Characteristics of product introduction process in low-volume manufacturing industries

A case study

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Abstract

Purpose – The purpose of this paper is to understand how the characteristics of low-volume manufacturing industries influence the product introduction process and factors which can facilitate that process in low-volume manufacturing industries.
Design/methodology/approach – A literature review and a multiple-case study were used to achieve the purpose of the paper. The multiple-case study was based on two product development projects in a low-volume manufacturing company.
Findings – The main identified characteristics of the product introduction process in low-volume manufacturing industries were a low number of prototypes, absence of conventional production ramp-up, reduced complexity of the process, failure to consider the manufacturability of the products due to an extensive focus on their functionality and increased complexity of resource allocation. It was determined that prior production of similar products could serve as a facilitator of the manufacturing process.
Research limitations/implications – The main limitation of this study is that the identified characteristics and facilitating factors are confined to the internal variables of the studied company. A study of the role of external variables during the product introduction process such as suppliers and customers could be the subject of future studies.
Practical implications – This research will provide practitioners in low-volume manufacturing industries with general insight about the characteristics of the product introduction process and the aspects that should be considered during the process.
Originality/value – Whereas there is a significant body of work about product introduction process in high-volume manufacturing industries, the research on characteristics of the product introduction process in low-volume manufacturing industries is limited.
Keywords Product development, Design-production interface, Industrialization process, Low-volume products, Production system development
Paper type Research paper

1. Introduction

Manufacturing companies must launch new products to the market over shorter intervals because of globalisation, the rapid introduction of new technologies and shorter product life cycles (Bellgran and Säfsten, 2010; Chryssolouris, 2006; Ishikura, 2001) among other reasons. Thus, rapidly launching new products to the market helps companies avoid negative outcomes, such as loss of market share, lost revenues and early product obsolescence (Adler, 1995; Hendricks and Singhal, 2008).

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The final process of product development projects 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 has considerable influence on the time to market and on product quality (Adler, 1995). It is defined as "transferring from engineering design to production including those activities required to make the product manufacturable and to prepare production" (Bellgran and Säfsten, 2010, p. 233). An efficient and effective product introduction process can lead to a shorter time to market and a more functional and cost-effective production system with fewer disturbances both during and after the product introduction process (Almgren, 1999c; Fjällström *et al.*, 2009. As a result, identifying salient characteristics of the product introduction process is critical for manufacturing companies to manage new product development projects effectively and to maintain competitiveness.

Introducing new products with low-production volumes implies specific characteristics for product development projects and consequently the product introduction process (Maffin and Braiden, 2001; Qudrat-Ullah *et al.*, 2012). The product introduction process has been studied mainly in high-volume manufacturing industries. Therefore, research on the characteristics of the product introduction process in low-volume manufacturing industries is limited (Surbier *et al.*, 2014). To fill this research gap, this paper formulated and answered the following two research questions:

RQ1. How do the characteristics of low-volume manufacturing industries influence the product introduction process?

RQ2. How can the product introduction process be facilitated in low-volume manufacturing industries?

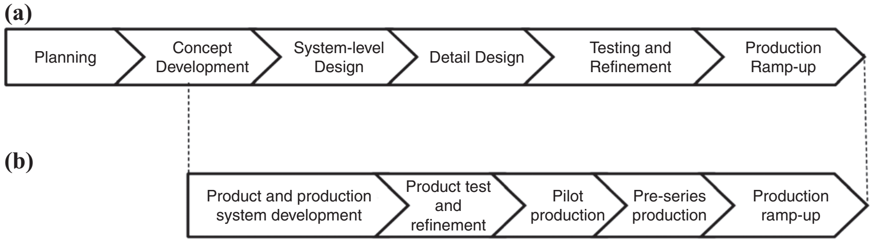
A multiple-case study method is selected to achieve this aim. As Almgren (1999b) divides the variables that affect the product introduction process into internal and external variables, only the internal variables are studied in this research and issues related to the external variables such as supplier or customer-related variables are excluded to narrow down the subject of this research.

2. The product introduction process

As the final sub-process of the product development process, the product introduction process has been defined differently by different researchers. Juerging and Milling (2005) posit that the product introduction process consists of three main phases: product development, production system development and production ramp-up. Moreover, these three phases can be implemented in parallel, overlapping or sequential fashion. Winkler *et al.* (2007) present a model for the product introduction process that consists of parallel development and realisation of a product and production system over the three phases of development, preparation and production ramp-up. On a more detailed level, Berg *et al.* (2005) refer to 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) present a more extended definition that also includes product and production system development and product test and refinement. Figure 1 shows the generic product introduction process and its relation to the product development process. Different phases of the product introduction process are described briefly in Table I based on Fjällström *et al.* (2009) and Johansen (2005).

Regardless of its various definitions, the aim of the product introduction process is to develop a production system to produce a product (Bellgran and Säfsten, 2010; Johansen, 2005; Winkler *et al.*, 2007) and to assure the manufacturability of that product (Olhager, 2000) by adapting product and production systems together (Johansen, 2005; Ruffles, 2000). In other words, the requirements of the three dimensions of product development discussed by Juerging and Milling (2005) – the product, production system and resources – should be fulfilled during the product introduction process. The product and production systems are developed during the product and production system development and refined mainly by development of engineering prototypes, pilot production/production prototypes, pre-series productions and finally production ramp-up and possible non-conformities between them are eliminated during the product introduction process (Berg *et al.*, 2005; Fjällström *et al.*, 2009; Ruffles, 2000; Winkler *et al.*, 2007).

The start of production during the final phases of the product introduction process is often characterised by high levels of production disturbances (Almgren, 2000; Fjällström *et al.*, 2009; Nyhuis and Winkler, 2004). Such disturbances typically lead to longer production cycle times (Apilo, 2003; Terwiesch and Bohn, 2001), lower production output (Fleischer *et al.*, 2003; Juerging and Milling, 2005; Terwiesch *et al.*, 2001) and lower product quality (Almgren, 1999b; Nyhuis and Winkler, 2004;



Notes: (a) Generic product development process based on Ulrich and Eppinger (2012); (b) product introduction process based on Johansen (2005) and their connections

Figure 1. Product development and product introduction processes

Table I. Description of the main phases of the product introduction process

Phase	Description
Product and production system development	Developing a new product/modifying an existing product along with considering manufacturability and functionality of the product in parallel with production system development/modification[b]
Product test and refinement	Validating the functionality of products and refining the design of them mainly by development of engineering prototypes outside of the production lines[a]
Pilot production (development of factory prototypes)	Production of prototypes that are not primarily intended for the end customer but used for validating the adaptability of products and production processes[a,b]
Pre-series production	Production is not necessarily intended for the end customer, in production lines but used for validating the adaptability of products and production processes[a]
Production ramp-up	Start of commercial production, increase the production rate until the planned volume, quality, etc. are reached[a,b]

Sources: [a]Fjällström *et al.* (2009), [b]Johansen (2005)

Terwiesch *et al.*, 2001). Most of these disturbances and their sources have been studied primarily as case studies and in the context of high-volume manufacturing industries (Surbier *et al.*, 2014). Various researchers have categorised the sources of disturbances differently. Almgren (2000) suggests four main sources: product, production technology, supply of material and personnel. Another categorisation suggested by Fjällström *et al.* (2009) and Nyhuis and Winkler (2004) and summarised by Surbier *et al.* (2014) divides the sources of disturbances into the following seven categories: product, production processes, supply chain and logistics, quality, methods and tools, personnel and cooperation and communication. These categories are summarised in Table II.

The majority of these disturbances are prevented or removed during the product introduction process (Bellgran and Säfsten, 2010; Johansen and Björkman, 2002; Ruffles, 2000). Different activities to mitigate or eliminate such disturbances during various phases of the product introduction process are further discussed in this section.

2.1 Product and production system development

During this phase the product and production systems are developed in parallel (Classen and Lopez, 1998; Johansen, 2005; Sharma, 2004; Winkler *et al.*, 2007). Coordinating this parallel development requires the early formation of a cross-functional team, a clear definition of goals and activities, the utilisation of formalised documents including plans and schedules, stage-gate models and work procedures and allocation of necessary resources from production at the beginning of this phase are necessary (Adler, 1995; Cooper, 1994; Ruffles, 2000; Valle *et al.*, 2003).

Adler (1995) summarises 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 are standards, plans and schedules, mutual adjustment and teams. The novelty level of the product and production systems defines the complexity of this phase as well as the entire product introduction process (Adler, 1995; Tidd and Bodley, 2002; Almgren, 1999a). In other words, a completely new product with a new production system implies the highest complexity whereas a modified product that is to be produced within an existing production system is characterised by the lowest complexity level (Almgren, 1999a). Therefore, Adler (1995) argues that novel products/production systems require more interactive coordination mechanisms (such as joint teams), whereas well-known products/production systems require less interactive mechanisms, i.e., standards and plans often suffice. Juerging and Milling (2005) discuss other aspects that also influence the complexity of this phase as well as the entire product

Table II. Sources of disturbances at the start of the production

Source of disturbance	Disturbance type
Product	Insufficient product specifications and lack of product maturity
Production system	Lack of maturity in production processes, manufacturability of the product and product-process fit
Supply chain and logistics	Problems with the quality and availability of supplied parts and components
Quality	Problems with quality of the final product
Resource management	Inaccurate resource planning and problems with data and information management
Personnel	Unclear definition of responsibilities, lack of qualified personnel and insufficient training of personnel
Design-production interface	Lack of cooperation and communication between different departments and functions, particularly between design and production

introduction process including complexity and variety of the product, level of concurrency of activities and the standardisation of production processes.

Regardless of the different complexity scenarios, the early involvement of production in this phase is emphasised in the literature. This involvement can reduce non-conformities between the product and production systems in later phases and can help to develop a common vision between product designers and production personnel (Adler, 1995; Lakemond *et al.*, 2007; Ruffles, 2000; Sharma, 2004; Woodcock *et al.*, 2000). The early involvement of production also facilitates the continuous cooperation and communication between design and production (Sharma, 2004). This cooperation and communication includes understanding production requirements (Lakemond *et al.*, 2007; Ruffles, 2000) and reviewing the manufacturability of products and the product/production system fit by means of design reviews (Adler, 1995; Classen and Lopez, 1998; Olhager, 2000). Design reviews allow the product designers to utilise methods such as design for manufacturability and assembly (DFM/DFA), which is mentioned as a critical tool in the product and production system development phase that makes the product manufacturable and that reduces product/production system non-conformities (Boothroyd, 1994; Dröge *et al.*, 2000; Lakemond *et al.*, 2007; Tidd and Bodley, 2002). Mountney *et al.* (2007) suggest gathering production system information early in the conceptual design phase to facilitate communicating information and knowledge from production to design and to avoid disturbances and non-conformities during the later phases of the product introduction process.

In general, many researchers highlight the role of effective implementation of the above-mentioned activities during the product and production system development phase in reducing costs and the duration of the product introduction process, in addition to reducing disturbances during production (Adler, 1995; Cooper, 1994; Kim and Wilemon, 2002; Ruffles, 2000; Valle *et al.*, 2003). These activities are also known as the upfront or front-end activities of the product development process (Cooper, 1994; Kim and Wilemon, 2002). Adler (1995) indicates that when the product/production system fit is less complex and more analysable, putting more efforts into front-end activities is even more advantageous.

2.2 Product test and refinement

During the second phase of the product introduction process, product design verification and refinement as well as testing the functionality of the product are conducted primarily by development of the engineering prototypes (Lakemond *et al.*, 2007; Ruffles, 2000). In this regard engineering prototypes are more important for completely new products than for modified products (Tidd and Bodley, 2002). These prototypes can be physical or virtual which are 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 the product and its manufacturability (Gibson *et al.*, 2004; Ruffles, 2000), and they provide a better understanding of the product features and possible problems by visualising 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. Whereas design reviews can continue to be utilised as a cooperation and communication mechanism between product design and production (Adler, 1995; Bruch and Bellgran, 2013; Frishammar, 2005; Ruffles, 2000; Twigg, 2002; Ylipää, 2000), granting production personnel access to engineering prototypes and encouraging their contribution to developing prototypes can also facilitate communicating the information about new product features to them (Lakemond *et al.*, 2007; Ruffles, 2000). Such access also helps the production personnel to develop the details of production processes such as the time, sequence and instructions of 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).

2.3 Pilot production (factory prototypes), pre-series production and production ramp-up

Pilot production are mainly aimed at verifying and refining the production system (Ruffles, 2000; Twigg, 2002). However, they also play an important role in controlling the product/production system. Cross-functional teams and design reviews can still be used as cooperation and communication mechanisms between design and production regarding the required adjustments in the product and production system during this phase (Adler, 1995).

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 at the start of production (Fjällström *et al.*, 2009; Fleischer *et al.*, 2003; Surbier *et al.*, 2014) and ends with fulfilment of the initial production goals such as intended production time, quality and volume (Almgren, 1999c; Carrillo and Franza, 2006; Fjällström *et al.*, 2009; Fleischer *et al.*, 2003; Johansen, 2005; Ruffles, 2000). During the production ramp-up the remaining problems and non-conformities are often identified and eliminated.

One of the main activities during production ramp-up that is highlighted in different research is the training of operators and production personnel in the production of a new product (Adler and Clark, 1991; Bellgran and Säfsten, 2010; Ruffles, 2000; Terwiesch and Yi, 2004). Terwiesch and Bohn (2001) posit 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 the experimentations are considered to be factors that influence the learning process in the product introduction process (Terwiesch and Bohn, 2001). Adler and Clark (1991) also justify the positive correlation between the number of products produced during the product introduction process and the learning process of the operators. In this regard, pre-series production and production ramp-up play an important role in training production personnel. To complement "learning by doing" training methods, virtual training and learning tools can be employed (Malmsköld *et al.*, 2012).

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

In summary, the studied literature shows that the product introduction process can be defined as the process of parallel development, realisation and adaptation of product and production systems. In high-volume manufacturing industries, this process typically consists of product and production system development, development of engineering prototypes, pilot production, pre-series production and production ramp-up.

3. Low-volume manufacturing industries

Annual production volumes that are less than 500 units (Jina *et al.*, 1997), full make-to-order production planning and a wide variety and high complexity of products distinguish low-volume manufacturing industries from high-volume industries (Jina *et al.*, 1997; Rahim and Baksh, 2003). Lakemond *et al.* (2007) consider the amount of technology used in the product, the number of parts and components and the novelty of the product as the complexity criteria of products. The order-winning criteria in low-volume manufacturing industries are tailored products with a wide variety and high speed of delivery (Jina *et al.*, 1997; Rahim and Baksh, 2003). The production systems of low-volume manufacturing industries are typically characterised by a high level of flexibility (Mohamed and Khan, 2012; Williamson, 2005). Providing such flexibility requires highly skilled workers (Mohamed and Khan, 2012; Bellgran and Aresu, 2003), universal production equipment (Hill, 2000), low levels of automation (Andersson *et al.*, 2014; Hill, 2000) and shared production resources among different products (Rahim and Baksh, 2003). The usual process choice for the low-volume manufacturing industries is jobbing or batch production (Mohamed and Khan, 2012). However, considering the definition of production volume by Hill (2000), i.e., quality multiplied by work content, line production can also be the appropriate process choice for producing complex low-volume products with high-work content. Moreover, the appropriate production planning policy in low-volume manufacturing industries is typically make-to-order (Jina *et al.*, 1997; Wrobel and Laudański, 2008).

According to Juerging and Milling (2005) and Van der Merwe (2004) a wider variety and higher complexity of products and less standardised production processes can lead to higher levels of complexity in product development projects and in the product introduction process. In addition, such characteristics result in fewer opportunities for engineering and factory prototypes and the absence of volume ramp-up at the end of the process (Javadi *et al.*, 2013; Qudrat-Ullah *et al.*, 2012). This issue leads to fewer chances for verification of the product and production system during the later phases of the product introduction process (Javadi *et al.*, 2013; Rahim and Baksh, 2003). Furthermore, Vallhagen *et al.* (2013) indicate that the main focus during the product introduction process in low-volume manufacturing industries is on the of the product rather than on its manufacturability. Therefore, optimising the production processes is not typically considered, and the only thing that is assured is that the producibility of the product by means of existing processes. However, the complexity and variety of low-volume products (Wallace and Sackett, 1996), a more frequent product introduction 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 because of their high cost relative to production volume, and the tendency to fit the new products into the current production system are additional characteristics of the product introduction process in low-volume manufacturing industries (Javadi *et al.*, 2013; Qudrat-Ullah *et al.*, 2012; Rahim and Baksh, 2003). Design and production resource bottlenecks are also intensified in low-volume manufacturing industries because of the intensive sharing of resources among multiple projects as well as the on-going production (Qudrat-Ullah *et al.*, 2012).

In addition to the facilitators previously discussed, certain other facilitating factors of the product introduction process are suggested based on the characteristics of low-volume manufacturing industries discussed above. 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) expound upon the importance of focusing on the front end, the simultaneity of activities and the use of CAD/CAM technologies in the product introduction of low-volume products. Olsen and Sætre (2001) also highlight the role of visualising the product structure in developing and producing low-volume products. However, Maffin and Braiden (2001) and Surbier *et al.* (2009) indicate that the specific requirements of the product introduction process in low-volume manufacturing industries necessitate customised solutions and facilitators tailored to the requirements of such industries. As a result, an understanding of the characteristics of the product introduction process in low-volume production is necessary to develop such solutions.

Since only very few studies have focused on low-volume manufacturing industries (Surbier *et al.*, 2014), the available literature regarding the product introduction process in such industries is limited. Therefore, this study aims to understand how the characteristics of low-volume manufacturing industries influence the product introduction process and to identify the facilitators of the product introduction process in low-volume manufacturing industries.

4. Method

As a result of the lack of empirical studies regarding the characteristics of the product introduction process in low-volume manufacturing industries, a multiple-case study was selected as the research methodology. This method is appropriate for understanding the dynamics of the subject of the study. The first-hand study of the product introduction process in a low-volume manufacturing company is expected to lead to a deeper understanding of this process (Eisenhardt, 1989; Voss *et al.*, 2002). The process suggested by Eisenhardt (1989) for case study research was adapted in this study to achieve the paper's aim. In particular, the process consists of the following eight main steps: definition of the research aim, selecting cases, crafting protocols, entering the field, analysing data, extending theory, enfolding literature and reaching closure. These steps are briefly presented in this chapter.

The research questions were defined based on the studied literature and lack of studies regarding the product introduction process in low-volume manufacturing industries. The studied literature was searched for initially in peer-reviewed journal and conference articles written in English and published between 1997 and 2013. 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-referenced books, doctoral theses and older articles as well as a few Swedish articles. The main keywords and phrases searched included "industrialisation", "product introduction", "product development", "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 paper.

In the case selection step, to answer the research questions, two product development projects were selected from a company that is an international manufacturer of underground construction and mining machines. The company with over 1,200 employees is a large company which develops new products and implements required modifications in its production system to accommodate new products. The company was selected because it possessed the main characteristics of low-volume manufacturing industries as stated by Jina *et al.* (1997) which are low-annual production volume, high complexity and variety of the products and following full make-to-order production policy. In addition, mining and construction equipment manufacturing or as it is mentioned by Jina *et al.* (1997) "earth moving equipment" are one of the most common examples of low-volume manufacturing industries. The selected unit of analysis was the product introduction process. However, since the product introduction process is carried out in product development projects and the activities and the events of the product introduction process are defined in relation to product development (Johansen, 2005), the study was conducted in the context of two product development projects. Those two newly started product development projects are hereafter referred to as Cases A and B. The products were two of the most common underground construction machines produced by the company, and their low-annual production volume, high complexity and variety made them appropriate choices for this study. More details are provided in Section 5 regarding the characteristics of the products. The cases were selected to follow the product introduction process as part of the product development projects and to study its characteristics. The product development project in Case A was limited to the upgrade of one of the modules of the product; therefore, the project was considered small. However, that module consisted of several parts and components and also involved several interfaces with other modules of the product. The goal of the product development project in Case B was a general upgrade of the product, and it was consequently considered a large project by the company. Cases A and B were followed for 11 and 20 months, respectively, from October 2012 to September 2013 (Case A) and to April 2014 (Case B).

During the third step, multiple sources of data were utilised to gather qualitative data about the product introduction projects in the selected cases. One of the main sources of data consisted of 25 semi-structured face-to-face interviews with people who were involved in different phases of the product introduction process who performed different functions in the studied projects (see, Table III). In addition, five more reference interviews were conducted with people involved in other product development projects at the company to complete and validate the data gathered from the cases. The length of the interviews varied from 30 to 80 minutes. Interviews were not the only source of data and the derived conclusions were validated by triangulating the collected data from different sources (Yin, 2013). These sources of data included documents, weekly project meetings, observations of other events in the projects, informal daily conversations with members of the projects and project documents.

Respondent's position	Total number of respondents	Number of interviews (respondents) Case A	Number of interviews (respondents) Case B	Number of reference interviews (respondents)
Product introduction project leaders	4	2 (1)	3 (1)	2 (2)
Product introduction preparers	3	1 (1)	1 (1)	1 (1)
Production engineers	3	1 (1)	1 (1)	1 (1)
Product development project leaders	2	1 (1)	2 (1)	–
Production flow leaders	5	2 (2)	2 (2)	1 (1)
Assembly operators	2	1 (1)	1 (1)	–
Prototype development managers	2	1 (1)	1 (1)	–
Designers	2	1 (1)	1 (1)	–
Prototype assembly operators	2	1 (1)	1 (1)	–
Total	25	11	13	5

Table III.
Information about the interviews

One of the most important studied documents was a database that was used for registering and solving problems during production. Records of disturbances during the early stages of production of the products in this database were studied to understand the main sources of disturbances and their causes, and these are presented in Figure 2. More details about the cases are presented in Section 5.

The data collection and analysis were conducted iteratively in an overlapping manner to ensure that the necessary adjustments in the data collection process were considered. Field notes and a diary were used to review the collected data and implement the required data collection adjustments. Collected data from the cases were continuously recorded, summarised and transferred to a case study record. The qualitative data from the interviews and other sources were combined with the quantitative data about disturbances during the production to strengthen the validity of findings.

Following the fifth step of the Eisenhardt (1989) process, the gathered data from each case were coded and categorised separately to identify the causal relations and common patterns (within the case analysis). Then, the results from the cases were compared with one another to understand their similarities and differences regarding the causal relations and common patterns (cross-case analysis). Studying two cases helped with following the replication logic and to compare the confirming and disconfirming findings of the cases, as suggested in the sixth step of the process. To enhance confidence in the findings of the case studies, reference interviews were conducted with other experts at the company who were involved in other product development projects (Table III). Through these interviews, general data about other on-going product development projects and their characteristics were gathered to validate and complete the data collected from the case studies (Mills, 2010).

Finally to enfold the literature as directed by the seventh step of the research process, the findings were compared with the reviewed literature to understand similarities and differences with the existing research and extend it and reach the closure of the research process.

5. Empirical findings

All the results were observed in both cases unless otherwise indicated. Table IV summarises information about the cases.

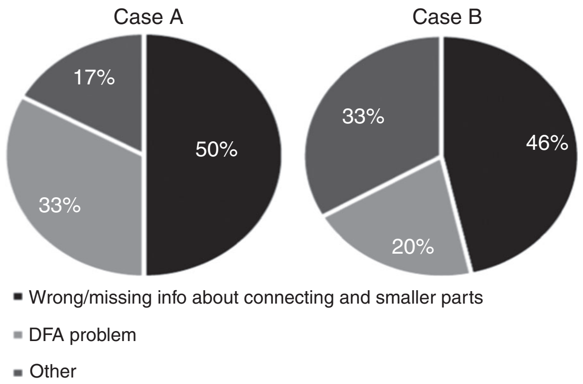


Figure 2.
Disturbances at the start of production of the products

5.1 General case information

The research was conducted at a Swedish company that designs and manufactures mining and underground construction machines for customers in different sectors of the international market. A wide range of products is offered by the company to satisfy the varied demands of its customers and markets depending on the requirements and regulations of these different markets. Products were manufactured in four main product families based on their functions and similarities in four different production lines. The operations on the lines were limited to the final assembly of the products. New products were designed to be manufactured in one of those production lines. During the study period, there were approximately 20 product development projects on-going in all four product families that had passed the product and production system development phase. The company utilised a matrix organisation to avoid the extra cost of assigning dedicated resources to each project.

Almost all the products including Products A and B were produced at annual production rates of less than 100 units. The products were highly customised to meet criteria such as customer demands and safety and environmental regulations in different markets. As a result, Products A and B were produced in seven and five different variants, respectively, and each variant included distinct options that made them highly variable. In addition, the products were complex and featured a high number of components and consequently many interfaces between components of the products, a high number of both product and component variants, and a variety of technologies used in the products, which implied different disciplinary complexity.

To avoid high-investment costs in dedicated assembly lines for several products, all the four assembly lines were designed to offer maximum flexibility to produce different products and accommodate new products. Eight and 12 different products and their variants were assembled in the assembly lines for Products A and B, respectively. The flexibility required to accommodate different products in the assembly lines was mainly provided by manual operations, using general purpose production equipment, highly skilled operators and relatively unrestrained assembly methods. Table IV summarises the characteristics of the products and the production systems of the studied cases.

The product development projects were managed by cross-functional teams consisting of a project leader and six sub-project managers from the design, prototyping, product introduction, purchase, marketing and aftermarket functions, who were responsible for the project tasks related to their respective departments.

Case name	Case A	Case B
Product characteristics		
Annual volume	<20	<30
Variety (excluding options)	5 variants	7 variants
Production system characteristics		
Cycle time (approximate)	96 hours	128 hours
Number of stations	6	4
Flexibility	Different products are produced at the same production line	
Automation level	Low, mainly manual	
Job rotation	No, jobs are allocated to the operators based on the required skills	
Equipment	General purpose	

Table IV. A summary of the characteristics of the products and production systems of the cases

These activities were basically followed according to a stage-gate model and a project manual that was a general and high-level description of the phases and activities of product development projects. The product introduction process was managed mainly by the product introduction managers according to a detailed operational guideline for product introduction activities that was developed by the product introduction department.

The product introduction department consisted of the department manager, product introduction project managers and production preparers, and it was established to facilitate the product introduction process of new product development projects. The product introduction project managers are responsible for planning, following up on, and controlling the product introduction activities in the product development projects. The production preparers' responsibility was developing the assembly sequence and instructions, identifying new parts and components of the products and introducing them to the production system by updating the bill of materials of products.

5.2 Product introduction process

The empirical findings from the case studies are presented in the following according to the different phases of the product introduction process.

Product and production system development. The aim of the product introduction process in both projects regarding the product were developing a modified versions of the existing products. In Project A the aim was to update one of the product modules to satisfy the requirements of a specific market whereas Project B was aimed to develop a generally modified version of an existing product. The complementary data gathered from the other on-going product development projects showed that none of the products were totally new and all of them were modified or upgraded version of the existing products. Furthermore, all of the new products were designed to be produced in the existing production lines.

Similarly, both of the products from the case studies were also to be produced in the existing assembly lines that also produce other products. As a result, the aim of the product introduction process in both projects was to apply the minimum number of changes to the assembly lines. In this regard, the products were to be tailored to the requirements and the limitations of the production systems. To understand these requirements, the expectations and limitations of production were gathered by the product introduction project managers and categorised and discussed with designers and with production personnel. These expectations covered issues such as unchanged connection interfaces of new components, assessing the DFA in product design, inclusion of assembly details in the drawings, reduction of the total number of components and avoiding late design changes.

Regardless of that, almost all of the focus in this phase was on the product and its functionality and very few evidences were observed about considering the inevitable changes in the production system and manufacturability of the products. Product introduction project managers coordinated regular design reviews with the participation of production engineers and operators and product designers. These sessions worked as a cooperation and communication mechanism to update the operators and production engineers about the critical changes in the product design. These changes and the product design were visualised through CAD models and also used for basic verification of product parts and components' fit. In few occasions some manufacturability-related issues were also discussed briefly.

Product test and refinement. To test and refine the design and functionality of the products, in addition to CAD models as basic virtual prototypes, only one physical engineering prototype of the modified module was developed in Case A, whereas two engineering prototypes were developed in Case B. These engineering prototypes were developed in the production systems mainly to verify the functionality of the products. To achieve that, the developed prototypes were tested at the factory as well as under real working conditions. 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 solving system was used during the later phases of the product introduction process. This problem-reporting database was utilised as a cooperation and communication tool, in addition to its use in design reviews. However, no indication of using the inputs from the introduction of similar products was observed in this phase.

In addition, to covering manufacturability issues of the products regarding the limitations and requirements of the assembly lines, one and two production operators were involved in Cases A and B, respectively. They helped with prototype development operators during the development of the prototypes with inputs regarding the existing equipment and abilities of the assembly lines. The production operators also helped the product introduction preparers to develop and modify the assembly sequences and instructions. However, this participation was limited because of resource allocation complexities between on-going production and several parallel on-going product development projects. Both the project team and production personnel believed that involvement of more production operators was necessary not only for refining the manufacturability of the product but also for training the production operators about the assembly of the new products. Because of the limited involvement of the production operators in prototype development and – as a consequence – in the development of the assembly instructions, and because of the limited number of prototypes, the opportunities for refining and improving the manufacturability of the products were similarly limited. The contributions of the production operators were mostly limited to their personal experience and opinions. In addition, there were no opportunities for optimising the assembly instructions as a critical part of the main production process. However, the assembly instructions from the previous versions of the products were mostly used as the reference for modification.

Pre-series production. Four first products produced in serial production were allocated to pre-series productions in Case B. However, based on the full make-to-order policy of the company and the high cost of the products, these four products were not produced until they were demanded by customers. As a result, the final verification of the product and production systems and their conformity was not assured because of considerable common deviations of real demands from the market estimations. Such a final verification was not considered at all in Case A as a small project.

The production of pre-series in Case B encountered many problems regarding both the product and the production system. There were major issues remaining in the product design, which had to be refined and led to late changes in the design of Product B. In addition, many problems surfaced during the production of pre-series that were mostly related to product manufacturability. These problems are described in greater detail in the "start of production" section. In addition to product-related problems, many issues occurred that were due to unprepared production systems and lack of consideration of limitations and requirements of the production system. These issues ranged from late delivery of new fixtures and tools and the difficulty of accommodating the production of pre-series in the on-going production plans to not considering the limitations of lifting and moving equipment.

Based on low-production volumes and non-continuous demand, it was not possible to plan a production ramp-up. Consequently, planning activities such as training of production personnel, final refinement of the product and the production system and adaptation, and reaching production goals (such as reducing the production cycle time) was also not feasible. As a result, many of these activities were moved to normal production or not implemented at all.

The findings from the start of production showed that many problems regarding manufacturability continued to occur in the production of the products. The recorded data from the start of production of both products (including the pre-series in Project B) were studied. These records only included problems and disturbances related to the products and their parts and components and did not cover the disturbances related to the production systems. A considerable part of the disturbances were related to the lack of information or incorrect information about connecting parts, such as nuts and bolts, cable sets and hydraulic hoses. In several instances, the information on the bill of material, drawings or assembly instructions did not match the product. Screws that were too long, tubes that were too short, or incompatible cable connections on the documents are examples of these problems. In some cases, no information was provided to the production about these parts and the operators had to find the parts by trial and error or based on experience alone. This type of disturbance was categorised under missing/wrong information about connecting parts.

There was another considerable type of disturbance related to assembling parts and components. On many occasions, the parts could not be assembled on the products because of non-conformity of interfaces, difficulty of accessing the place of the part on the product or the possibility of damaging other parts during assembly work. This category of disturbances was referred to as DFA problems.

Other types of disturbances ranged from functionality of the parts and components to incorrect or late delivery; these were categorised as other. Figure 2 shows the share of each type of disturbance in the studied projects. As Figure 2 shows, approximately half of the disturbances in both projects were caused by missing or incorrect information about connecting parts. The disturbances caused by DFA problems were also a considerable share of the total disturbances, at 20 and 33 per cent of the disturbances in Cases B and A, respectively. However, these shares were smaller in the large project.

In addition, many modifications were also required in the production system when products were handed over to the assembly lines. One of the most frequent and considerable modifications after the start of production was to refine the sequences and instructions of the assembly process which was the main production process.

6. Product introduction process in low-volume manufacturing industries

In contrast with the generic product introduction process which is suggested by Johansen (2005) and consists of five phases (see, Figure 1), the findings from the studied product development projects show that the product introduction process in low-volume manufacturing industries is typically limited to the initial three phases. Since low-volume products are costly and demand for them is limited, having many engineering prototypes and running several pilot production runs and pre-series productions is considered to be a luxury in low-volume manufacturing industries. The results show that the number of physical engineering prototypes is limited to two products. Further, pilot or pre-series productions are completely dependent on demands from customers and typically do not exceed more than a handful of products because of low-production volumes and the order-driven production policy of the company. The traditional ramp-up process is not feasible at all because demand is limited and in many cases non-continuous. Figure 3 shows the product introduction process in low-volume manufacturing industries, which contrasts with the general product introduction process presented in Figure 1.

As the gathered data from the cases and other on-going product development projects suggest, another characteristic of product introduction in low-volume manufacturing industries is that new products are typically modified versions of existing products. This is mainly due to high variety and the customisability of the products which is an order-winning criteria for low-volume manufacturing industries. A direct outcome of such variety in products is using a single flexible production system with slight modifications to produce different products to avoid high-investment costs in several production systems, as suggested by Qudrat-Ullah *et al.* (2012).

Moreover, the empirical data regarding high numbers of disturbances related to the design of manufacturing and small connecting parts suggest that designers' main focus remains on the functionality of the products rather than on their manufacturability. As the designers and even all project team members paid their attention to the functionality of the products, many details of the products such as information about the connecting parts and DFM/DFA issues were left to be finalised during the pre-series and final production. This finding is consistent with the findings in Vallhagen *et al.* (2013) that suggest that only the producibility of products is assured – and not their manufacturability – during the product introduction process in low-volume manufacturing industries. In addition, using shared human resources among several product development projects during the product introduction process as well as the on-going production is another characteristic observed in the studied cases. This resource sharing mainly undermines the involvement of production operators and engineers in the product introduction process, which intensifies overlooking the DFM criteria even more.

In the following, the influences of the above-mentioned characteristics on the different sources of disturbances during the product introduction process are discussed. In addition, possible ways to mitigate the negative consequences of such disturbances and to facilitate the product introduction process in low-volume manufacturing industries are briefly presented in the next section.

6.1 Product

Focusing more on the functionality and under-prioritising its manufacturability leads to handing over the product to production with insufficient or incorrect details, in addition to leading to difficulties during the assembly of the products, which can cause frequent disturbances in the early production stages. In addition, the lack of opportunities to refine

Note: The grey pattern represents limited implementation of the phase

Figure 3. The product introduction process in low-volume manufacturing industries

the product and remove bugs due to a limited number of engineering prototypes can lead to a lack of product maturity and late engineering changes. However, because the products in low-volume manufacturing industries are typically modified versions of previous products, these effects can be mitigated by using the experiences and information from the introduction of previously manufactured similar products.

6.2 Production system

The production system is typically modified slightly to produce new products in low-volume manufacturing industries. As it facilitates the product introduction process to avoid too many activities related to the production system design, in most of the cases it leads to considering the production system "as is". Thus, slight but necessary changes in the production system are typically considered during very late stages of the process or even later during normal production. This problem is intensified by the lack of opportunities to test and refine the production system based on the limited number of pre-series productions and the infeasibility of traditional production ramp-up. An important example of that in the studied cases was the lack of opportunities for developing and refining the assembly instructions.

6.3 Design-production interface (cooperation and communication)

Whereas development of prototypes, pilot production runs and pre-series production are critical for final refinement of the product and the production system and adapting them together (Johansen and Björklund, 2003; Lakemond *et al.*, 2007; Ruffles, 2000; Twigg, 2002), The lack of these opportunities in low-volume manufacturing industries makes the communication and cooperation between design and production even more important. However, based on the model presented by Almgren (1999a), the complexity of the introduction process – which is mainly related to the cooperation and communication between design and production – should generally be reduced in low-volume manufacturing industries mainly because of the reduced newness of product and production system in such industries. Since products are typically modified versions of existing products and the production system is typically slightly modified the degree of complexity of product introduction process should be reduced. The usual complexity level of the product introduction process in low-volume manufacturing industries is marked on Almgren's model of product introduction complexity in Figure 4.

As a result, the appropriate time for coordinating the verification of the manufacturability of the product and the conformity of the product and production system would be in the earlier phases of the product introduction process when the product is designed (Adler, 1995; Twigg, 2002). In addition, mutual adjustments would be an appropriate coordination mechanism for the product introduction process in low-volume manufacturing industries because the novelty of the process is mediated (Adler, 1995; Twigg, 2002). However, it is important to gather the information and experiences from similar previous projects and share such information with those involved in the introduction process of new products to ensure that the information is used during the process.

6.4 Quality

Lack of opportunities for refining the product and production system and adapting them together can result in quality issues arising at the start of production. However, this phenomenon should be investigated in more detail in future studies.

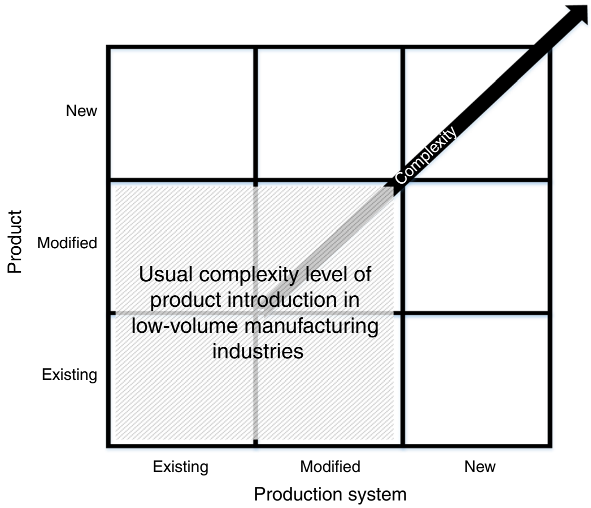


Figure 4. The typical complexity level of product introduction in low-volume manufacturing industries (the grey pattern) on the complexity model of Almgren (1999a)

6.5 Resource management

Shared resources among different product development projects and on-going production intensifies resource management problems. Involvement of production personnel and other production resources in the product introduction process is necessary, whereas in many cases, it is not easy to plan because of their involvement in the on-going production of other products.

6.6 Personnel

The traditional production ramp-up which has a critical role in the training of the production personnel (Terwiesch and Bohn, 2001) is not feasible during the product introduction process in low-volume manufacturing industries. Therefore, it is difficult to train production personnel to produce new products as one of the main activities during the production ramp-up. However, once again, the experiences and information from the production of similar products previously can be used to compensate for lack of training opportunities.

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

Many facilitators suggested in studies in the general and high-volume manufacturing context can also be applied to the product introduction process in low-volume manufacturing industries, such as front-end engineering (Cooper, 1994; Kim and Wilemon, 2002) and early involvement of production in the product introduction process (Adler, 1995; Lakemond *et al.*, 2007; Ruffles, 2000; Sharma, 2004; Woodcock *et al.*, 2000). Visualisation of design information and work instructions through CAD/CAM technologies (Gibson *et al.*, 2004; Malmsköld *et al.*, 2012; Ruffles, 2000; Kumar and Wellbrock, 2009; Olsen and Sætre, 2001) was another facilitator which was utilised in the projects. Particularly, during the test and refinement of the products and design reviews CAD models were used to partially compensate for lack of opportunities to develop physical prototypes and to communicate information about the new features of new products to the project teams as well as production personnel. Furthermore, design reviews as suggested by Adler (1995), Classen and Lopez (1998) and Olhager (2000) were conducted in the studied product development projects to facilitate the product introduction process. However, a high level of disturbances during the introduction of new products in the cases (despite the partial implementation of most of such facilitators) indicates that more customised solutions are required to facilitate the product introduction process in low-volume manufacturing industries as it suggested by Surbier *et al.* (2014) and Maffin and Braiden (2001). These customised solution are particularly needed to compensate for the lack of opportunities for testing and refinement and for a lack of sufficient human resources for product development projects.

The high number of disturbances related to incorrect or missing information about the connecting parts suggests that design details are neglected, under-prioritised or not communicated in the production. In addition, the large share of the DFA disturbances in the production of new products indicates that designers did not consider the limitations and requirements of production. In other words, both types of main disturbances indicate failure of communication and understanding between design and production about their requirements and limitations.

Lack of resources because of the involvement of project members in several projects and on-going production and lack of opportunities for testing and refinement were the main causes behind this communication and understanding challenge. However, one main (potential) way of overcoming this challenge was neglected in the studied cases. Both products in both cases were modified versions of existing products and their production was planned in existing production lines, which meant that potentially the main part of the disturbances related to the DFA problems and lack of design details might have been avoided by utilising the information and experiences from the introduction of previous similar products. However, the similar patterns of occurrence of disturbances in both cases – in addition to the information gathered from the reference interviews – suggests that there was no formal way of communicating and using the information and experiences from the introduction of previous similar products established either in production or in design. As a result, a process should be established to continuously gather the inputs from designers and production personnel about their experiences and information based on on-going product introductions. These inputs should cover but not necessarily be limited to the disturbances both in design and production, the sources of such disturbances, and the possible solutions to such disturbances. An example of this type of mechanism is the database of the product-related disturbances that was used in this study. The accumulated information should be analysed, categorised and fed back to design and production as an input for similar later projects to be used as a compensation for the lack of opportunities to test and refine the product and production system and to adapt them together. Figure 5 represents the suggested process for gathering, sharing and using information and experiences from the introduction of new products. The suggested process facilitates the product introduction process in low-volume manufacturing industries by benefiting from the potential of reduced complexity of the product introduction process (Figure 4) in these industries. Collecting, sharing and using the information about disturbances of introduction of previous similar products helps low-volume manufacturing industries to avoid repetition of similar disturbances during the introduction of new version of similar products by identification and removing the sources of disturbances.

The entire process can be coordinated and facilitated by product introduction project managers. As the empirical findings show, product introduction project managers were successful at implementing basic examples of this type of coordination

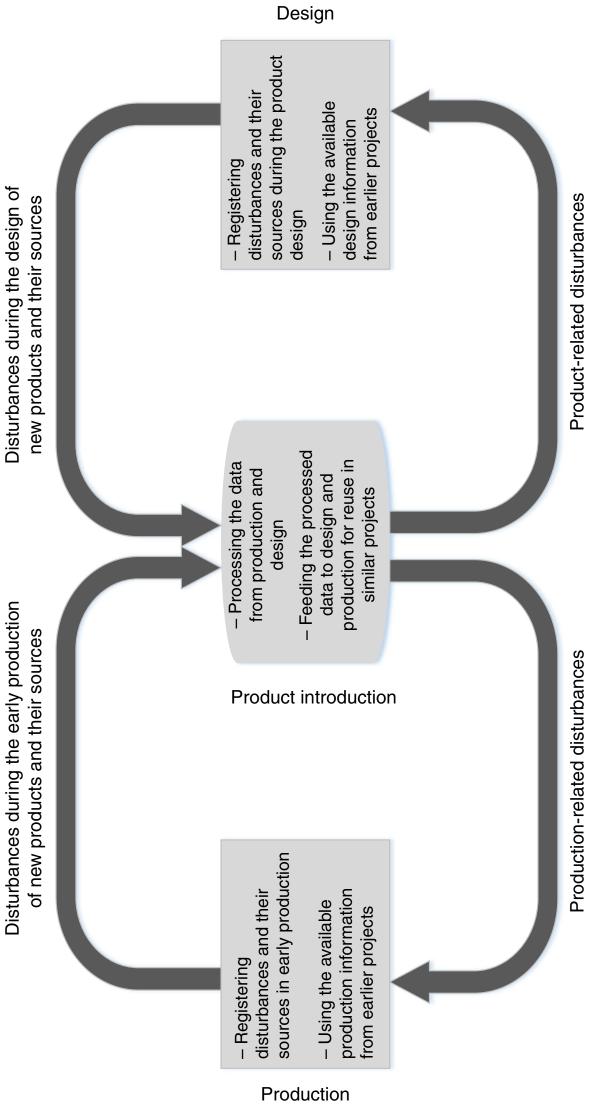


Figure 5.
The basic process to gather, share and use the information and experiences from introduction of similar products to improve the product introduction process

in the studied cases, such as by gathering and transferring the production expectations to the designers and coordinating design reviews. The role of the product introduction project manager as the coordinator of the process might also partially compensate for the lack of human resources both in production and design, which is essential for low-volume manufacturing industries.

In addition to the suggested process, other facilitators might be applied to improve the product introduction process in low-volume manufacturing industries. Since a large source of disturbances involved missing or incorrect information about connecting parts, a final design review that is focused on design details regarding the connecting parts should be included in the product introduction process – preferably with the involvement of production personnel. This final review of design details as an approval gate in the product introduction process can ensure that the information about all parts, including connecting parts, exists and that the information is correct before handing over new products to production. Once again, the information from similar previous products can be useful in this design reviews.

Another facilitating method for the product introduction process in low-volume manufacturing process is the training of the designers regarding a production system's capabilities, requirements and limitations. Since production systems are only slightly modified for the production of new products, their capabilities and limitations remain almost the same. As a result, a general training for the designers, e.g., working with production operators in the production lines for short periods of time, helps them to learn the capabilities and limitations of the production system and to consider them in the design of new products. This method leads to fewer DFA problems during the introduction of new products and can partially compensate for the insufficient involvement of production personnel in the product introduction process.

8. Conclusions

This paper addressed the influences of the characteristics of low-volume manufacturing industries on the product introduction process and its facilitators. In this regard, first, this paper provided a general definition for the product introduction process based on the current literature. Regarding the research questions of the paper, we identified the influences of the characteristics of low-volume manufacturing industries on the product introduction process through a literature study and a multiple-case study. These influences were mainly studied based on the sources of disturbances in the product introduction process. Finally, some facilitating factors for the product introduction process in low-volume manufacturing industries were introduced based on the empirical findings. In this regard, the paper contributes to the current literature by adding knowledge about the characteristics of the product introduction process and its facilitators in low-volume manufacturing industries.

The main identified influences of the characteristics of low-volume manufacturing on the product introduction process in low-volume manufacturing industries include the following:

- low number of prototypes;
- absence of conventional production ramp-up;
- reduced complexity of the product introduction process resulting from the low newness of product and production system;

- lack of considering manufacturability of the products because of extensive focus on the functionality of the products; and
- increased complexity of resource allocation because of involvement of the production personnel and other project members in the on-going production activities and other projects.

In addition, a process for collecting, sharing and using the information and experiences from introduction of previous similar products was suggested to facilitate the product introduction process by using the potential reduced complexity of the product introduction process in low-volume manufacturing industries. The suggested process helps to avoid repetition of similar disturbances during the introduction of new products and to compensate for lack of opportunities for test and refinement of new products in low-volume manufacturing industries. Furthermore, the following additional facilitators of the product introduction process in low-volume manufacturing industries were identified:

- including a dedicated product introduction project manager in the product development project teams;
- a final design review with focus on design details and manufacturability of products; and
- training the designers about the capabilities and limitation of production systems.

This paper provides the practitioners in low-volume manufacturing industries with insights regarding the influences of the characteristics of low-volume manufacturing industries on the product introduction process. It also contributes to the identification of common disturbances during the product introduction process in low-volume manufacturing industries and offers some solutions to mitigate these disturbances. The heightened importance of using the production of previous similar products as a source of learning and as compensation for the lack of opportunities to test and refine products and production systems in the introduction of similar new products was discussed as a possible facilitator.

A limitation of this study is that the identified characteristics and facilitating factors are confined to the internal variables of the studied company. A study of the role of external variables during the product introduction process – such as suppliers and customers – might be the subject of future studies. In addition, the suggested process for transferring information and experience from the introduction of previous products should be developed in greater detail, particularly with regard to the content of the information and experience transfer between different functions. Another possibility for future research is to investigate alternative methods for production operators' training to compensate for the lack of opportunities for training in low-volume manufacturing industries. Furthermore, since both of the cases were studied at the same company, conducting similar studies in other low-volume manufacturing companies – preferably in other sectors – can help to validate the results of this research and to extend its findings by comparing the results of different cases from different companies and sectors. Moreover, investigating the role of cross-project information transfer in improving the product introduction process in low-volume manufacturing industries can be studied in future research.

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