TOWARDS TAILORING THE PRODUCT INTRODUCTION PROCESS FOR LOW-VOLUME MANUFACTURING INDUSTRIES

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Abstract

As the closing phase of product development projects, the product introduction process significantly influences the time to market and product quality. The rapid launching of new products to market aids manufacturing companies in avoiding crucial consequences, such as a loss of market share and revenue and the early obsolescence of products in a globalised market. Therefore, the characteristics and influential factors of the product introduction process must be identified to facilitate the management of new product development projects and to maintain competitiveness for manufacturing companies.

The management and support of product introduction processes in low-volume manufacturing industries require solutions that are tailored to the characteristics and requirements of these industries. However, studies on the characteristics of low-volume manufacturing industries and their influence on the product introduction process are limited. Therefore, the objective of the research presented in this thesis is to develop knowledge about the product introduction process and its facilitators in low-volume manufacturing industries by focusing on the characteristics of products and production systems in these industries. To fulfill this objective, the characteristics of low-volume manufacturing industries and their influence on the product introduction process were investigated via literature reviews and a multiple-case study. In addition, the facilitators of the product introduction process in low-volume manufacturing industries were examined. A case study was performed, comprising two longitudinal real-time cases and two retrospective cases, all within one Swedish company.

The characteristics of low-volume products and production systems are studied in this research. The identified influences of these characteristics on the product introduction process include few engineering prototypes, limited and uncertain numbers of pre-series productions and the infeasibility of conventional production ramp-up. Other identified influences include the modification of existing products instead of the development of entirely new products, the use of existing production systems with slight modifications for new products, a high frequency of introducing new products, and an extensive focus on the functionality of products instead of their manufacturability.

Finally, the utilisation of knowledge and experiences from the development and production of prior similar products was identified as a potential facilitator of the product introduction process in low-volume manufacturing industries. A process was suggested to support the product introduction process in low-volume manufacturing industries in gathering, sharing and using knowledge and experiences from the production of prior similar products. This process can compensate for the lack of opportunities to test and refine products and production systems during the product introduction process in low-volume manufacturing industries.
Acknowledgements

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I would like to express my gratitude to my supervisors at MDH, Professor Monica Bellgran and Doctor Jessica Bruch. Their guidance and discussions were an invaluable source of inspiration in different stages of my research. I would also like to thank my supervisor at the company, Peder Hallemark, who made this research possible with his support and helpfulness. Furthermore, I would like to thank Professor Emeritus Mogens Myrup Andreasen and Doctor Jayakanth Srinivasan for helping me with fruitful discussions and great ideas.

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A special thanks goes to my friends, who have made life more fun: Sasha, Sara, Mohammad, Amir, Ieva, Nima A., Amy and Nima G.

I send my deepest gratitude to my mother and my sister for their love and support from thousands of kilometres away. Finally and most importantly, I would like to thank my beloved girlfriend, Mersedeh, for her encouragement and support.
Publications

Appended Papers

This thesis is based on the following papers, which are referred to in the text by Roman numerals as follows.

I  Javadi, S. Bruch, J. Bellgran, M. (Accepted), *Product development in low-volume manufacturing industries: characteristics and influencing factors*, accepted for publication and presentation at the International Conference on Engineering Design (ICED 15), Milan, Italy, *Javadi is the corresponding author and presenter of the paper.*


IV  Javadi, S. Bruch, J. (2015), *Start of Production in Low-Volume Manufacturing Industries: Disturbances and Solutions*, Submitted for presentation and publication at Advances in Production Management System Conference (APMS 15), Tokyo, Japan, *Javadi is the corresponding author and presenter of the paper.*

Additional Publications

1. Introduction

This chapter introduces the background of the research area and presents the reader with an explanation of the motivation behind the research presented in this thesis. After the background and research motivation are described, the research questions are presented. Furthermore, the limitations of the research are discussed. Finally, an outline of the thesis is described.

1.1. Background

Manufacturing companies are forced to launch new products to the market in shorter intervals due to various factors, such as globalisation, faster introductions of new technologies and shorter product life cycles (Bellgran and Säfsten, 2010, Chryssolouris, 2006, Ishikura, 2001). Achieving a shorter time to the market protects companies from crucial consequences, such as losing markets and revenue and early outdating of products (Adler, 1995, Hendricks and Singhal, 2008).

The closing phase of the product development process is the product introduction process, which is also known as the industrialisation process (Bellgran and Säfsten, 2010, Berglund et al., 2012). The product introduction process is defined as “transferring from engineering design to production, including those activities required to make a product manufacturable and to prepare production” (Bellgran and Säfsten, 2010, p 233). The product introduction process has a considerable influence on the time to market and the quality of a product (Adler, 1995). An effective and efficient product introduction process can lead to a shorter time to market/pay back and a more functional and cost-effective production system, with fewer disturbances during the product introduction process and start of production. (Almgren, 1999c, Fjällström et al., 2009, Säfsten and Aresu, 2002). As a result, the characteristics and influential factors of the product introduction process must be identified to facilitate the management of new product development projects and to maintain competitiveness for manufacturing companies.
The identification of these characteristics will provide vital new knowledge for improving this process and for developing solutions to remove or mitigate sources of disturbance during the product introduction process and the early stages of production.

1.2. Research motivation

Many common disturbances that occur at the start of production of new products, such as low production output, low quality of the products and long production cycle times (Almgren, 2000, Apilo, 2003, Juerging and Milling, 2005a) are associated with inefficient and ineffective implementation of product introduction process. Some example causes of these disturbances include lack of maturity of the product and production processes, inaccurate resource planning, lack of cooperation and communication between design and production and insufficient training of production personnel (Almgren, 2000, Fjällström et al., 2009, Nyhuis and Winkler, 2004).

In the current body of literature regarding the product introduction process, studies of the above-mentioned disturbances, their causes and the factors that can eliminate or mitigate them are limited and more research is required to support and facilitate the product introduction process (Juerging and Milling, 2005a, Krishnan and Ulrich, 2001, Surbier, 2010). Furthermore, most of the current studies regarding the product introduction process have been conducted in the context of high-volume manufacturing industries (Jina et al., 1997, Surbier et al., 2013). However, many manufacturing companies do not fit into the context of high-volume manufacturing. Airplanes, trains, mining and construction equipment, agricultural machines and intermediate goods, such as valves and pumps, are some examples of products that are manufactured with low yearly production volumes and with a high level of customizability and variety (Jina et al., 1997, Surbier et al., 2013).

Improvement and facilitation of the product introduction process in low-volume manufacturing industries require solutions tailored to the requirements of these industries (Maffin and Braiden, 2001, Surbier et al., 2009). These requirements both directly and indirectly result from the differences between low-volume and high-volume manufacturing industries, primarily regarding their products and production systems. Therefore, an identification of the differences between low-volume and high-volume manufacturing industries, with a focus on the characteristics of products and production systems, is necessary. Furthermore, the influences of these differences on the characteristics of the product introduction process in low-volume manufacturing industries should be
studied to investigate how this process can be improved and more effectively and efficiently implemented. Such an understanding will aid in providing tailored solutions for low-volume manufacturing industries to improve and facilitate the product introduction process.

As reported by Surbier et al. (2013) and Maffin and Braiden (2001), studies on the product introduction process in low-volume manufacturing industries are very limited, indicating a knowledge gap regarding the product introduction process in low-volume manufacturing industries. Thus, there is a need to evaluate the influences of the characteristics of low-volume manufacturing industries on the product introduction process and to determine how the product introduction process can be facilitated based on these influences. Such research would also lead to insights concerning management and facilitation of the product introduction process in low-volume manufacturing industries based on the characteristics and requirements of these industries.

1.3. Research objective and research questions

Regarding the identified research gap on the product introduction process in low-volume manufacturing industries described in the background section, the objective of this research project is defined as follows:

To develop knowledge about the product introduction process and its facilitators in low-volume manufacturing industries by focusing on the characteristics of products and production systems in these industries

Achieving this objective will provide a basis for further research on the topic and to develop practical methods and tools for facilitating the product introduction process in low-volume manufacturing industries. To fulfil the research objective, the three research questions were posed:

RQ1. What are the main characteristics of low-volume manufacturing industries in comparison to high-volume ones regarding their products and production systems?

The first research question is formulated to study the characteristics of low-volume manufacturing industries regarding their products and production systems as the context of this research.

RQ2. How do the characteristics of low-volume manufacturing industries influence the product introduction process?

The second research question is designed to understand the influences of the characteristics of low-volume manufacturing industries identified on the product introduction process.
RQ3. How can the product introduction process in low-volume industries be facilitated?

The third research question is aimed at identifying which factors can facilitate the product introduction process in low-volume manufacturing industries.

The research questions are addressed via a case study of a low-volume manufacturing company located in Sweden that produces off-road and underground construction machines. In addition, a literature review is conducted, focusing on both the product introduction process and low-volume manufacturing industries.

1.4. Scope and delimitations

Because product introduction is a sub-process of the product development process, the entire product development process is the context of this research, focusing on the product introduction process. The case studies conducted in this research are limited to the off-road and off-road construction machine manufacturing industry because this project was supported by companies from this sector. In addition, the empirical findings of this research are based on data gathered from a single company. However, the literature study was not limited to publications related to this industry, and studies based on other sectors were also reviewed.

This research project was also limited to the internal variables of the product introduction process. More specifically, the characteristics of low-volume manufacturing industries were primarily studied in the context of low-volume products and production systems and their effects on the product introduction process. As a result, the roles of other variables, such as external variables including customers or suppliers in the product introduction process, were not studied in this research. The main reason for this delimitation was to focus the research topic.

Finally, because the product introduction process is considered to be the interface between product development and production, the research presented in this thesis contributes to the overlapping areas of product development and production, focusing on low-volume manufacturing industries, as illustrated in Figure 1.
1.5. Thesis outline

The thesis continues in Chapter 2 with a presentation of the research methodology. Chapter 3 describes the theoretical frame of reference for the thesis. Chapter 4 presents a summary of the empirical findings from this research. In Chapter 5, a summary of the appended papers, which are the basis of this thesis, are presented. In Chapter 6, the findings of the research are discussed in more detail, focusing on the “characteristics of the product introduction process in low-volume manufacturing industries and its facilitators”. The thesis ends with conclusions and possible future research in Chapter 7.
2. Research methodology

In this chapter, the methodology of the research project presented in this thesis is discussed. The chapter begins with a description of the scientific view and approach and continues with the methodological approach. Then, the research strategy and research process are presented. Finally, the chapter ends with a discussion on the quality of the research.

2.1. Scientific view and approach

Different scientific views can be selected not only depending on a researcher’s view on knowledge but also according to the nature of the posed research questions. Whereas a research view can vary along a continuum between positivism and interpretivism (Saunders et al., 2009) or positivism and hermeneutics (Arbnor and Bjerke, 2008), the scientific view in this research leans more towards the positivistic side and can be considered as realistic according to the definition of Saunders et al. (2009). The objective of this thesis is to develop knowledge about the product introduction process and its facilitators in low-volume manufacturing industries by focusing on the characteristics of products and production systems in these industries. As a result, the system must be explained objectively and data must be collected from an observable reality that complies with the realistic scientific view (Saunders et al., 2009). In the realistic scientific view, observable phenomena provide credible data and facts (Saunders et al., 2009). However, a researcher can be biased by external variables, such as their background and world views.

Furthermore, to ensure that the research has practical applications, an abductive (retroductive) approach was selected. This approach helps one gain new insight about “existing phenomena by examining them from a new perspective” (Kovács and Spens, 2005, p138), which is the case in this research. The existing literature on the product introduction process in low-volume manufacturing industries, which is not sufficiently considered in the literature (Surbier et al., 2013), is examined below. Examining the existing literature in a new context can be regarded as a new perspective. In an abductive approach, suitable theories are
evaluated to explain empirical observations, a process called theory matching. The theory matching process implies a “back and forth” movement between empirical study and theory (Dubois and Gadde, 2002) to generate propositions by extending an existing theory or finding a new matching framework (Andreewsky and Bourcier, 2000). As a result, the abductive approach matches the purpose of this research and helps to extend the existing theory on the product introduction process to the context of low-volume manufacturing industries. Figure 2 illustrates the abductive research approach. The first four steps of this approach, from Step zero to Step three, were used in this research.

Figure 2. The abductive research process based on (Kovács and Spens, 2005).

2.2. Methodological approach
The methodological approach of this research was based on the framework of Blessing and Chakrabarti (2009), which is called the design research methodology (DRM). The framework consists of four steps: research clarification, descriptive study 1, prescriptive study and descriptive study 2. As Figure 3 indicates, the studies included in this thesis cover the research clarification and the first descriptive study as the input for a prescriptive study, which is expected to be continued after this thesis. To be more specific, the research area was identified via research clarification through literature studies. Then, through the empirical studies, the first descriptive study was conducted to describe the characteristics of low-volume manufacturing industries and the product introduction process in such industries. Finally, the identified factors that facilitate the product introduction process in low-volume manufacturing industries are considered as input to a future prescriptive study.
2.3. Research method

Because the case study is a suitable research method for addressing how and why questions and are also an appropriate means for developing and extending theories (Voss et al., 2002, Yin, 2013), case study was selected as a suitable research method for this work. A case study allows a researcher to study a phenomenon in its natural setting and can lead to a relatively complete understanding of the nature and complexity of the complete phenomenon (Meredith, 1998). The studied phenomenon can be individuals, organisations, processes, programs or events (Yin, 2013). In addition, the case study research method benefits from existing theoretical propositions to develop new propositions, which complies with the objective of this research.

Due to the lack of empirical studies on the characteristics of the product introduction process in low-volume production systems, a multiple-case study was selected as the research method. This method is appropriate for understanding the dynamics of the study subject. A first-hand study of the product introduction process in a low-volume manufacturing company is expected to lead to an increased understanding of this process (Eisenhardt, 1989, Voss et al., 2002).
As Leonard-Barton (1990) and Yin (2013) stated, different sources of evidence can be used in case study research, including observations, systematic interviews, archival records, documents and physical artefacts. Empirical data for the case studies presented in this research were primarily collected through interviews, documents and direct observations. The data collection process is described in more detail in the research process section. As previously mentioned, the empirical data were mostly qualitative.

2.4. Research process

The research presented in this thesis consisted of two main parts. First, to cover the current research and the frame of reference in the related field of study, a theoretical review was conducted. Secondly, a longitudinal empirical study was performed to answer the research questions and to achieve the objective of this research.

Figure 4 presents the sequence of the study phases for the research presented in this thesis. The main component of the empirical study was based on a real-time, in-depth, multiple-case study consisting of two cases. These cases were addressed in Phases 2 to 4 with different focal points in each phase related to the objective and research questions of this study. The data were complemented with two retrospective case studies in Phase 3, and the results were finalised and integrated in Phase 5.

The process suggested by Eisenhardt (1989) for building and extending theory was followed in this study, which matches the general research process of Kovács and Spens (2005). The research process is briefly presented in Table 1. In the following parts of this chapter, the characteristics of the cases and the details of the study phases are presented.
Figure 4. Timeline of the research project.
Table 1. The research activities according to the steps of the case-based research process suggested by (Eisenhardt, 1989).

<table>
<thead>
<tr>
<th>Step</th>
<th>Activity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Getting started</td>
<td>Definition of research questions</td>
<td>Early definition of tentative research questions</td>
</tr>
</tbody>
</table>
| Selecting cases       | Theoretical, non-random sampling              | - Selection of cases from low-volume manufacturing industries to extend the theory on the product introduction process to low-volume manufacturing industries  
                          |                                                                                                                                             | - Two low-volume real-time cases to replicate the findings  
                          |                                                                                                                                             | - One additional high-volume case in Paper II to present polar types  
                          |                                                                                                                                             | - Two additional retrospective low-volume cases to replicate and support the findings                                                                                                     |
| Crafting protocols    | Multiple data collection methods              | A more traditional approach of gathering primarily different qualitative data was used in the case studies                                                                                       |
| Entering the field    | Overlap data collection and analysis          | Data collection and analysis processes were overlapped within and between the phases                                                            |
| Analysing data        | Within-case analysis                          | Data gathered from each case were analysed separately to observe the patterns within each case                                                   |
| Cross-case pattern matching |                                              | - Cross-case pattern matching was conducted to understand similarities and differences  
                          |                                                                                                                                             | - A pair of real-time low-volume cases were selected and completed; later, a pair of retrospective cases were added to reduce the risk of biases related to a special case |
| Extending theory      | Iterative documentation of evidence for each construct | The findings of cases regarding the characteristics of low-volume manufacturing industries, the product introduction process in such industries and its facilitators were continuously documented |
|                       | Replication logic across cases                | Two real-time cases were studied to examine the replicability of the results; furthermore, two retrospective cases were added to replicate some of the findings |
|                       | Search evidence for the “why” behind relationships | Relationships between the characteristics of low-volume manufacturing industries and the product introduction process in such industries were the focal points of the study |
| Enfolding literature  | Comparison with literature                    | The literature findings were iteratively compared with the studied literature in different phases of the research to understand the similarities and differences between the present findings and the literature |
| Reaching closure      | Theoretical saturation when possible          | This step was performed only for the scope of this research; further research is required to complete the findings of this work                                                                 |
2.4.1. General description of the cases and the company

The case study company is an international manufacturer of underground and off-road construction equipment. The company develops new products and conducts required modifications to its production system to accommodate new products.

The research was primarily based on a real-time, multiple-case study consisting of two product development projects, which are referred to as Case A and Case B. In addition, two retrospective cases were also studied, primarily in Phase 3, which are referred to as Case C and Case D. Finally, an external case from a high-volume manufacturing company, which is named Case E (Case C in Paper II) in this thesis, was utilised in Phase 3 a. Case study E was conducted by the co-author of Paper II and will be described more in its corresponding phase. Cases from the low-volume manufacturing company were selected as theoretical samples because this company exhibits the main characteristics of low-volume manufacturing industries, as stated by Jina et al. (1997). All cases except Case E had a yearly production volume of less than 50 products and followed a full make-to-order production policy. In four cases, the studied products also included various options and variants. The production systems in all cases except Case E were limited to the final assembly lines of the products. A multiple-case design was preferred to a single-case design to reduce the possible risk of biases that could arise from the unique characteristics of a single project. This design also helped in replicating the findings.

Case A was a product upgrade project that was considered as a small project by the company’s definitions. The goal of the project was to upgrade one of the modules of the product without changing the other components or features. The project was initiated based on special requirements of the customers. Case B was a major product upgrade project involving essential changes in a product family and was categorised as a large project at the company. The project goal was to upgrade products to meet the new legislative requirements for some markets. Case C and Case D were two finished product development projects. Whereas Case C was a small project with a similar goal and from the same product family as Case A, Case D was a large project with a goal similar to that of Case B. The use of product development projects with different scopes, i.e., large and small projects, also provided an opportunity to compare the effect of differences between these projects, such as the number of prototypes and pre-series production. Moreover, a comparison of retrospective cases with real-time cases allowed for a comparison of the effects of newly established coordination methods in the real-time cases.
The studied events of Case C and Case D took place over 11 and 20 months, respectively. Cases A and B were followed up for 11 and 20 months from October 2012 to September 2013 and April 2014, respectively. These periods cover the entire product development project for Case A and the beginning of the project to the production of two products as a pre-series in Case B. In addition, disturbances at the start of production of the products were studied as a follow-up in both cases, primarily through observations, document studies and interviews.

In addition, embedded units of analysis were used to cover the focal points of this research in different phases. In Case A and Case B, the characteristics of the product introduction process were used as embedded units of analysis throughout the research. In addition, for Cases A, B, C and D, the disturbances during the early stages of production were an embedded unit of analysis, which was primarily used in Phase 3. Table 2 provides brief information about the cases and their structures.

Multiple sources were utilised for data collection, including semi-structured interviews, document studies and observations. Informal conversations were also conducted, primarily to collect data regarding the background of the company and the projects and other required data.

The data collected from the cases were continuously recorded, summarised, transferred to a case study record and iteratively analysed using within- and cross-case analysis according to the process suggested by (Eisenhardt, 1989).
Table 2. Summary of the studied cases.

<table>
<thead>
<tr>
<th>Case name</th>
<th>Type, context and phases of study</th>
<th>Structure</th>
<th>Main purpose</th>
</tr>
</thead>
</table>
| A         | Real-time study in a low-volume context during Phases 2 to 4 | Case  
Embedded UoA 1  
Embedded UoA 2  
Product development project A  
Characteristics of the product introduction process  
Sources of disturbances in early production | To study the characteristics of the product introduction process in low-volume manufacturing industries |
| B         | Real-time study in a low-volume context during Phases 2 to 4 | Product development project B  
Characteristics of the product introduction process  
Sources of disturbances in early production | To study the characteristics of the product introduction process in low-volume manufacturing industries |
| C         | Retrospective study in a low-volume context during Phase 3 | Product development project C  
Sources of disturbances in early production | To replicate some of the findings from Cases A and B |
| D         | Retrospective study in a low-volume context during Phase 3 | Product development project D  
Sources of disturbances in early production | To replicate some of the findings from Cases A and B |

2.4.2. Phase 1

In this phase, peer-reviewed journal and conference articles written in English and published between 1997 and 2012 were searched. Databases and search engines, such as Science direct, Scopus and Google scholar, were used to retrieve articles. The search was later extended to the most commonly referenced books, doctoral theses, older articles and a few Swedish articles. The review was updated during the course of the
research, and more recent articles from 2013 and 2014 were also reviewed. The main keywords for searching included product introduction, industrialisation, production ramp-up, product launch and start of production. These keywords were also searched in combination with low-volume, small-volume, make-to-order and engineer-to-order products/production systems to cover the focal point of the thesis. In addition, because the aerospace industry is one of the most well-researched low-volume manufacturing industries, aerospace was also used in combination with other keywords.

2.4.3. Phase 2

Phase 2 aimed to further understanding of the characteristics of low-volume manufacturing companies. This phase was designed as a complementary empirical component of the research to clarification and familiarisation of low-volume industries. Because the literature on low-volume manufacturing industries is very limited (Surbier et al., 2013), a general understanding of the characteristics of low-volume manufacturing industries was necessary. As a result, the aim of this phase was threefold:

1. Investigate the characteristics of low-volume manufacturing companies mentioned in the literature using empirical evidence.
2. Complete the definition of low-volume manufacturing industries using characteristics that are not considered in the existing literature, focusing on the characteristics related to production systems and products. In this regard, inter-relations among the characteristics of low-volume products and production systems were also studied.
3. Understand the influences of the identified characteristics of low-volume manufacturing industries on the product development process as the context of the product introduction process.

To achieve the research objective, the characteristics of the product development process, focusing on the products and production systems related to Case A and Case B, were studied to capture the different characteristics of the products and production systems and their inter-relations.

The main source of data was direct observation. The observations were collected by attending weekly project meetings and other related meetings, such as design reviews. In addition, other project activities, including some of the prototype development activities, were observed.
Following the product introduction project, the leaders’ daily activities provided another source of observation. These observations were documented via field notes and, in some cases, by recording the meetings. The second source consisted of documents related to the production system design and the requirements and limitations of the design process. Finally, 14 interviews were conducted with the key players of the product introduction process in the case studies to understand their perspectives regarding the characteristics of low-volume manufacturing industries, to confirm the data gathered from the two other sources and to triangulate the gathered data (Yin, 2003, Yin, 2013). The interviews were semi-structured and lasted between 20 and 60 minutes. Table 3 shows the details of the interviews in Phase 2. The material from the interviews in this phase was also used in the later phases. The interview questions were mainly designed to cover the following aspects: the background of the respondent, the product development in the company and their opinions on its weaknesses and strengths, the challenges of developing new products within the case company, the differences in comparison to high-volume manufacturing companies (if the participants had any experience or knowledge in that area), and the formal and informal mechanisms available in the cases to coordinate product development projects, focusing on the design-production interface. The results of this phase are primarily presented in Paper I.

Table 3. Interviews during Phase 2. Each respondent was interviewed only once during this phase.

<table>
<thead>
<tr>
<th>Respondent’s position</th>
<th>Number of respondents and interviews</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product introduction project leaders</td>
<td>2</td>
</tr>
<tr>
<td>Product introduction preparers</td>
<td>2</td>
</tr>
<tr>
<td>Production engineers</td>
<td>2</td>
</tr>
<tr>
<td>Main project leaders</td>
<td>2</td>
</tr>
<tr>
<td>Production flow leaders</td>
<td>2</td>
</tr>
<tr>
<td>Assembly operators</td>
<td>2</td>
</tr>
<tr>
<td>Prototype development managers</td>
<td>1</td>
</tr>
<tr>
<td>Designers</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>14</td>
</tr>
</tbody>
</table>

To analyse the data, initial inputs from the literature were compared to the identified characteristics of low-volume manufacturing industries. The gathered data were compared with the literature to find similarities, differences and unmentioned characteristics of low-volume products and production systems. Then, the relationships between the characteristics of the products and production systems and their influences on the product development process were analysed by searching for causal
relations by following and matching patterns in the case studies. Finally, a general complementary comparison with the literature and the high-volume manufacturing context was conducted to highlight similarities and differences.

2.4.4. Phase 3

Based on the timeline, Phase 3 was initiated in parallel with Phase 2 and continued until Case B was completed. This phase was designed to determine how the characteristics of low-volume manufacturing industries influence the product introduction process in comparison to high-volume manufacturing industries. For this purpose, an external case of a product development project from a high-volume company (Case C in Paper II) was used to compare polar examples and to evaluate the differences with more transparency, as suggested by Pettigrew (1990). The case study was conducted by one of the co-authors of Paper II during an 8-month period at a service provider in the automotive industry, which was responsible for the development, industrialisation and assembly of the product. The company produces its products in high volume and with limited variants.

The primary data sources in Phase 3 included observations from weekly project meetings, product development activities, and design reviews. In addition, project documents were used to complete the data gathered from observations. The gathered data were analysed to identify the characteristics of products and production systems and to map the product introduction process in each case. Then, the relations between the characteristics of the products and production systems and the characteristics of the product introduction process in Cases A and B were analysed using different data sources. Thereafter, the low-volume cases were compared and cross-analysed to identify similarities and differences between the cases and the findings. Finally, the findings were compared to the results for the high-volume case for a final verification of the characteristics related to low-volume manufacturing industries and to identify the characteristics that are generalizable from the high-volume literature.

To complete the findings of this phase, more data were gathered. A valuable source of data from the studied documents was the disturbance registration database, which was utilised to register, follow up and resolve the disturbances that occurred during the product introduction process. Approximately 200 records from this database were studied, categorised and analysed to identify the types and sources of disturbance during the product introduction process in Case A and Case B. To enrich and validate the outcomes of these documents, records related to two
other product development projects, i.e., Case C and Case D, were studied as retrospective data to investigate the similarities and differences in the patterns of other projects.

In addition to the interviews in Phase B, an additional 15 semi-structured interviews were conducted with the primary people involved in the product introduction process to confirm and complete the results from other sources. The durations of the interviews in Phase 3 were between 30 and 80 minutes. The interviews in this phase were designed to primarily encompass the challenges of different activities in the product introduction process in the case studies, both from the design and production perspective, the formal and informal available sub-processes of the product introduction process and possibilities for improvement. Table 4 provides details of the interviews.

Table 4. Interviews during Phase B and Phase C.

<table>
<thead>
<tr>
<th>Respondent’s position</th>
<th>Number of respondents</th>
<th>Number of interviews</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Introduction Project Leaders</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Product Introduction Preparers</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Production Engineers</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Main Project Leaders</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Production Flow Leaders</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Assembly Operators</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Prototype Development Managers</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Designers</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Prototype Assembly Operators</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>25</strong></td>
<td><strong>29</strong></td>
</tr>
</tbody>
</table>

A root-cause analysis was conducted to identify the disturbance sources observed in the gathered data. Then, the disturbances were categorised according to their main causes at the product introduction process level. In addition, the patterns observed in the case studies were compared to identify the similarities and differences from two different perspectives. This comparison was first conducted between the retrospective cases (Case C and Case D) and the real-time cases (Case A and Case B) and then between the large projects (Case B and Case D) and the small projects (Case A and Case C). Finally, the identified causes were again compared with the literature to determine similarities and differences. In this phase, the seven disturbance sources presented by Surbier et al. (2013) were used as an analysis model to study the effect of the characteristics of low-volume manufacturing industries on different
disturbance sources during the product introduction process. The activities and outcomes of this phase are partially presented in Paper II and Paper III.

2.4.5. Phase 4
The main aim of this phase was to extend the existing theory on the product introduction process and its facilitators in low-volume manufacturing industries. As a result, the gathered data and the outcomes of the earlier phases were used to identify possible facilitators of the product introduction process in low-volume manufacturing industries. In this regard, the gathered data were reanalysed with a focus on the primary goal of this phase. More specifically, the sources and types of disturbances identified in Phase 3 were inputs to this phase to identify facilitators of the product introduction process in low-volume industries. In addition to the general facilitators of the product introduction process, some suggestions are given for facilitating this process in low-volume manufacturing industries based on a comparison with the literature. The results of this phase are presented in Paper III.

2.4.6. Phase 5
This phase was planned to finalise and integrate the results from all of the previous phases and to reach a closure. To achieve this purpose, all of the outcomes of the previous phases were reviewed and compared to understand and highlight their relationships. Furthermore, a final comparison with the literature was conducted to finalise the findings. As part of this comparison, the influences of the characteristics of the product introduction process in low-volume manufacturing industries were analysed with respect to the sources of disturbance in early production suggested by Surbier et al. (2013).

2.5. Quality of the research
Evaluating the quality of a research project is an important, yet difficult task, especially in regard to qualitative research. A common approach for ensuring the quality of the research is to increase its validity and reliability. Validity is usually considered at three different levels: construct, internal and external validity. Whereas internal validity is not considered in descriptive studies (Saunders et al., 2009), the other two are discussed below.
Construct validity is concerned with the level of conformity between what is actually studied and the intended subject of study (Saunders et al., 2009). Different strategies have been suggested to increase construct validity, such as data triangulation (Yin, 2013), control by participants of the study, long-term observation and peer examination (Merriam, 1988). These strategies were utilised as much as possible. Most of the gathered data were verified by at least three sources and triangulated. In addition, the participants in the case studies controlled and commented on the findings through periodic presentations of the results at the case company. The case studies were performed over a long period of time and followed up, as described previously in the research process section. Finally, other researchers were asked to review and comment on the findings for verification and improvement.

External validity is concerned with the extent of generalizability of the findings of a study. In research based on a case study, the generalizability concerns analytic generalisation instead of statistical generalisation (Yin, 2013). The analytic generalisation of this research is based on modifying/advancing the theoretical concepts related to the product introduction process, which is in line with the analytic generalisation principles suggested by Yin (2013). Two of the research questions were also formulated in the “how” form to support the analytic generalizability of the findings to other cases in different settings (Yin, 2013).

In addition, some strategies were followed to increase the generalizability of the findings, such as a comparison with theory and the use of a multiple-case study design, as suggested by Eisenhardt (1989) and Yin (2013). The inclusion of two cases in the main research design increased the analytic generalizability of the findings by replication. In addition, some of the results were verified in the two retrospective cases. Furthermore, the empirical findings from the case studies were continuously compared with the reviewed literature to find justifying and contradicting theories and to explain similarities and differences with theory, which was suggested by (Eisenhardt, 1989).

Reliability refers to the replicability of research results. More specifically, the use of similar data collection and analysis techniques should lead to similar findings if a study is repeated or conducted by another researcher (Saunders et al., 2009). Because the research presented in this thesis was primarily qualitative, a recreation of the study conditions is not possible. Organisations and humans are subject to constant change, which leads to the infeasibility of complete replication of the studies (Merriam, 1998). However, to partially compensate for this challenge, the research methodology has been transparently described. In addition, a case study database was used to document the data gathered from the different sources.
2.5.1. The researcher’s role

The researcher’s role can influence different aspects of a study, including its quality (Saunders et al., 2009). Because the researcher began his cooperation with the case company based on this research project, the external researcher role was formally adopted. However, the continuous presence of the researcher at the case company as a member of the product introduction department during the research project helped to avoid typical external researcher problems. For example, access to different data sources was completely facilitated by the company. In addition, this hybrid role of the researcher provided the opportunity for constant, two-way communication between the researcher and the case company. As mentioned previously, the empirical findings of the research were continuously communicated to the case company for verification and further extension. This communication between researcher and company was maintained through various means, such as daily informal conversations and more formal periodical revisions of the research. Because the research was not designed to affect the case company at this stage, the influences of the research and researcher on the company at this stage of the research project remained far from interactive. However, it can be argued that this constant communication may have gradually influenced the mind-set of the members of the product introduction department and other participants in the case studies, i.e., in the projects.

This hybrid approach of external and internal researcher role not only helped to overcome disadvantages related to the external researcher role, such as difficulties in accessing sources of data, but also prevented some disadvantages associated with the role of an internal researcher. For example, this approach helped to prevent the inhibition of research interactions by tasks related to the employee role and to avoid biases and preconceptions about the company and context that might be implied by an internal researcher (Saunders et al., 2009).
3. Frame of reference

This chapter presents the theoretical frame of reference used in this research. The chapter begins with a brief review of the product development process and continues by defining the product introduction process. Thereafter, the sources of disturbance in the product introduction process are discussed. The chapter ends with a discussion of the literature regarding low-volume manufacturing industries.

3.1. The product development process

The product development process as the context of the product introduction process is of great importance in this study. The product development process “is the sequence of steps or activities that an enterprise employs to conceive, design and commercialise a product” (Ulrich and Eppinger, 2012, p14) or “is the process by which an organisation uses its resources and capabilities to create a new product or improve an existing one” (Cooper, 2003, p117). Other researchers, such as Bellgran and Säfsten (2010) and Magrab et al. (2009), used the product realisation term with a very similar definition but with more emphasis on the integrity and dependency of the product and production system development. An earlier example of various processes suggested in the literature to support and improve product development is the integrated product development process presented by Andreasen and Hein (1987). This process consists of five stages: investigation of need, product principle, product design, production preparation and execution. The process covers the activities of product development in the three domains of marketing, design and manufacturing. More recently proposed processes include the integrated product and process design and development presented by Magrab et al. (2009) and the integrated product development process described by Prasad (1996). Another example that is broadly recognised in the literature is the product development process developed by Ulrich and Eppinger (2012), which consists of six stages. The stages consist of planning, concept development, system level design, detail design, testing and refinement and production ramp-up and, similar to the process of Andreasen and
Hein (1987), cover the activities in the marketing, design and manufacturing domains during these stages. Different stages of the product development process can be sequential, overlapping or parallel based on different factors that influence the product development process (Ulrich and Eppinger, 2012).

Nearly all of the aforementioned product development processes have common characteristics regardless of their distinctions. The most notable common characteristics are their consideration of parallel and, if possible, integrated development of products and production systems and the early involvement of different functions in the process through multidisciplinary teams and continuous communication. These characteristics are aimed at preventing undesired consequences, such as late and costly changes in products and production systems, disturbances during early production and decreased product quality (Almgren, 1999c, Bellgran and Säfsten, 2010, Johansen and Björkman, 2002). The product development process developed by Ulrich and Eppinger (2012) is primarily referenced in this research as the general product development process due to its generality and recognition in the literature.

Various factors influence the product development process; these factors were summarised by Cooper (2003) as production process and technology, product characteristics, project structure and team, organisational context and external environment. Among these various factors, the characteristics of the products and production systems have considerable influences on the product development process and product introduction as its final sub-process (Clark and Wheelwright, 1992, Johansen, 2005).

Most of the activities of the product introduction process are covered during the last three phases of the product development process, which are briefly described in Table 5. These activities primarily support the detailed design and development of the production system and the testing and refinement of products and production systems. Engineering prototypes, also known as alpha prototypes, are usually developed outside of the production system to test the functionality and performance of a product (Johansen, 2005, Ruffles, 2000, Ulrich and Eppinger, 2012). Beta prototypes or pilot production runs aim to test and refine the production system and to ensure conformity between a product and its production system (Johansen, 2005, Ruffles, 2000, Twigg, 2002). Therefore, these prototypes are manufactured in the production system, and the products are often sold to customers (Berg et al., 2005, Ulrich and Eppinger, 2012).

The production ramp-up phase is the final stage of refinement for the production system and for the adaptation of production systems with a product. The production ramp-up phase begins with the start of
production and ends with the fulfilment of initial production goals, such as the intended production time, quality and volume (Carrillo and Franza, 2006, Fjällström et al., 2009, Fleischer et al., 2003). One important activity during production ramp-up is training of the workforce for the production of new products (Ruffles, 2000, Terwiesch and Yi, 2004). Terwiesch and Bohn (2001) reported a positive correlation between the number of products produced during the production ramp-up and the learning process of the operators.

Table 5. Main product introduction activities in the product development process, which is based on Bellgran and Säfsten (2010) and Ulrich and Eppinger (2012).

<table>
<thead>
<tr>
<th>Phase</th>
<th>Detailed design</th>
<th>Testing and refinement</th>
<th>Production ramp-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities</td>
<td>Detailed and parallel design of products and production systems including</td>
<td>- Test overall performance, reliability and durability of products by developing alpha/engineering prototypes and implement necessary design changes</td>
<td>- Reaching the production goals, such as intended cycle time, capacity or quality</td>
</tr>
<tr>
<td></td>
<td>- Defining part geometries and specifications</td>
<td>- Test and refine production and assembly processes as well as the fit of the products and the production systems by developing beta/beta prototypes or pilot production</td>
<td>- Training the workforce</td>
</tr>
<tr>
<td></td>
<td>- Defining production and assembly processes and designing the required tooling</td>
<td></td>
<td>- Eliminating remaining problems in the production system</td>
</tr>
<tr>
<td></td>
<td>- Ordering long-lead tooling</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2. The product introduction process

Juerging and Milling (2005) stated that the product introduction process consists of three main phases, namely the product development, production system development and production ramp-up, which can be parallel, overlapping or sequential. Winkler et al. (2007) presented a model for the product introduction process that consists of parallel development and realisation of the product and production system in three phases of development, preparation and production ramp-up. At a more detailed level, Berg et al. (2005) described the main phases of the product introduction process as test production, pilot production and production ramp-up. However, Fjällström et al. (2009), Johansen (2005) and Ruffles (2000) presented a more extended definition of the product introduction process that also includes the conceptual study and development of engineering prototypes.
Regardless of the differences among the definitions mentioned above, the aim of the product introduction process is to develop the production system needed to produce a product (Bellgran and Säfsten, 2010, Johansen, 2005, Winkler et al., 2007) and to ensure the manufacturability of that product (Olhager, 2000) by adapting the products and production systems together (Johansen, 2005, Ruffles, 2000). More specifically, the requirements of the three aspects of the product development mentioned by Juerging and Milling (2005) should be fulfilled during the product introduction process. These three dimensions are the product, production system and resources. The products and production systems are developed during the conceptual study and then refined through engineering prototype development, pilot production/production prototypes, pre-series productions, and finally production ramp-up; possible non-conformities are eliminated during the product introduction process (Berg et al., 2005, Fjällström et al., 2009, Ruffles, 2000, Winkler et al., 2007). Different phases of the product introduction process are briefly described in Table 6 based on Fjällström et al. (2009) and Johansen (2005).

Table 6. Description of the main phases of product introduction based on Fjällström et al. (2009)\(^1\) and Johansen (2005)\(^2\).

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptual study</td>
<td>Development of a new product/modification of an existing product while considering the manufacturability and functionality of the product in parallel with production system development/modification(^2)</td>
</tr>
<tr>
<td>Engineering/alpha prototypes</td>
<td>Development of prototypes from the production lines to validate the functionality of the products(^1)</td>
</tr>
<tr>
<td>Pilot production runs/beta prototypes</td>
<td>Production of prototypes not primarily intended for the end customer, which is used for validating the adaptability of products and production processes(^1,2)</td>
</tr>
<tr>
<td>Pre-series production</td>
<td>Production not necessarily intended for the end customer (in production lines), used for validating the adaptability of products and production processes(^1)</td>
</tr>
<tr>
<td>Production ramp-up</td>
<td>Start of commercial production; increase of production rate until the planned volume and quality are reached(^1,2)</td>
</tr>
</tbody>
</table>

To summarise the studied literature, the product introduction process can be defined as the process of parallel development, realisation and adaptation of a product and its corresponding production system. In high-volume manufacturing industries, this process usually consists of a conceptual study, the development of engineering prototypes, pilot production, pre-series production and production ramp-up. These phases are usually related to the product development because this process
includes the product introduction process. The relationship between product development and the product introduction process is illustrated in Figure 5.

![Figure 5. Generic product development process (a) based on Ulrich and Eppinger (2012) and the product introduction process (b) based on Johansen (2005); their connections are also illustrated.](image)

The different phases of the general product introduction process are described in more detail below.

### 3.2.1. The conceptual study

During a conceptual study, the products and production systems are designed in parallel (Classen and Lopez, 1998, Johansen, 2005, Sharma, 2004, Winkler et al., 2007). To coordinate these parallel activities in this phase and in later phases of the product introduction process, the early formation of a cross-functional team, a clear definition of goals and activities, the use of formalised documents (including plans and schedules), stage-gate models and work procedures, and the allocation of necessary resources from production are necessary at the beginning of this phase. (Adler, 1995, Cooper, 1994, Ruffles, 2000, Valle et al., 2003). Berglund et al. (2012) and Dröge et al. (2000) also stated that the standardisation of work procedures, materials and parts can simplify the conceptual study and the entire product introduction process.

Adler (1995) summarised the mechanisms of coordination of product and production system adaptation into four categories based on the level of interaction between product design and production. These categories include standards, plans and schedules, mutual adjustment and teams. The level of novelty of the products and production systems defines the complexity of both the conceptual study phase and the entire product introduction process (Adler, 1995, Tidd and Bodley, 2002). More specifically, a completely new product with a new production system implies the highest level of complexity, whereas a modified product that
will be produced in an existing production system has the lowest complexity level (Almgren, 1999a), which is shown in Figure 6.

![Figure 6. Influence of the product and production system novelty on the complexity of the product introduction process (Almgren, 1999a).](image)

Therefore, Adler (1995) argued that novel products and production systems require more interactive coordination mechanisms, such as joint teams, whereas less interactive mechanisms, such as standards and plans, are sufficient for well-known products or production systems. Juerging and Milling (2005) discussed other aspects that influence the complexity of the conceptual study phase and the entire product introduction process, including the complexity and variety of a product, the level of concurrency of activities and standardisation of the production processes.

Regardless of the complexity scenario, the early involvement of production in the conceptual study phase is emphasised in the literature. This early involvement can reduce non-conformities between products and production systems in later phases and can aid in developing a common vision between product designers and production (Adler, 1995, Lakemond et al., 2007, Ruffles, 2000, Sharma, 2004, Woodcock et al., 2000). The early involvement of production also facilitates continuous knowledge transfer and sharing between product designers and production (Sharma, 2004). This knowledge transfer includes understanding production requirements (Lakemond et al., 2007, Ruffles, 2000) and reviewing the manufacturability of products and the
product/production system fit through design reviews (Adler, 1995, Classen and Lopez, 1998, Olhager, 2000). Design reviews allow the product designers to utilise various methods, such as design for manufacturability and assembly (DFM/DFA), which has been reported as a critical tool in the conceptual study phase to ensure that a product is manufacturable and to reduce product/production system non-conformities (Boothroyd, 1994, Dröge et al., 2000, Lakemond et al., 2007, Tidd and Bodley, 2002). Mountney et al. (2007) suggested developing a manufacturing knowledge system early in the conceptual design phase to facilitate knowledge transfer from manufacturing to design and to avoid disturbances and non-conformities during the later phases of the product introduction process.

In general, several researchers have highlighted the role of the effective implementation of the aforementioned activities during the conceptual study phase in reducing the costs and the duration of the product introduction process and in reducing disturbances during commercial production (Adler, 1995, Cooper, 1994, Kim and Wilemon, 2002, Ruffles, 2000, Valle et al., 2003). These activities are also known as upfront or front-end activities of the product development process (Cooper, 1994, Kim and Wilemon, 2002). Adler (1995) stated that putting more effort into front-end activities is even more important when the product/production system fit is less complex and more easily subjected to analysis.

3.2.2. Developing engineering prototypes (alpha prototypes)

During the engineering prototype development phase in the product introduction process, engineering prototypes are developed with the main purpose of product design verification and refinement and for testing the functionality of a product (Lakemond et al., 2007, Ruffles, 2000). In this regard, engineering prototypes are more important for completely new products than modified ones (Tidd and Bodley, 2002). These prototypes can be physical or virtual, i.e., developed by computer-aided design (CAD) technologies (Gibson et al., 2004, Malmsköld et al., 2012). Virtual prototypes can be utilised to verify the fit of parts and components of a product and its manufacturability (Gibson et al., 2004, Ruffles, 2000). Such prototypes also allow for a better understanding of the product features and possible problems by visualizing the product design (Gibson et al., 2004).

During this phase, mutual parallel development of the product and production system continues with the same cross-functional team as in the previous phase (the conceptual study). While design reviews can still be utilised as a knowledge transfer tool between product design and
production (Adler, 1995, Bruch and Bellgran, 2013, Frishammar, 2005, Ruffles, 2000, Twigg, 2002, Ylipää, 2000), the access of production personnel to the engineering prototypes and their contribution in developing prototypes can also facilitate knowledge transfer regarding new product features (Lakemond et al., 2007, Ruffles, 2000). This access also helps the production personnel to develop the details of the production processes, such as the time, sequence and instructions of the production/assembly processes (Ruffles, 2000). Such prototypes also allow the production personnel to identify non-conformities in the product and production system (Lakemond et al., 2007, Ruffles, 2000).

3.2.3. Pilot production runs (beta prototypes), pre-series production and production ramp-up

Pilot production runs are mainly aimed at verifying and refining the production system (Ruffles, 2000, Twigg, 2002). However, pilot production runs play an important role in controlling the product/production system fit because the beta prototypes are produced in the production system (Johansen, 2005, Ruffles, 2000, Twigg, 2002). The development of physical beta prototypes in the developed production system is still necessary due to the limitations and high costs of virtual technologies for simulating different aspects of production systems (Gibson et al., 2004, Lakemond et al., 2007). Cross-functional teams and design reviews can still be used as a cooperation and communication mechanism between design and production for the required adjustments of the product and production system during this phase (Adler, 1995, Twigg, 2002).

During pre-series production and production ramp-up, verification of the production system and adaptation of the product and production system continue (Johansen, 2005, Ruffles, 2000, Twigg, 2002). Production ramp-up begins with the start of production (Fjällström et al., 2009, Fleischer et al., 2003, Surbier et al., 2013) and ends with the fulfilment of initial production goals, such as the intended production time, quality or volume (Almgren, 1999c, Carrillo and Franz, 2006, Fjällström et al., 2009, Fleischer et al., 2003, Johansen, 2005, Ruffles, 2000). During the production ramp-up, remaining problems and non-conformities are identified and eliminated.

One of the main activities during production ramp-up that is highlighted in different classifications is the training of operators and production personnel for the production of a new product (Adler and Clark, 1991, Bellgran and Säfsten, 2010, Ruffles, 2000, Terwiesch and Yi, 2004). Terwiesch and Bohn (2001) stated that underestimating the importance of learning and education in the product introduction process
can lead to complex and costly problems in commercial production. The amount and effectiveness of experimentation are considered to influence the learning process in the product introduction process (Terwiesch and Bohn, 2001). Adler and Clark (1991) found a positive correlation between the number of products produced during the product introduction process and the learning process of the production personnel. In this regard, pre-series production and production ramp-up play an important role in training the production personnel. To complement “learning by doing” training methods, virtual training and learning tools can also be used (Malmsköld et al., 2012).

Several researchers, such as Säfsten et al. (2006) and Carrillo and Franza (2006), have argue that the preparatory activities in the earlier phases of the product introduction process play an important role in facilitating the production ramp-up and reducing disturbances during the early production. Säfsten et al. (2006) presented several aspects to consider during such preparatory activities, which can be categorised as sources of disturbance during early production. In addition, other factors, such as a correct choice of ramp-up strategies and operating patterns to facilitate the production ramp-up, have been discussed in different studies in the context of high-volume manufacturing industries (Clark and Fujimoto, 1991, Meier and Homuth, 2006, Schuh et al., 2005).

3.3. Sources of disturbance in the product introduction process

The start of production and production ramp-up are primarily characterised by high levels of disturbance with regard to different aspects of production (Almgren, 2000, Fjällström et al., 2009, Nyhuis and Winkler, 2004). Such disturbances usually lead to longer production cycle times (Apilo, 2003, Terwiesch and Bohn, 2001), lower production outputs (Fleischer et al., 2003, Juerging and Milling, 2005a, Terwiesch et al., 2001) and a lower quality of products (Almgren, 1999b, Nyhuis and Winkler, 2004, Terwiesch et al., 2001). The sources of these disturbances have been studied primarily in case studies and in the context of high-volume manufacturing industries (Surbier et al., 2013). Different researchers have categorised sources of disturbance in various ways. Almgren suggested four main sources: product, production technology, supply of material and personnel (Almgren, 2000). Moreover, Fjällström et al. (2009), Nyhuis and Winkler (2004) and (Surbier et al., 2013) divided the sources of disturbance into seven categories: product, production processes, supply chain and logistics,
quality, methods and tools, personnel and cooperation and communication. These categories are briefly described in Table 7.

Most of the aforementioned disturbances can be prevented or eliminated during the product introduction process by the activities previously described.

Table 7. Identified sources of disturbance during the product introduction process (Surbier et al., 2013).

<table>
<thead>
<tr>
<th>Source of disturbance</th>
<th>Disturbance type description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>Insufficient product specifications and lack of product maturity</td>
</tr>
<tr>
<td>Production processes</td>
<td>Lack of production process maturity, manufacturability of the product and product-process fit</td>
</tr>
<tr>
<td>Supply chain and logistics</td>
<td>Problems with the quality and availability of the supplied parts and components</td>
</tr>
<tr>
<td>Quality</td>
<td>Problems with the quality of the final product</td>
</tr>
<tr>
<td>Methods and tools</td>
<td>Inaccurate resource planning and problems with data and knowledge management</td>
</tr>
<tr>
<td>Personnel</td>
<td>Unclear definition of responsibilities, lack of qualified personnel and insufficient training of personnel</td>
</tr>
<tr>
<td>Cooperation and communication</td>
<td>Lack of cooperation and communication between different departments and functions, especially between design and production (design-production interface)</td>
</tr>
</tbody>
</table>

3.4. Low-volume manufacturing industries

3.4.1. Characteristics of products and production systems in low-volume manufacturing industries

Jina et al. (1997) defined the low-volume production rate as 20-500 units per year as a distinction from high-volume and engineer-to-order production. In addition, three other main characteristics for low-volume products are often mentioned in the literature, i.e., high-complexity, high-variety and high-cost products (Jina et al., 1997, Mohamed and Khan, 2012, Qudrat-Ullah et al., 2012). Hill (2000) stated that low-volume products are customised rather than special products, such as engineer-to-order or standard high-volume products. This difference implies that products are customised to the needs of different customers but that the production rate is not limited to one product, which is the case for the production rate of engineer-to-order products, and is also not as high as the production rate of high-volume products.
The production systems in low-volume manufacturing industries usually characterised by flexibility (Mohamed and Khan, 2012, Williamson, 2005). Providing such flexibility requires highly skilled workers (Bellgran and Aresu, 2003, Mohamed and Khan, 2012), universal production equipment (Hill, 2000, Rahim and Baksh, 2003), a low level of automation (Andersson et al., 2014, Hill, 2000) and shared production resources among different products (Rahim and Baksh, 2003). The usual process choice for low-volume manufacturing industries is jobbing or batch production (Mohamed and Khan, 2012). However, considering the definition of production volume by Hill (2000), which is quality multiplied by work content, line production may also be an appropriate process choice for the production of complex, low-volume products with high work content. Moreover, the appropriate production planning policy in low-volume manufacturing industries is make-to-order (Jina et al., 1997, Wrobel and Ludański, 2008).

In this research, the characteristics of low-volume manufacturing industries mentioned by Jina et al. (1997) were primarily adopted:

- Low yearly production volume (20-500 units);
- High variety and customizability of products;
- High-complexity products; and
- Complete make-to-order production policy.

3.5. The product introduction process in low-volume manufacturing industries

Very few studies have focused on product development and product introduction in low-volume manufacturing industries (Surbier et al., 2013). However, some general statements can be applied to the characteristics of low-volume manufacturing industries. According to Juerging and Milling (2005b) and Van der Merwe (2004), a wider variety and higher complexity of products and fewer standardised production processes can lead to a higher level of complexity in product development projects and, consequently, in the product introduction process. In addition, such characteristics result in fewer opportunities for engineering and beta prototypes (Qudrat-Ullah et al., 2012). This issue leads to reduced chances for verifying the product and production system in the later phases of the product introduction process (Rahim and Baksh, 2003). Furthermore, Vallhagen et al. (2013) reported that the main focus during the product introduction process in low-volume manufacturing industries is on the functionality of a product rather than its manufacturability. Therefore, the optimisation of the production processes is not usually considered, and the only point that is ensured is
that a product is producible with the existing processes. In contrast, the complexity and variety of low-volume products (Wallace and Sackett, 1996), more frequent product introductions and fewer opportunities for refining the product design during production (Rahim and Baksh, 2003) increase the importance of the product introduction process and its outcomes.

The undesirability of major changes in production systems based on their high costs relative to the production volume and the tendency to fit new products into the current production system represent additional characteristics of the product introduction process in low-volume manufacturing industries (Qudrat-Ullah et al., 2012, Rahim and Baksh, 2003). Design and production resource bottlenecks are also intensified in low-volume manufacturing industries due to the intensive sharing of resources between several projects and on-going production activities (Qudrat-Ullah et al., 2012).

In addition to the previously mentioned general facilitators of the product introduction process, some facilitating factors of the product introduction process in low-volume manufacturing industries have been suggested based on the aforementioned characteristics. These factors include reaching a clear and early definition of the customers’ requirements (Qudrat-Ullah et al., 2012, Srinivasan et al., 2003) and a functional engineering organisation (Kumar and Wellbrock, 2009, Qudrat-Ullah et al., 2012). Kumar and Wellbrock (2009) discussed the importance of focusing on the front-end activities, concurrency of the activities and the use of CAD/CAM technologies in the product introduction of low-volume products. Olsen and Sætre (2001) also highlighted the role of visualizing the product structure for the development and production of low-volume products. However, Maffin and Braiden (2001) and Surbier et al. (2009) stated that specific requirements of the product introduction process in low-volume manufacturing industries necessitate customised solutions and facilitators tailored to the requirements of these industries. As a result, for developing such solutions, an understanding of the characteristics of the product introduction process in low-volume production is necessary.
3.6. Highlights of the studied literature

The highlights of the studied literature are summarised as follows:

- The product introduction process is the final and one of the main subprocesses of the product development process. Most of the activities in the product introduction process are covered during the last three phases of the product development process, which include detailed design, testing and refinement and production ramp-up.

- The product introduction process can be defined as the process of parallel development, realisation and adaptation of the product and its corresponding production system.

- The product introduction process in high-volume manufacturing industries usually consists of a conceptual study, the development of engineering prototypes, pilot production, pre-series production and production ramp-up. These phases are usually connected to the product development as a process that includes the product introduction process.

- Engineering prototypes play a significant role in the testing and refinement of product functionality, whereas pilot production runs and pre-series production are very important for testing and refining product manufacturability and production systems and for adapting product and production systems together. Production ramp-up is also important for resolving the remaining problems in the production system, reaching production goals, such as a production cycle time, and training the production personnel.

- The complexity of the product introduction process grows with increasing novelty of the product and production system.

- The main sources of disturbance during the product introduction process include the product, production processes, supply chain and logistics, quality, methods and tools, personnel and cooperation and communication.

- Low-volume manufacturing industries are primarily characterised by a low yearly production volume (20-500 units), high variety and customizability of products, high complexity of products and a complete make-to-order production policy.

- Specific requirements for the product introduction process in low-volume manufacturing industries necessitate customised solutions and facilitators tailored to the requirements of such industries.

- Studies on the product introduction process in low-volume manufacturing industries and its facilitators are limited.
4. Empirical findings

*In this chapter, the empirical findings of the research from the case studies are summarised and briefly described.*

4.1. General product development arrangements

As mentioned in the method chapter, the case company produces a wide range of products to meet the demands of different markets and customers. As a result, the number of product development projects was relatively high. A comparison with another company in the same industry but with high-volume products showed that the number of ongoing product development projects that passed the conceptual study phase was approximately 30% higher in the low-volume case company, whereas the high-volume manufacturing company benefitted from approximately 20% more human resources dedicated to product development projects.

The products of the case company were manufactured in four main product families according to their functions and similarities in four different production lines. The operations on the production system were limited to the final assembly of the products. New products were designed to be manufactured on one of these production lines.

A product development guide was used for managing product development projects and was primarily based on a stage-gate model, similar to the processes discussed in the frame of reference (Chapter 3.1.). The product introduction activities were primarily managed by product introduction project leaders and product introduction preparers who were part of the product introduction department.

The product introduction department was a newly established department at the company and began working in the spring of 2012 with the goal of facilitating the product introduction process in new product development projects and reducing disturbances in the production of new products. The department consisted of a department manager, product introduction project leaders and product introduction preparers. The product introduction project leaders were representative of the department in the product development projects. These leaders were responsible for planning product introduction activities and following up
their implementation during the course of the projects. The preparers were responsible for the implementation of some of the activities, such as developing/updating the assembly processes during the prototype development and pre-series productions, developing/updating the bill of material and ensuring that the problems occurring during the product introduction process were registered and followed up. Both product introduction project leaders and preparers were involved in several product development projects. Most of the activities of the product introduction process were followed up based on a guideline developed by the members of the department. The stage-gate model and the product introduction activities are briefly presented in Figure 7.

Because the product introduction department was newly established at the studied company, its position, organisation and related processes were still under development during this research. The effects of some of these changes on the product introduction process are presented in Paper IV.

All of the product development projects were managed by cross-functional teams, which consisted of a project leader and six sub-project managers from design, prototyping, product introduction, purchasing, marketing and aftermarket functions, who were responsible for the project tasks related to their respective departments.
Figure 7. The stage-gate model and product introduction guidelines used at the case company.
4.2. Characteristics of products and production systems

The characteristics of the products and production systems of the company are presented below. These findings are mainly based on Case A and Case B.

4.2.1. The products

The yearly production volumes of the products were less than 100 units per year. The products were highly customised to satisfy different criteria, such as customer demands and the safety and environmental legislations of different markets. As a result, there were seven and five variants of Products A and B, respectively, in addition to several available options for each variant, which made them highly variable. The products were also complex, with many components and many interfaces between the components of the products, numerous product and component variants, and different technologies used in the products, which implied different disciplinary complexities.

4.2.2. The production systems

Because investing in the establishment of dedicated assembly lines for each product was not feasible due to the high variety of products at a low yearly production rate, four different flexible assembly lines were utilised to assemble various products in the same product families. Therefore, the selected assembly lines were used for different products and their variants. In the assembly line for Product A, seven products and their variants were assembled, while for Product B, 12 products and their variants were assembled. To keep the assembly lines as flexible as possible for handling different products and adopting new ones, the assembly work was almost completely manual and the tools and equipment in the lines were mostly universal. The alterations in the assembly lines for changing from one product to another were limited to minor adjustments, such as a change of fixtures. In addition, the manual work combined with the complexity and variety of products demanded a high level of skill from the operators. Because the product assembly consisted of high work content and required over 400 man-hours, a line setting was selected despite the low quantity of the products. The assembly lines for Products A and B consisted of four and six work stations, respectively, with an average of four operators in each station. The number of operators in the stations varied to maintain flexibility in the capacity of the lines. Because the demands were low for the products
and the costs of the products were high, a complete make-to-order production planning policy was followed in both lines to avoid the high costs of tied-up capital related to the storage of costly products. Table 8 summarises the characteristics of the products and the production systems used in the case studies.

Table 8. Characteristics of the products and production systems in Case A and Case B.

<table>
<thead>
<tr>
<th>Case name</th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yearly volume</td>
<td>&lt;20</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Variety (excluding options)</td>
<td>5 variants</td>
<td>7 variants</td>
</tr>
<tr>
<td><strong>Production system characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle time (approx.)</td>
<td>96 hours</td>
<td>128 hours</td>
</tr>
<tr>
<td>Number of stations</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Different products were produced on the same production line</td>
<td></td>
</tr>
<tr>
<td>Automation level</td>
<td>Low, primarily manual</td>
<td></td>
</tr>
<tr>
<td>Job rotation</td>
<td>No, jobs were allocated to the operators based on the required skills</td>
<td></td>
</tr>
<tr>
<td>Equipment</td>
<td>General purpose</td>
<td></td>
</tr>
</tbody>
</table>

4.3. The product introduction process

A summary of the product introduction process for Case A and Case B is presented below. More details are presented in Paper II and Paper III. The objectives of the product introduction process in both projects involved the development of a modified version of an existing product. In Project A, the objective was to update one of the product modules to satisfy the requirements of a specific market, whereas the objective of Project B was to develop a generally modified version of an existing product. A brief survey of all other ongoing product development projects demonstrated that none of the products were completely new and that all projects were modified or upgraded versions of existing products.

Both products were to be produced on the assembly lines for the existing products. As a result, the objective of the product introduction process in both projects was to apply as few changes as possible to the assembly lines. In this regard, the products were to be tailored to the requirements and limitations of the production systems.
Because Case A was a small project, the product introduction process consisted of a conceptual study and the development of only one physical engineering prototype of the modified module and CAD models. Because Case B was a large project, its product introduction process was more extensive. Two engineering prototypes were developed outside of the production system in Case B. Moreover, the first four products that were produced in serial production were allocated to pre-series production in Case B. Based on the complete make-to-order policy of the company and the high cost of the products, these four products were not produced until they were requested by customers. As a result, a final verification of the products and production systems and their conformity was not performed due to considerable common deviations of real demands from market estimations. A final verification was not considered at all in Case A.

Due to low production volumes and discontinuous demands, a conventional production ramp-up was not feasible. Consequently, planning activities, such as the training of production personnel, final refinement of the product and production system, adaptation and the achievement of production goals, such as reducing the production cycle time, were infeasible. As a result, many of these activities were moved to normal production or not implemented. Table 9 summarises the information for the product introduction process in Case A and Case B.

Table 9. Summary of the information on the product introduction process in Case A and Case B.

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product development goal</strong></td>
<td>Partial modification of the product</td>
<td>General modification of the product</td>
</tr>
<tr>
<td><strong>Production system development goal</strong></td>
<td>Applying as few changes as possible to the current production systems</td>
<td>Applying as few changes as possible to the current production systems</td>
</tr>
<tr>
<td><strong>Conceptual study</strong></td>
<td>Design and development of the product</td>
<td>Design and development of the product</td>
</tr>
<tr>
<td><strong>Prototype development</strong></td>
<td>One engineering prototype of the modified module</td>
<td>Two engineering prototypes of the entire product</td>
</tr>
<tr>
<td><strong>Pre-series production</strong></td>
<td>No pre-series</td>
<td>One product; could be extended to four products depending on customer demand</td>
</tr>
</tbody>
</table>
a combined adaptation. The disturbances caused by these challenges are presented in the next section.

4.4. Disturbances at the start of production

The disturbances studied at the start of production for all four cases from the low-volume manufacturing company, i.e., Cases A, B, C and D, are presented below. The empirical data encompass disturbances related to the products and the production system. The findings of this section are described in more detail in Paper III and Paper IV.

The product-related disturbances were primarily categorised into three sub-categories. Several disturbances were related to a lack of information or incorrect information regarding connecting parts. The other major source of disturbance was problems in assembling the parts and components. On several occasions, the parts could not be assembled on the products due to a non-conformity in the part interfaces, difficulties in accessing the location of the part on the product or the possibility of damaging other parts during assembly. This category of disturbance was denoted as design for assembly disturbance. Other sources of disturbance ranged from the functionality of the parts and components to the incorrect or late delivery of the parts; these disturbances were categorised as other. Figure 8 shows the contribution of each type of disturbance in the studied projects. As Figure 8 shows, approximately half of the disturbances in all of the projects were caused by missing or incorrect information regarding connecting parts. This proportion was reduced in the real-time cases, i.e., Case A and Case B, compared to the retrospective cases, i.e., Case C and Case D. The disturbances caused by design for assembly problems accounted for a significant portion, varying from 20 to 33% of disturbances. However, this share was smaller in the large projects, Case B and Case D.

Similar contributions for each type of disturbance were observed in all four cases. However, the percentage of missing and incorrect information regarding connecting parts was approximately 4% lower in the large projects (Case B and Case D) compared to their smaller counterparts (Case A and Case C). In addition, this share was reduced by approximately 8% in the real-time cases in comparison with the retrospective cases.

In addition to the aforementioned product-related disturbances, production-related disturbances were also studied in the cases. These disturbances were primarily caused by late consideration of the required changes in the production system for producing the new products. In general, a lack of consideration of the production requirements was
repeatedly mentioned in different sources of data for the studied cases. Furthermore, assembly instructions for a new part of the production system were not completed or optimised; the instructions were improved as the first products were assembled.

![Pie charts showing contribution of each type of disturbance in each case.](image)

*Figure 8. Contribution of each type of disturbance in each case.*

### 4.5. Supporting and facilitating actions performed during the product introduction process

The findings regarding supporting and facilitating actions during the product introduction process are presented in this section and are primarily based on Case A and Case B. These facilitating actions were mainly conducted and coordinated by the product introduction project leaders as a part of their efforts to improve the product introduction process in the case company. More details are presented in Paper III.

During the conceptual study phase, the product introduction project managers coordinated regular design reviews with the participation of production engineers, operators and product designers. Design reviews served as a cooperation and communication mechanism to update the operators and production engineers about critical changes in the product design. The changes and product designs were visualised via CAD
models and were employed for a basic verification of product parts and the fit of the components. Occasionally, some manufacturability-related issues were also briefly discussed. The design reviews were continued during the prototype development phase.

In addition to the design reviews, the non-conformities of the products identified during prototype development were reported to the designers for design refinement. The problems and developed solutions were stored in a digital database for further reference. The same problem-reporting and problem-solving system was employed during the subsequent phases of the product introduction process. In addition to the design reviews, this problem-reporting database was utilised as a cooperation and communication method. However, there was no indication that the inputs from the introduction of similar products were used in this phase.

Another activity for supporting the product introduction process included gathering the production requirements during the conceptual study phase. To understand these requirements, the expectations of the production personnel and the limitations of the production system were gathered by the product introduction project managers, categorised and subsequently discussed with designers and production personnel. These expectations addressed various issues, such as unchanged connection interfaces of new components, and considered the design for assembly, the inclusion of assembly details in the drawings, a reduction in the total number of components and the prevention of late design changes.

Furthermore, to increase the involvement of the production personnel in the product introduction process and to address the manufacturability issues of the products with respect to the limitations and requirements of the assembly lines, one production operator and two production operators were involved in Project A and Project B, respectively. These operators aided the prototype development operators during prototype development by providing input about the existing equipment and capabilities of the assembly lines. The production operators also assisted the product introduction preparers develop and modify the assembly sequences and instructions. However, this participation was limited due to resource allocation complexities between on-going production and several parallel on-going product development projects. The project team and production personnel believed that the involvement of more production operators was necessary not only for refining the manufacturability of the product but also for training the production operators on the assembly of new products. The opportunities for refining and improving the manufacturability of the products were limited due to the limited involvement of the production operators in the prototype development, the consequent development of the assembly instructions, and limitations in the number of prototypes.
4.6. Highlights of the empirical findings

The main findings of the empirical studies are as follows:

- The case company used a stage-gate model based on the generic product development process.
- The case company had more ongoing product development projects with fewer resources compared to high-volume companies in a similar branch.
- A newly established product introduction department was responsible for coordinating the product introduction process at the case company.
- The products were highly customizable and complex, with high variety and a low yearly production volume.
- The assembly lines were flexible to produce various current products and to accommodate new ones. This flexibility was primarily achieved by using universal production equipment, highly skilled production personnel and a low level of automation. In addition, a complete make-to-order production policy was followed at the case company.
- In the studied cases, the goal of the product introduction process was to introduce a modified version of a current product while applying the minimum number of changes to the production system.
- The number of engineering prototypes and the pre-series production were limited, and production ramp-up was infeasible.
- The main types of disturbance in the case studies included a lack of consideration of the design for assembly criteria, incorrect or missing information about small connecting parts and a late consideration of required changes in the production systems.
- Design reviews, the visualisation of design information and a problem-reporting database for documenting product-related disturbances were used in the cases to support and facilitate the product introduction process. In addition, the gathering and communication of production expectations and the involvement of production operators in the product introduction process were used by the product introduction department to facilitate the product introduction process in the real-time cases.
5. Paper summary

In this chapter, a summary of the appended papers is presented as part of this research.

Paper I: Product development in low-volume manufacturing industries: characteristics and influencing factors

This paper was based on the empirical findings from Case A and Case B in combination with theoretical findings from the studied literature. The aim of Paper I was to examine the characteristics of low-volume manufacturing industries regarding their products and production systems and their inter-relations. Furthermore, this study also aimed to understand the effects of these characteristics on the product development process in low-volume manufacturing industries and to compare the process with the generic product development process, which is generally referenced in the context of high-volume manufacturing industries. A study of the characteristics of product development (as the context of product introduction process) was necessary to provide the basis required for a further examination of the product introduction process.

The general characteristics of the low-volume products and production systems and their inter-relations were discussed and presented in Paper I. The influences of these characteristics on the product development in low-volume manufacturing industries were also described based on the findings from Case A and Case B. A lack of opportunities for testing and refinement, extensive resource sharing among different product development projects and ongoing production, the development of modified versions of existing products rather than new products, the tailoring of new products to the requirements of existing production systems and the high frequency of product introduction were identified as the main characteristics of low-volume products and production systems influencing the product development projects; these effects are discussed in Paper I. In addition, the generic product development process suggested by Ulrich and Eppinger (2012) was modified for low-volume manufacturing industries according to the findings of Paper I, which is illustrated in Figure 9.
Paper II: Challenges in the industrialisation process of low-volume production systems

The second appended paper was based on Case A, Case B and Case E, which was denoted as Case C in the paper. This study aimed to study the characteristics of the product introduction process in low-volume manufacturing industries in more detail by comparing the practices of product introduction in low- and high-volume manufacturing industries. Therefore, the goal of the paper was to investigate the challenges of the product introduction process in low-volume manufacturing industries. The study focused on the challenges caused by the characteristics of low-volume manufacturing industries.

The empirical findings highlighted the different characteristics of the product introduction process in low-volume manufacturing industries in comparison with high-volume ones. The results showed that few prototypes and pre-series productions, the difficulty of involving production personnel in the product introduction process due to resource allocation difficulties and the late finalisation of assembly instructions for the main production process are some of the characteristics of the product introduction process in low-volume manufacturing industries. Additionally, the modification of existing production systems instead of the development of new systems for new products was identified as another characteristic of the product introduction process in low-volume manufacturing industries.

Paper III: Product introduction process in low-volume manufacturing industries: a case study

The research presented in this paper was primarily aimed to understand the effects of the characteristics of low-volume manufacturing industries on the product introduction process. A secondary purpose of the research
was to determine which factors contribute to facilitating the product introduction process in low-volume manufacturing industries. The paper was based on empirical data from Case A and Case B in combination with a literature study.

Based on the studied literature, the product introduction process was generally defined as the process of parallel development, realisation and adaptation of products and production systems. In high-volume manufacturing industries, this process usually consists of a conceptual study, the development of engineering prototypes, pilot production, pre-series production and production ramp-up.

The main characteristics identified for the product introduction process in low-volume manufacturing industries are as follows:

- A limited number of engineering prototypes and pre-series/pilot production runs and the infeasibility of production ramp-up;
- Product and production system modification rather than the development of new products and production systems;
- A lack of consideration of the manufacturability of products due to the additional focus on the functionality of products and a consideration of the production system “as is”; and
- Difficulty regarding the involvement of production personnel due to resource allocation issues.

Figure 10 compares the product introduction process in low-volume manufacturing industries with the general product introduction process defined based on the literature.

Figure 10. Comparison of the phases of the product introduction process in high-volume manufacturing industries (a) and low-volume ones (b). The grey colour represents limited implementation of the phases.

In addition, the positive and negative influences of the aforementioned characteristics on the sources of disturbance during the early production stage of products were discussed. Finally, a basic process based on using knowledge and experiences from the introduction of prior similar products was suggested to facilitate the product introduction process in low-volume manufacturing industries.
Paper IV: Start of production in low-volume manufacturing industries: disturbances and solutions

The aim of this paper was to identify the sources of disturbance encountered at the start of production of new products in low-volume manufacturing industries and to suggest general solutions for their elimination or mitigation. The empirical data presented in this paper were based on the disturbances observed during the product introduction process for Case A, Case B, Case C and Case D. The disturbances were primarily categorized into product-related and production system-related disturbances. The sources of disturbance were discussed; some facilitators were suggested to avoid or mitigate the disturbances. The product-related disturbances were primarily categorized into three sub-categories:

- Incorrect/missing information regarding small/connecting parts;
- Design for assembly problems; and
- Other.

Production-related disturbances were generally caused by a late consideration of the required changes in the production system to produce the products.

The main sources of disturbance during the product introduction process in low-volume industries were outlined as follows:

1. Intensified focus on product functionality rather than manufacturability due to a lack of resources to cover all manufacturability aspects and a lack of opportunities for testing, refining and adapting the product and production system; and
2. A late consideration of required changes in the production system caused by considering the production system “as is” and by considering the system to be unrealistically flexible.
6. The product introduction process in low-volume manufacturing industries and its facilitators

In this chapter, the results of the research and the implications related to the objective of the research and the research questions are analysed and discussed. The characteristics of low-volume manufacturing industries regarding their products and production systems and their influences on the product introduction process are presented. Finally, a basic model to support the product introduction process in low-volume manufacturing industries is presented.

The discussion in this chapter is primarily based on the empirical findings presented in Chapter 4 and Chapter 5 and the studied theory.

6.1. Characteristics of low-volume manufacturing industries

In line with the findings of Jina et al. (1997), low-volume products were empirically determined to be highly customizable. As a result, they have a broad range of variety. The variety of the products combined with the number of technological aspects and disciplines involved in the products, the number of parts and components and their interfaces make the products highly complex. In addition, the low-volume products are typically costly, which is partially due to a high level of customizability.

The characteristics of low-volume products influence their corresponding production systems. A very flexible production system is required to be able to manufacture various highly customizable products. This flexibility is necessary to avoid high investments in new production systems for several different products and their variants, which have low production volumes. Providing such flexibility in production systems without costly investments in highly automated flexible production systems usually involves several requirements, such as the use of universal production equipment, a high level of manual work, a high demand on operators’ skills and resource sharing among the production of different products, which was suggested by Hill (2000), Mohamed and
Khan (2012) and Qudrat-Ullah et al. (2012). In addition, the low demand for each product and the high cost of the products impose a complete make-to-order production planning policy on low-volume manufacturing companies. Figure 11 shows the main characteristics of low-volume products and their influence on the characteristics of corresponding low-volume production systems.

**Figure 11. Characteristics of low-volume products and production systems and their inter-relations as identified in the empirical findings.**

6.2. The product introduction process

The findings from the case studies show that the product development and introduction processes in the case company were affected by a combination of the aforementioned characteristics of the product and production system. Figure 12 provides a summary of these influences.
One of the most considerable influences of the identified characteristics is the make-to-order production policy, which results from the low production volume and high cost of the products. This policy does not allow one to develop many prototypes during the testing and refinement phase. These characteristics also result in a low, discontinuous demand for the products, which leads to the infeasibility of implementing a conventional production ramp-up. Therefore, the implementation of the two last phases of the product development model of Ulrich and Eppinger (2012) faces serious challenges in low-volume manufacturing. As a direct result, the product introduction process at the product introduction level in low-volume manufacturing industries is usually limited to a conceptual study, the development of engineering prototypes and limited pre-series/pilot production runs. Based on the results of Paper IV, the higher number of prototypes and pre-series production runs in Case B and Case D aided in an earlier identification of design-for-assembly problems and in a reduction in production disturbances related to design-for-assembly. However, the numerous engineering prototypes, pilot production runs and pre-series productions was considered a luxury in the low-volume product introduction projects studied. The number of physical engineering prototypes was limited to a couple of products and pilot or pre-series productions and was dependent on customer demands. Due to the low production volumes and the make-to-order production policy, the
prototypes did not typically exceed a handful of products. Figure 13 illustrates the product development and introduction processes based on the case studies. Compared with the generic product development process, which is visualised in Figure 5 (Ulrich and Eppinger, 2012), the production ramp-up phase is not feasible in low-volume manufacturing industries and test and refinement opportunities are limited. At the product introduction process level, in addition to the infeasibility of the production ramp-up phase, pilot production runs and pre-series production are considerably limited in comparison with high-volume manufacturing industries.

As another characteristic of the product development in the studied low-volume manufacturing company, new products were typically modified versions of existing products. This phenomenon was primarily due to the high variety and customizability of the products, which was an order-winning criterion for the low-volume manufacturing company. A direct outcome of such variety in the products was the use of a single flexible production system that was capable of producing different products with slight modifications to avoid high investment costs in several production systems, which was suggested by Qudrat-Ullah et al. (2012). In tailoring new products with the limitations of existing production lines, despite the high level of flexibility in the production system, the design for the manufacturing and assembly criteria should include additional factors, such as the limitations of existing manufacturing equipment, capacity and human resources.

Figure 13. The product introduction process (b) as a sub-process of the product development process (a) in low-volume manufacturing industries. The grey colour represents limited implementation of the phases. (The different arrow sizes do not represent any characteristics of the phases.)

The wide variety of products and the ability to customize these products to meet the requirements of different customers and markets result in a
high frequency of product introduction, whereas limited production volumes do not allow for the use of dedicated resources for the introduction of each product. As a result, a matrix organisational model was used in the studied cases/company to share resources among different projects and with ongoing production activities. Although this approach aids in avoiding additional costs by using dedicated resources for the introduction of each product, it involves some challenges, such as problems in prioritizing the activities and providing enough resources to the different priorities.

Moreover, the empirical data regarding the numerous disturbances related to the design for manufacturing and small connecting parts suggest that the designers were primarily focused on the functionality of the products rather than their manufacturability. Because the designers and all project team members emphasised the functionality of the products, many details of the products, such as information regarding the connecting parts and DFM/DFA issues, were left to be finalised during the pre-series and final production. These results are in line with the findings of Vallhagen et al. (2013), who suggested that during the product introduction process in low-volume manufacturing industries, only the producibility of the products is ensured, not their manufacturability. Although this is also a well-known problem in high-volume manufacturing industries, this issue is considerably intensified by the characteristics of low-volume manufacturing industries. The high variety and customizability of the products intensify the importance of the functionality of the products in the product development process. Furthermore, the numerous ongoing product development projects and the sharing of human resources increase the problem of overlooking design for manufacturability criteria. The sharing of human resources among several product development projects during the product introduction process and the ongoing production is another characteristic that was observed in the studied cases. This resource sharing generally undermines the involvement of the production operators and production engineers in the product introduction process, which further intensifies the problem of overlooking the DFM criteria.

Table 10 summarises the characteristics of the product introduction process in the studied low-volume manufacturing company; their challenges potential benefits are also presented.

In the following, the influences of the aforementioned characteristics on the different sources of disturbance during the product introduction process which are categorised by Surbier et al. (2013) are discussed.
Table 10. Characteristics of the product introduction process in low-volume manufacturing industries, including their challenges and potential benefits.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Challenges</th>
<th>Potential benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Few engineering prototypes</td>
<td>Lack of opportunities to test and refine the functionality of the products</td>
<td>Reduced product introduction time and budget</td>
</tr>
<tr>
<td>Limited and uncertain number of pre-series productions</td>
<td>Lack of opportunities to test and refine the production processes or to adapt the product and production system together</td>
<td>Reduced product introduction time and budget</td>
</tr>
<tr>
<td>Infeasibility of conventional production ramp-up</td>
<td>Difficulty of implementing ramp-up activities such as reaching production goals and training production operators</td>
<td>Reduced product introduction time and budget</td>
</tr>
<tr>
<td>Modification of existing products rather than the development of completely new products</td>
<td>Chance of overlooking opportunities for innovation</td>
<td>Reduced complexity of the product introduction process and opportunity to use existing knowledge about the products</td>
</tr>
<tr>
<td>Use of existing production systems with slight modifications for new products</td>
<td>- Chance of overlooking opportunities for innovation &lt;br&gt;- Under-prioritizing the production system requirements and considering the production system “as is”</td>
<td>Reduced complexity of the product introduction process and opportunity to use existing knowledge about the production system</td>
</tr>
<tr>
<td>High frequency of introduction of new products</td>
<td>Difficulty in allocating resources and involving the production personnel</td>
<td>More opportunities to use cross-project learning</td>
</tr>
<tr>
<td>Focus on product functionality rather than manufacturability</td>
<td>Neglecting design details and DFM/DFA requirements</td>
<td></td>
</tr>
</tbody>
</table>

Product: A strong focus on a product’s functionality combined with an under-prioritisation of its manufacturability result in the product moving to production with insufficient or incorrect details and difficulties during product assembly, which can cause frequent disturbances in the early production stages. In addition, a lack of opportunities to refine the product and resolve issues due to the limited number of engineering prototypes leads to a lack of product maturity and late design changes. However, because the products in the studied low-volume company were typically modified versions of previous products, these effects can be mitigated by drawing upon experiences and information from the introduction of prior similar products.
**Production system:** The production system is usually slightly modified to produce new products in low-volume manufacturing industries. Although this approach facilitates the product introduction process by avoiding many activities related to the production system design, in most cases, it leads to considering the production system “as is”. As a result, slight necessary changes in the production system are usually only considered in very late stages of the product introduction process or even later during normal production. This problem is intensified by a lack of opportunities to test and refine the production system due to the limited number of pre-series productions and the infeasibility of a traditional production ramp-up. An important example of this issue in the studied cases was a lack of opportunities for developing and refining the instructions of assembly which was the main production process.

**Design-production interface (cooperation and communication):** The lack of opportunities for a final refinement in the product and the production system and for adapting them together makes the communication and cooperation between design and production even more important in low-volume manufacturing industries. However, based on the model presented by Almgren (1999a), the complexity of the introduction process, which is primarily related to the cooperation and communication between design and production, is generally reduced in low-volume manufacturing industries. This trend is primarily due to the reduced novelty of the product and production system in such industries. Because products are usually modified versions of existing products with only slight modifications to the production system, the degree of complexity of the product introduction process should be reduced (Figure 14).

However, to benefit from the advantage of reduced complexity, it is important to gather knowledge and experiences from prior similar projects and share them with those involved in the introduction process of new products and ensure that the knowledge is used during the process.
Figure 14. The typical complexity level of product introduction in low-volume manufacturing industries (based on Almgren (1999a)).

**Quality:** A lack of opportunities for refining the product and production system and for adapting them together can result in increased quality issues at the start of production. This issue should be further investigated in future studies.

**Resource management:** Resource sharing among different product development projects and with ongoing production intensifies resource management problems. Involvement of the production personnel and other production resources in the product introduction process is necessary; although in many cases, this is not easy to achieve due to their involvement in the ongoing production of other products.

**Personnel:** A traditional production ramp-up was often infeasible during the product introduction process in the studied cases. Therefore, the training of production personnel to produce new products as one of the main activities during the production ramp-up faces considerable difficulties. This issue also leads to a higher level of skills being required for new production personnel, such as operators. Because the complexity of the products is high and the learning opportunities are limited, the entry level of skills for new production personnel should be higher. However, again, the experiences and knowledge obtained from the production of prior similar products can be used as a partial compensation for the lack of opportunities for training and learning of the production personnel. The positive and negative influences of the characteristics of the product introduction process in the case studies on the sources of disturbance are summarised in Table 11.
Table 11. Influences of the characteristics of the product introduction process in low-volume manufacturing industries on the sources of disturbance.

<table>
<thead>
<tr>
<th>Sources of disturbance</th>
<th>Influences</th>
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</thead>
<tbody>
<tr>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Insufficient design details, insufficient product maturity, and late design changes</td>
</tr>
<tr>
<td>Production system</td>
<td>Considering production processes “as is”, late changes and refinements in the production systems, and immature and non-optimised production processes</td>
</tr>
<tr>
<td>Design-production interface</td>
<td>Increased need for collaboration and communication between design and production</td>
</tr>
<tr>
<td>Quality</td>
<td>Possible increase in quality problems due to immaturity of the product and production system</td>
</tr>
<tr>
<td>Resources</td>
<td>Difficulty related to the involvement of resources, including the production personnel</td>
</tr>
<tr>
<td>Personnel</td>
<td>No opportunities for conventional training of personnel</td>
</tr>
</tbody>
</table>

6.3. Facilitating the product introduction process in low-volume manufacturing industries

Many facilitators suggested by studies for high-volume manufacturing cases can also be applied to the product introduction process in low-volume manufacturing industries. Some examples include front-end engineering (Cooper, 1994, Kim and Wilemon, 2002), early involvement of production in the product introduction process (Adler, 1995, Lakemond et al., 2007, Ruffles, 2000, Sharma, 2004, Woodcock et al., 2000), the visualisation of design information and work instructions through CAD/CAM technology (Gibson et al., 2004, Kumar and Wellbrock, 2009, Malmsköld et al., 2012, Olsen and Sætre, 2001, Ruffles, 2000) and design reviews (Adler, 1995, Classen and Lopez, 1998, Olhager, 2000). The results from Paper IV showed that the
formalised application of some of these facilitators in Cases A and Case B led to decreased disturbances in production caused by design for assembly problems in comparison to Case C and Case D. Examples of the facilitators used in Case A and Case B include design reviews, earlier and more formalised involvement of production personnel and the visualisation of design information.

Apart from the aforementioned general facilitators, the low novelty of the product and production system in the product introduction process in low-volume manufacturing industries is potentially a substantial advantage. According to Adler (1995) and Twigg (2002), the appropriate time for coordinating the design-production interface, including verifying the manufacturability of the product and the conformity of the product and production system, for products and production systems with a lower level of novelty is during the earlier phases of the product introduction process in which the product is designed. In addition, mutual adjustments would be an appropriate coordination mechanism for the product introduction process in low-volume manufacturing industries because the novelty and complexity of the process are mediated (Adler, 1995, Twigg, 2002). One way to benefit from the lower level of novelty and extent of change in the product and production system is to use experiences and knowledge from ongoing production and previous projects as a source of learning to compensate for the lack of opportunities for trial and error in the product development process. Because new products are typically a modified version of existing products and the production system is almost unchanged, disturbances from earlier and current projects can be used to avoid similar problems when introducing new products. The reoccurrence of similar types of disturbances with comparable contributions in the production of similar products (Figure 8) supports the usefulness of utilizing knowledge and experiences from the introduction of prior similar products. However, learning from other products requires a constant and effective knowledge transfer from production and projects to the product design.

In addition, because new products are commonly manufactured in an existing production system in low-volume manufacturing industries, it is very important to ensure that up-to-date knowledge regarding the capabilities and limitations of the production system is conveyed to the designers. Thus, in low-volume manufacturing industries, inputs from manufacturing to product development should not be limited to conventional inputs, such as available production technology. These inputs should also include detailed information on the limitations of the existing production system, such as available production equipment and tools, physical limitations of production plants, and the available production resources and capacity. In this regard, the product
In summary, a constant and effective knowledge transfer from production to design should be considered as an important component of the development of customised solutions for product development and product introduction in low-volume manufacturing industries, as suggested by Surbier et al. (2013) and Maffin and Braiden (2001). This knowledge transfer flow should include the limitations and requirements of the existing production system and knowledge about sources of disturbance in the development and production of similar products. An effective use of the transferred knowledge should also be considered in the product design and product development process. One way to achieve this goal is to develop guidelines or a framework of design for low-volume manufacturing/assembly to include limitations and requirements of the existing production systems and to eliminate sources of production disturbance in the design and development criteria.

To accumulate knowledge and experiences from the introduction of previous products, a process could be established to continuously gather inputs from the designers and production personnel about their experiences and knowledge from ongoing product introductions. These inputs could cover, but would not necessarily be limited to, disturbances both in design and production, the sources of these disturbances, and possible solutions to the disturbances. An example of this mechanism is the database of product-related disturbances used in this study. The accumulated knowledge should be analysed, categorised and fed back to design and production as an input for future similar projects to compensate for a lack of opportunities to test and refine the product and production system and to adapt them together. The entire process can preferably be coordinated and facilitated by product introduction project managers. Examples of this coordination in the studied cases include gathering and transferring production expectations to the designers and coordinating the design reviews. In this regard, including the role of a product introduction project manager in the product development projects as a facilitator of the product introduction process should be considered because a considerable positive effect was indicated in the studied cases. Figure 15 illustrates the suggested process.
Disturbances during the early production of new products and their sources

- Register the disturbances and their sources in early production
- Use the available production knowledge from earlier projects

Disturbances during the design of new products and their sources

- Register disturbances and their sources during the product design
- Use the available design knowledge from earlier projects

Production-related disturbances

Product-related disturbances

- Process the data from production and design
- Feed the processed data to design and production for reuse in similar projects

Figure 15. The process of gathering, sharing and using information and experiences from the introduction of similar products to facilitate the product introduction process.
7. Conclusions and future research

This chapter begins with the conclusions of this research and continues with a discussion regarding the fulfilment of the research objective. Thereafter, the contribution and quality of the presented research are presented. Finally, future research is discussed.

7.1. Conclusions and fulfilment of the research objective

The main objective of the research presented in this licentiate thesis was to develop knowledge about the product introduction process and its facilitators in low-volume manufacturing industries by focusing on the characteristics of products and production systems in these industries. Three research questions were formulated to fulfil the objective of this research. To answer the research questions, a theoretical frame of reference was presented to provide a basis for the research project, in addition to a case-based study consisting of 5 cases covering both theory and empirics. The research resulted in a broader understanding of the characteristics of the product introduction process and its facilitators in low-volume manufacturing industries by identification of influences of characteristics of low-volume product and production systems on the product introduction process.

To improve and support the product introduction process in low-volume manufacturing industries in reaching a shorter time to market/payback with fewer production disturbances and higher product quality, the identification of factors that affect the product introduction process is important. Therefore, the characteristics of low-volume products and production systems were identified, and their influences on the product introduction process were studied.

To answer the first research question, i.e., “What are the main characteristics of low-volume manufacturing industries in comparison to high-volume ones regarding their products and production systems?”, the main characteristics of low-volume products were discussed in Chapter 5.1.
These characteristics included

- Low yearly production volumes;
- High cost;
- High complexity; and
- High variety and customizability.

The aforementioned characteristics of low-volume products impose the following characteristics on low-volume production systems:

- Complete make-to-order production policy;
- High level of manual work;
- Use of universal production equipment; and
- Sharing of production resources among different products.

The aforementioned characteristics of low-volume products and production systems influence the product introduction process, which exhibits the following characteristics:

- Few engineering prototypes;
- Limited and uncertain number of pre-series productions;
- Infeasibility of conventional production ramp-up;
- Modification of existing products rather than development of entirely new products;
- Use of existing production systems with slight modifications for new products;
- High frequency of introduction of new products; and
- Extensive focus on functionality of products rather than manufacturability.

The challenges and potential benefits resulting from the characteristics of the product introduction process in low-volume manufacturing industries were discussed in Chapter 6.2. Some of the most important challenges include a lack of opportunities for testing and refining the product and production system and difficulty in conducting primary production ramp-up activities, such as training the production personnel. The main potential benefits include decreased complexity of the product introduction process and the use of knowledge and experiences from the development and production of similar products.

In this manner, the second research question, i.e., “How do the characteristics of low-volume manufacturing industries influence the product introduction process?”, was answered.

To answer the third research question, “How can the product introduction in low-volume industries be facilitated?”, the facilitators of
the product introduction process in low-volume manufacturing industries were discussed in Chapter 5.3.

The results of this research demonstrate that some general facilitators, such as design reviews, front-end engineering and early involvement of production in the product introduction process, can be applied to the product introduction process in low-volume manufacturing industries. Moreover, the results indicate that the inclusion of a product introduction coordinator in the product introduction process can considerably facilitate the process, especially in low-volume manufacturing industries, where human resources are limited and are extensively shared among several product development projects.

More importantly, the use of knowledge and experiences from the development and production of prior similar products was identified as an important facilitator of the product introduction process in low-volume manufacturing industries.

7.2. Contributions

The objective of this research was to develop knowledge about the product introduction process and its facilitators in low-volume manufacturing industries by focusing on the characteristics of products and production systems in these industries. Therefore, this research contributes to the scientific community in terms of increasing knowledge and adding to the theory about the product introduction process in low-volume manufacturing industries and its facilitators. Moreover, this research also provides relevant knowledge to the industry, with detailed and implementable facilitators of the product introduction process in low-volume manufacturing industries.

7.2.1. Scientific contribution

The primary scientific contribution of this work is its coverage of the identified knowledge gap regarding the product introduction process in low-volume manufacturing industries. As a result, this research has contributed to a broader understanding of the product introduction process by identifying the influences of the characteristics of low-volume manufacturing industries on the product introduction process and the factors that can facilitate this process in low-volume manufacturing industries. The related literature was reviewed, and a general definition of the product introduction process was presented based on this review. Furthermore, the characteristics of the product introduction process in low-volume manufacturing industries were investigated both via the
literature and empirical studies. Finally, the facilitators of the product introduction process in low-volume manufacturing industries were identified and analysed at a general level.

7.2.2. Industrial contribution
This research project provides practitioners in low-volume manufacturing industries with a general understanding of the characteristics of the product introduction process in those industries. The research can also provide practitioners with general information about managing and facilitating the product introduction process in low-volume manufacturing industries.

7.3. Quality of the presented research
Different aspects of the quality of the presented research were discussed in Chapter 2.5. The methodological approach presented in Chapter 2 was followed to ensure and increase the quality of the research. However, it was impossible to perfectly cover all research quality aspects.

It can be argued that this research may be limited by the fact that all of the empirical data regarding low-volume manufacturing industries were gathered from a single company. This approach may jeopardise the quality of the research regarding its generalizability to other cases. In addition, the reproducibility of the conducted research may be a matter of question. Because the empirical data in this research were gathered in a dynamic industrial environment that is subject to continuous changes, conducting the same research in the future will most likely not lead to identical results.

The role of the researcher in this research project was described in detail in Chapter 2.5.1. Being aware of the described role of the researcher, objectivity was a focal point during this research project to maintain the quality of the research and to avoid common problems that are caused by the role of the researcher.

7.4. Future research
During this work, several additional research opportunities were revealed. First and foremost, a detailed study of the use of knowledge and experiences from the production and development of similar products in low-volume industries to facilitate the product introduction process is necessary. In this regard, the next step of the research aims to understand
the perspective of production personnel and product designers regarding the constituent content of gathered and exchanged knowledge and experiences from the production and development of prior similar products. In addition to the content of the information, effective and efficient ways to coordinate the gathering, sharing and use of the information could be a topic for further study.

Furthermore, the integration of different facilitators of the product introduction process in low-volume manufacturing industries into a framework or a guideline for implementation is very important for transferring the results of this research to practitioners.

Finally, because the empirical data in this research were gathered from a single company, a diversity of cases would be of interest for further research to both broaden the scope and validate the findings of the research. In this regard, replicating this study with additional low-volume manufacturing companies, preferably from other branches, would increase the quality and validity of this research.
References


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