PRODUCT DEVELOPMENT IN LOW-VOLUME MANUFACTURING INDUSTRIES: CHARACTERISTICS AND INFLUENCING FACTORS

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Abstract
Product development process has a considerable effect on factors such as time to market and quality of product which are vital for manufacturing companies to remain competitive. Therefore, study of the factors which influence the product development process such as characteristics of products and production systems is necessary to support and improve the product development process. Since most of the studies have been conducted in the context of high-volume manufacturing industries, the influences of characteristics of low-volume products and production systems on the product development process in such industries have not been considered sufficiently. In this paper, characteristics of low-volume products and production systems, their inter-relations and their influences on the product development process have been studied through a multiple case study. A general map of characteristics of low-volume products and production systems and their inter-relations was presented in this paper. Moreover, the influences of these characteristics on product development process including the reduced complexity of the process and lack of opportunities for test and refinement were discussed.

Keywords: New product development, product introduction, low-volume, production preparation

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1 INTRODUCTION

Developing new products in a shorter time with a high quality is a necessary competence for manufacturing companies to remain competitive in the globalized market with ever-decreasing product life cycles and increasing pace of emergence of new technologies. As a result, identification of different factors which influence the product development (PD) process and improvement of the process is receiving increasing attention among the researchers. During the PD process, the transition from concept development to the production and distribution is done by product and production system development (Johansen 2005) and is finalized during the product introduction (PI) process. PI process is the closing sub-process of the PD process and its main goal is to test and refine product and production system, adapt them together and reach the intended production goals. Therefore, the characteristics of product and production system have a highly considerable influence on the PD process and PI process (Almgren 1999a, Cooper 2003, Lakemond et al. 2007). In this regard, identification of these characteristics in different industries provides a better understanding of the PD process and its requirements.

Different factors which influence the PD and PI process has been studied mostly in the context of high-volume manufacturing industries (Surbier et al. 2013). Since the low-volume manufacturing industries have their own characteristics and requirements, customized solutions are required for improvement of the PD process in such industries (Maffin and Braiden 2001, Surbier et al. 2013). As a result, identifications of factors which influence PD process and its sub-processes such as PI process is necessary for further improvement of the PD process in low-volume industries.

Therefore, the purpose of this paper is to identify the characteristics of products and production systems in the context of low-volume manufacturing industries, their inter-relations and their influence on the PD process. The study is mainly based on an embedded multiple-case study in combination with a literature study. The research is mainly focused on the design-manufacturing interface and does not cover external factors such as issues related to customers or suppliers. The paper continues with a brief review of frame of reference, the research methodology and the empirical findings. Discussion section follows the empirical findings and conclusions of the paper are presented in the last section.

2 FRAME OF REFERENCE

2.1 Product development process

Product development process, also known as product realization process (Johansen 2005, Magrab et al. 2009), as it is defined by Ulrich and Eppinger (2012 p.12) “is the sequence of steps or activities that an enterprise employs to conceive, design and commercialize a product” or more briefly “is the process by which an organization uses its resources and capabilities to create a new product or improve an existing one” (Cooper 2003). Different processes have been proposed to support PD. An earlier example is the 5-stage integrated PD process suggested by Andreasen and Hein (1987) which consists of investigation of need, product principle, product design production preparation and execution phases and covers them in the domains of marketing, design and manufacturing. The later examples are the integrated product and process design and development by Magrab et al. (2009) and the integrated PD process by Prasad (1996). Another more recent example and one of the most recognized ones in the literature is the PD process developed by Ulrich and Eppinger (2012). The process has six stages which are planning, concept development, system level design, detail design, testing and refinement and production ramp-up and covers the activities of marketing, design and manufacturing functions during these phases.

Regardless of differences of the various PD processes, almost all of them share a similar characteristics which are considering parallel and, if it is possible, integrated development of product and production system and early involvement of different functions in the process through multidisciplinary teams and continuous communication. These characteristics help to avoid consequences such as late and costly changes in product and production system, disturbances during early production and decreased product quality (Almgren 1999b, Bellgran and Säfsten 2010, Johansen and Björkman 2002). In this paper, the product design and development process developed by Ulrich and Eppinger (2012) is mainly referred as the general PD process due to its generality and recognition in the literature.

Several factors affect the PD process which are summarized by Cooper (2003) as production process and technology, product characteristics, project structure and team, organizational context and external environment. Among these factors, characteristics of product and production systems have considerable influences on the PD process and PI as its closing sub-process (Clark and Wheelwright 1992, Johansen 2005).

Most of the activities of the PI process are covered during the last three phases of the PD process which are briefly described in Table 1. These activities mainly support the detail design of the production system and test and refinement of product and production system through developing and testing prototypes. Engineering prototypes are usually developed outside of the production system to test the functionality and performance of the product (Johansen 2005, Ruffles 2000, Ulrich and Eppinger 2012). Factory prototypes or pilot productions are aimed to test and refine the production system and assure the conformity between the product and the production system (Johansen 2005, Ruffles 2000, Twigg 2002). Therefore, these prototypes are manufactured in the production system and the products are often sold to the customers (Berg et al. 2005, Ulrich and Eppinger 2012).

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

Table 1. Main PI activities in PD process, based on Bellgran and Säfsten (2010) and Ulrich and Eppinger (2012)

Phase	Detail design	Testing and refinement	Production ramp-up
Activities	Detail and parallel design of product and production system including • Defining parts geometry and specifications • Defining production and assembly processes and designing the required tooling • Ordering long-lead tooling	• Test overall performance, reliability and durability of product by developing alpha/engineering prototypes and implement necessary design changes • Test and refine production and assembly processes as well as product and production system fit by developing beta/factory prototypes or pilot production	• Reaching the production goals such as intended cycle time, capacity and quality • Training the workforce • Eliminating remaining problems in the production system

In general, Almgren (1999a) discusses that the newness of the product and the production system increases the complexity of the PD process as well as the PI process. In addition to the novelty of product and production system, Lakemond et al. (2007) suggest that the complexity and the degree of change of the product and the production system as critical characteristics which affect the PD process. Weber (2005) summarizes different aspects of complexity into number of components, number of interdependencies between components, number of variants and number of disciplines involved in the product/production system.

Regarding the influence of mentioned characteristics of product and production system on PD process, identification of those characteristics in low-volume manufacturing industries is necessary to understand and support the PD process in such industries.

2.2 Products, production systems and PD in low-volume manufacturing industries

Jina et al. (1997) define the low-volume production rate between 20 to 500 units per year to distinguish it from high-volume and engineer-to-order production. In addition, three other main characteristics for low-volume products are named in the literature which are high complexity, high variety and high cost of products (Jina et al. 1997, Qudrat-Ullah et al. 2012, Mohamed and Khan 2012). Hill (2000) states that low-volume products are customized rather than special or standard as they are in respectively engineer-to-order and high-volume production. It means that products are customized to the needs of different customers but the production rate is not limited to one product as engineer–to-order products or as high as high-volume products.

The production systems of low-volume manufacturing industries are usually characterized by flexibility (Mohamed and Khan 2012). Providing such flexibility requires highly skilled workers (Mohamed and Khan 2012, Bellgran and Aresu 2003), universal production equipment (Rahim and Baksh 2003, Hill 2000), 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 the 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 can also be the appropriate process choice for 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 Laudański 2008).

Although the frequency of PD and PI is higher in low-volume manufacturing industries due to variety of products (Rahim and Baksh 2003), the literature about the PD process and its sub-processes such as PI in low-volume manufacturing industries is very limited (Surbier et al. 2013, Maginness et al. 2014). As Qudrat-Ullah et al. (2012) state, new production systems are rarely developed for manufacturing new products. Instead, new products are designed to be manufactured in the existing production systems. In addition, the focus of product designers in low-volume manufacturing industries is on producibility rather than manufacturability (Vallhagen et al. 2013). In other words, product functions, characteristics and performance are considered much more than production optimization and conventional design for manufacturability criteria due to less product maturity in low-volume manufacturing industries compared to high-volume ones (Vallhagen et al. 2013). Although application of some common supporting methods and tools of PD have been done in low-volume manufacturing context such as lean PD (Qudrat-Ullah et al. 2012) and DFM/DFA (Gauthier et al. 2000, Stauffer and Smith 2005, Andersson et al. 2014, Vallhagen et al. 2013), the literature is still very limited and many of those studies are not concentrated on the requirements of low-volume manufacturing industries. Since customized solutions are required to tailor the conventional PD and PI processes to the requirement of low-volume manufacturing industries (Maffin and Braiden 2001, Surbier et al. 2013), identification of influences of characteristics of low-volume products and production systems on the PD process is critical to develop such solutions.

3 METHOD

Due to lack of empirical studies about the influences of the characteristics of low-volume product and production systems on the PD process, case study was selected as the research method. Case study is an appropriate method to understand the dynamics of the study subject. The first hand study of the PD process in a low-volume manufacturing company is expected to lead to increased understanding of the influences of the characteristics of low-volume products and productions system on the PD process (Eisenhardt 1989, Voss et al. 2002). Therefore, an embedded multiple-case study design was selected to achieve the aim of this research.

Two PD projects were selected as the main cases and they were studied in the context of an international company which manufactures underground construction and mining machines. Each case contains two embedded units of analysis which were the related product and production system of each project. The purpose of this design was to study the characteristics of products, production systems and PD process in low-volume context and to understand their inter-relations and their influences on each other. The projects and products are referred hereafter as Project A and B.

Project A and B were followed up for respectively 11 and 14 months from October 2012 to respectively September and December 2013. Multiple sources were utilized for data gathering including semi-structured interviews, document studies and observations. Informal conversations were

also carried out mostly to complete the data about the background of the company and projects and other required data.
29 semi-structured face-to-face interviews were conducted with the team members of the projects as well as the production engineers, production flow leaders and operators. Time of the interviews varied between 30 to 80 minutes. Interviews were not the only source of data and the deducted conclusions are validated through triangulating the collected data from different sources (Yin 2013). Documents such as the data base for disturbances during the production and documents related to the products, production system and projects, emails and informal communications, direct observations from events of the projects such as the project meetings and design reviews were other sources of information in the case study. In addition, some retrospective data from similar products and PD projects was gathered to avoid misunderstandings related to the special characteristics of the studied products and projects. Collected data from the cases was continuously recorded, summarized and transferred to a case study record and iteratively analysed. The suggested process by (Eisenhardt 1989) was utilized for analysing the data by conducting within and then cross-case analyses and a comparison with the studied literature.
The studied literature were searched initially among peer reviewed journal and conference articles written in English and published between years 1999 to 2014. Scopus, Web of Science and Google scholar were used as the main data bases and search engines to retrieve articles. The search was later extended to the most referred books, doctoral thesis and older articles. The main keywords for searching was product development, product realization and product introduction in combination with low-volume, small volume, make-to order and aerospace product/production/manufacturing to cover the focal point of the paper.

4 RESULTS

The empirical findings are described briefly in the following order. First the company as the main context is described, then the two PD projects are presented and finally characteristics of products and production system as the embedded units of analysis are briefly discussed.

4.1 The company

The research was conducted in a Swedish company which was a leading brand in design and manufacturing of mining and underground construction machines in the international market. It offered a wide range of products to meet different needs and requirements of different customers and markets. Products of the company were divided into four main product families according to their functions and similarities. Each product family was manufactured in a separate production line and the operations in the production lines were limited to the final assembly of the products. During the study period, there were around 20 ongoing PD projects in all four product families which had passed the concept development phase. As a result, the company utilized a matrix organization to fulfil the required resources of all projects and to avoid the extra costs of having dedicated teams for each project regarding the low production volumes of the products.

4.2 PD projects

Both studied projects were led by multidisciplinary teams consisted of different team members from different functions including project management, design and prototyping, purchasing, aftermarket, production and PI project leaders. The goal of both projects were to develop modified versions of existing products. The goal of Project A was upgrading one of the modules of the product in order to respond to the demand of a specific market. General upgrade of a product to meet the new environmental legislations of the European market was the aim of Project B. As a result, Project B had a larger scope and was considered as a large project by the company whereas Project A was considered as a small project.
Due to high costs and low demand for the products, no prototypes were planned for Project A and in Project B one prototype was planned which could be followed by three factory prototypes depending on the demand for the product. However, only one prototype was developed until the end of this study due to lack of demand for product B. The empirical findings indicated that including more prototypes in the projects were more desirable to refine the products, adapt them to the production system and reduce the disturbances during the production. However, they were not affordable because of high cost

of products and low demand for them. Instead, the project teams utilized other tools and methods to avoid leaving the errors and non-conformities to the production. Some of these tools and methods were design reviews and front-loading by early involvement of different functions including production and PI project leaders. During the design reviews, changes and new features of products were discussed with the production engineers and production flow managers to understand the requirements of the production system. However, the discussions were mostly limited to the possible solutions for production of the new features.

In addition, interviews with respondents from production and retrospective study of the records of disturbances during early production of two similar products indicated that many of such disturbances related to non-conformity of the products to the production system capabilities and unawareness about required changes in the production system. As the interviews and the studied documents suggested, these kind of disturbances were common in different projects and start of production of different products.

In general, two main types of disturbances constituted a considerable part of disturbance during the start of production of the products. The first type was difficulties related to the assembling of the products. Products could not be assembled easily because of difficulties to access the components, non-conformity of the components together or missing or wrong information about connecting parts such as nuts and bolts, hoses and cables. The other common type of disturbance was insufficient or late consideration of the required changes in the assembly lines. The examples of these disturbances were non-conformity of the products with available production equipment such as lifting tools and late delivery of new fixtures and tools. Furthermore, assembly instructions as a new part of production system were not completed neither optimized and they were improved during assembling first products.

4.3 The Products

The yearly production volumes were under 100 units per year. They were highly customized to satisfy different criteria such as customer demands and safety and environmental legislations of different markets. As a result, there were seven and five variants of respectively Product A and B in addition to many options available for each variant which made them highly variable. The products also were complex regarding high number of components and consequently many interfaces between the components of the products, high number of both product and component variants, and different technologies used in the products which implied different disciplinary complexity.

4.4 The Production systems

Since investing in establishing dedicated assembly lines for each product were not feasible due to high variety of products and low yearly production rate of them, four different flexible assembly lines were utilized 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, a total of seven products and their variants were assembled and for product B, 12 products and their variants. To keep the assembly lines as flexible as possible to be capable of handling different products and adopting new ones, the assembly work was almost totally done manually and the tools and equipment in the lines were mostly universal. The alterations in the assembly lines for changing from one product to another was limited to the minor adjustments such as change of fixtures. In addition, the manual work in combination with the complexity and variety of products demanded a high level of skill from operators. Since the assembly of the products consisted of high work content and took over 400 man-hours, a line setting was selected despite the low quantity of the products. The assembly lines for Product A and B were consisted of respectively four and six work station with averagely four operators in each station. The number of operators in the stations were variable to maintain the flexibility on capacity of the lines. Since the demands were low for products and the cost of products were high, a full make-to-order production planning policy was followed in both lines to avoid high costs of tied-up capital related to storage of costly products.

5 DISCUSSION

In line with Hill (2000), Mohamed and Khan (2012) and Qudrat-Ullah et al. (2012), the findings suggest that the characteristics of the production system in low-volume manufacturing industries is directly influenced by the characteristics of the products. The production system should be as flexible as possible to be able to manufacture different products. Such flexibility is necessary to avoid high investments in new production systems for several different products and their variants with low production volumes. Embedding flexibility in production systems without costly investments usually implies characteristics such as using universal production equipment, high level of manual work, high demand on operators' skills and sharing the resources among production of different products. In addition, the low demand for each product and high cost of the products impose full make-to-order production planning policy to the low-volume manufacturing companies. Figure 1 shows the main characteristics of low-volume products and the characteristics which are imposed to the low-volume production systems by the characteristics of the products.

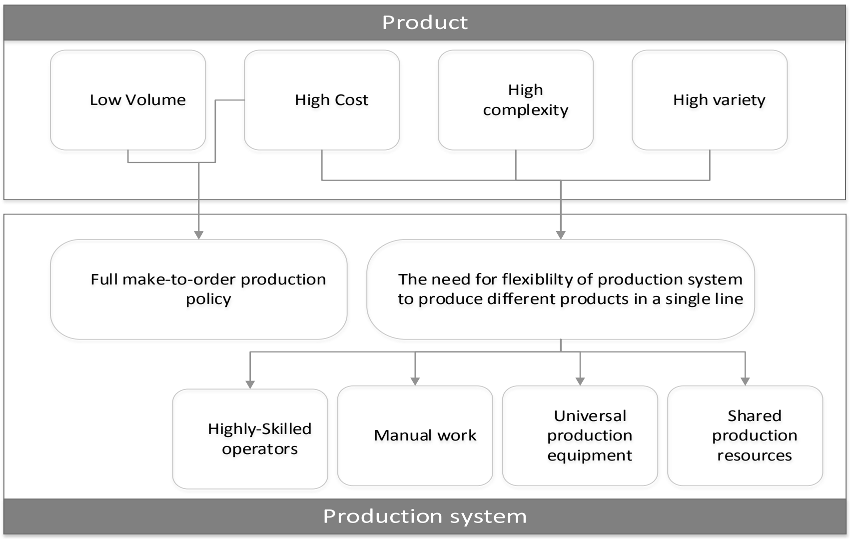

Figure 1. characteristics of low-volume products and production systems and their inter-relations

The combination of the product and production system characteristics in low-volume manufacturing industries, have some consequences which affect the PD process. Figure 2 shows the summary of these consequences. First of all, the make-to-order production policy which is a result of low production volume and high cost of products does not allow to develop high number of prototypes during the test and refinement phase. It also implies that due to discontinuous and low demand for the products, the production ramp-up phase cannot be carried out in the conventional way. As a result, the implementation of the two last phases of PD model of Ulrich and Eppinger (2012) face serious challenges in low-volume manufacturing. Therefore, many activities related to the PI process as one of the key sub-processes of PD such as test and refinement of product and production system, adjusting them together and training the workforces cannot be accomplished. Compensation of absence of these activities requires alternative solutions for low-volume manufacturing industries to secure the quality and lead-time of the development of the product and the production system.

Another implication of manufacturing different products in a single production line is tailoring new products into the limitations of the existing production lines. It means that despite high level of flexibility of the production system, design for manufacturing/assembly criteria should include extra factors such as considering the limitations of existing manufacturing equipment and tools.

The wide variety of products and tailoring them to the requirements of different customers causes high frequency of PI whereas limited production volumes does not allow the use of dedicated resources for each project. As a result, a matrix organizational model is used to share the resources between different projects as well as ongoing production activities. Although it helps to avoid extra costs for using dedicated resources for each project, it implies some disadvantages such as problems in prioritizing the activities and providing enough resources for the different priorities.

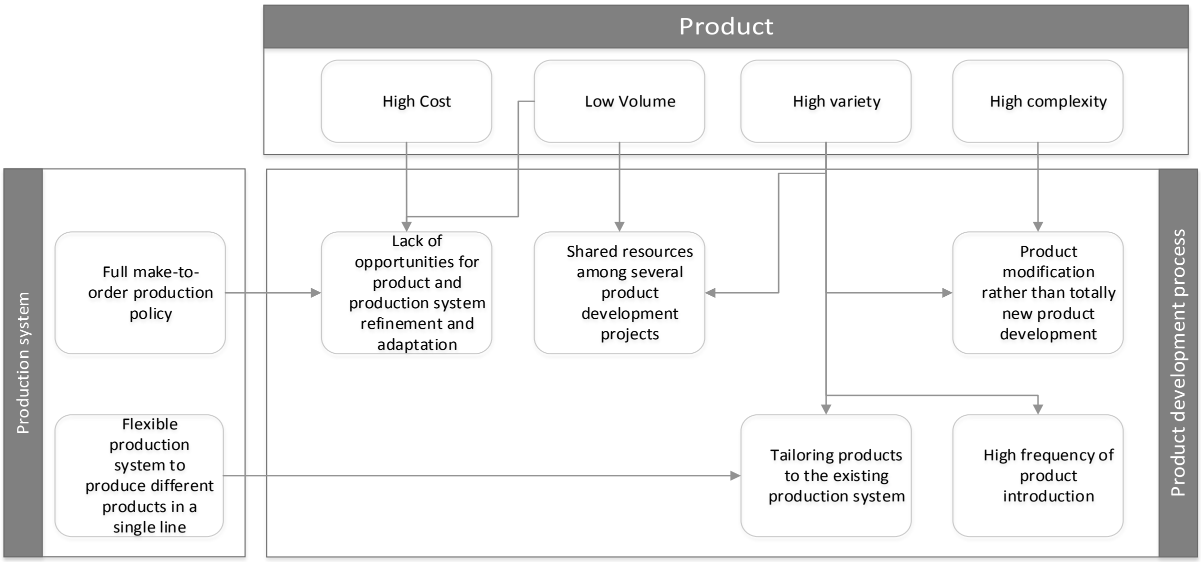

Figure 2. Influences of characteristics of low-volume products and production systems on PD process

In addition to the above mentioned challenges, the PD process in low-volume manufacturing industries benefits from some advantages caused by the characteristics of products and production systems in such industries. On the one hand, the high complexity of the low-volume products and the high level of customization generally leads to modification of existing products rather than developing totally new products. On the other hand, using the existing production systems to manufacture new products almost eliminate the need to develop new production processes. The reduced novelty and low degree of change of product and production system result in considerable decrease of complexity of the PI process and consequently, the PD process (Almgren 1999a, Lakemond et al. 2007). Figure 3 shows the usual complexity of PD and PI in low-volume manufacturing industries.

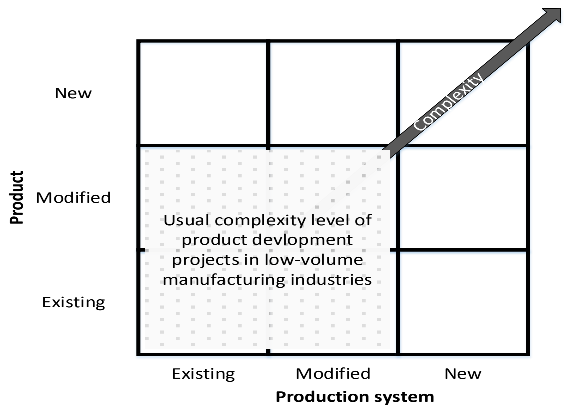

Figure 3. Complexity level of PD and PI in low-volume manufacturing industries, based on Almgren (1999a)

According to the results, only complete implementation of first four phases of generic PD process is usually possible in the low-volume manufacturing industries. Figure 4 compares the generic PD process with the PD process in low-volume manufacturing industries. The testing and refinement phase is limited due to limited number of prototypes and the low and discontinuous demand for the products. Production ramp-up is not feasible either because of similar reasons which reduces the opportunities for finalizing the production system refinement and training the workforce. As a results many activities and goals of the PI process cannot be accomplished. However, part of these challenges can be mitigated by the reduced complexity of new PI. All in all, the results of the study justifies the need for customizing design-manufacturing relation according to the characteristics of low-volume manufacturing industries and the above-mentioned differences of PD process in such industries in comparison with high-volume manufacturing industries.

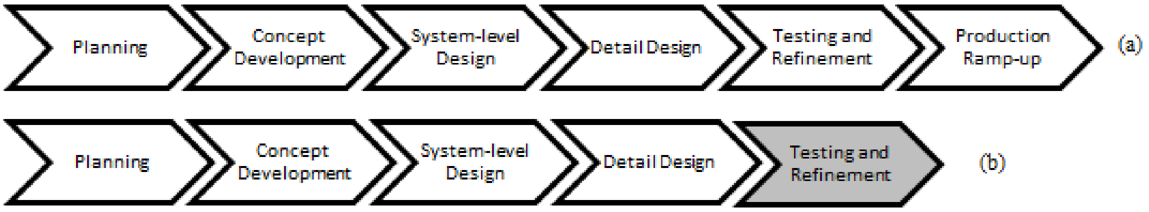

Figure 4. PD process in low-volume manufacturing industries (b) in comparison with generic PD process (a) based on Ulrich and Eppinger (2012). Testing and refinement phase is limited (marked with grey colour) and production ramp-up phase usually is not feasible.

6 CONCLUSIONS

The paper provided a general map of characteristics of low-volume product, production systems, PD process and their inter-relations through an embedded multiple-case study in combination with a brief literature review. The influences of characteristics of product and production system on the PD process in low-volume manufacturing industries were presented. The PD process in low-volume manufacturing industries is characterized by the reduced complexity of PD which is a result of low novelty and low degree of change in product and production systems in PD projects in such industries. The second major characteristic is lack of opportunities for test and refinement of product and production system and absence of conventional production ramp-up which is caused by low production volumes, high cost of the products and full make-to-order production policy.

This study is an opening to further study of characteristics, requirements and facilitators of the PD and PI process in low-volume manufacturing industries. An interesting area for further research on facilitating PD and PI processes in low-volume manufacturing industries is the knowledge transfer from production of earlier products to the PD projects. This knowledge transfer flow can compensate for the lack of trial and error opportunities during the PD projects in low-volume manufacturing industries. Furthermore, influence of other factors besides product and production system characteristics on the PD process in low-volume manufacturing industries should be studied. Also external factors such as suppliers and customers can be covered in the future research.

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