definitions in development projects, changed project models, change of team members and organisational changes. Thus it has also been difficult to isolate the unit of analysis and draw conclusions regarding what affects what.

When possible, several sources were used in data collection. Also, to ensure the quality of the research, results have been discussed with the informants. In Paper

II, the results were proofread and commented on by project leaders in order to ensure that they were valid. Another reason to have the paper proofread is that the development projects studied are classified. Therefore, all the results from the data collected cannot be used and presented, which limits the quality of the research. Further, this research has not been conducted in real R&D for manufacturing environments. The cases studied were chosen to be as close to this context as possible. Thus the access to and choice of development projects affect the research results.

Finally, the following bullet points present some other possible objections to the research performed.

- The case studies were conducted at one company, which limits the generalisability of the results. One case company is not a representative sample of all manufacturing industry, and therefore future research studies should be expanded to include more manufacturing companies.

- The phenomenon studied may have been affected during the studies, thus possibly distorting the outcome in some way. It is a balancing act to observe without influencing the phenomenon.

- Only written notes were taken during the semi-structured interviews, which limits the data analysis.

6.4 FUTURE WORK

As in most learning situations, this research has provided just as many ideas for future work as it has provided knowledge and answers. Further, the support for pre-development of new manufacturing technologies has not been implemented and validated. The long-term objective of this research is to develop complete support for pre-development that helps manufacturing companies to develop their production system and competitiveness. However, the research findings and theoretical reviews have identified areas of future work that will add value to the support.

Manufacturing readiness level

Different readiness scales were found during the literature review, and they are used in different applications. However, there is a lack of research in the use of readiness scales in a manufacturing context. The readiness scale used in Case Study 2 builds on best practice and is used in the arms industry. It would be interesting to further develop the MRL scale and adapt it to the manufacturing industry. One of the problems of all readiness scales is the definition of maturity level. Definitions might be context-dependent and thus it can be difficult to use a readiness scale in another context than that for which it was meant. A possible future research project would be to define maturity levels of the manufacturing industry. It would also be interesting to further investigate what assessment areas should be covered in such a framework.

Pre-development and organisation

Pre-development of new manufacturing technologies requires an organisational structure with dedicated resources. Two important factors in the proposed support for pre-development of new manufacturing technologies are cross-functional teams and knowledge. Therefore the following questions would be interesting to investigate further: What is a suitable organisation for pre-development? What types of competences are needed in such pre-development functions?

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