Supporting the development of a HMLV production cell

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ABSTRACT

Production system development is challenging for manufacturing companies, and development of HMLV production cells entails additional challenges. Thus, the aim of this study is to support the development of a HMLV production cell, and the following research questions were asked:

RQ1: *What are the challenges of developing a HMLV production cell?*
RQ2: *What are the critical factors to consider when developing a HMLV production cell?*
RQ3: *How can the development of a HMLV production cell be supported?*

A literature review in combination with a case study were performed to fulfill the aim and answer the research questions. The literature review was conducted to gain knowledge from previous studies, whilst the case study was performed to complement the theoretical findings. The selected case is the development of a HMLV production cell in the department of engine machining at Scania, which is planned to perform production activities for various departments of Scania. The primary data was collected through observations and interviews.

The identified challenges of developing a HMLV production cell were production planning, utilization of equipment, product quality and material flow. The identified critical factors to consider when developing a HMLV production cell were production flexibility, production competence, production technology, pilot production, manufacturing strategy, order management system and standardization. The identified challenges of developing a HMLV production cell and the critical factors to consider when developing a HMLV production cell can support manufacturing companies by informing what challenges to expect prior to developing a HMLV production cell, and what critical factors can mitigate these challenges.

Two ways of supporting the development of a HMLV production cell are recommended to Scania: creating a structured order management system and performing a pilot production for the milling operation of the core box reparation process. During this study, it was discovered that different HMLV production cells have different capabilities, challenges, and therefore also different critical factors. As such, a recommendation for further research is to investigate how the development of different types of HMLV production cells can be supported by using a multiple case study research design, and to compare the challenges and critical factors for the development for the different types of HMLV production cells.

Keywords: Manufacturing industry, High mix low volume, Case study, Production system development, Critical factors, Challenges

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Thank you for taking the time to read our thesis!

Violet Mohammadpour
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ABBREVIATIONS

DM	Department of engine machining at Scania
DF	Department of foundry
HMLV	High mix, low volume

1. INTRODUCTION

In this section, the background is initially described, followed by the problem formulation, aim and research questions. Lastly, the project scope is presented.

1.1. BACKGROUND

Manufacturing companies are highly pressured by increasing competitiveness, it is hence of importance for companies to understand how to develop production systems effectively to gain a competitive advantage (Bellgran & Säfsten, 2010; Singh, et al., 2005). Furthermore, manufacturing companies are required to continuously develop and improve their production systems to become the best in their respective market (Modig & Åhlström, 2011). Production systems have a significant impact on manufacturing capabilities and performance, it is hence essential to achieve successful production system development (Bruch & Rösiö, 2015). Production system development is performed to e.g., increase system throughput, efficiency, and quality, as these features are achieved through better designed production systems (Bellgran & Säfsten, 2010). During development of production systems, it is essential to have a holistic perspective, both regarding humans and technology. Furthermore, for successful production system development to be performed, it is essential that companies identify, explore, and plan developments with the motive to improve their production operations and production systems (Bellgran & Säfsten, 2010).

Customer demands are changing rapidly, and manufacturing companies must be able to handle the increasing variety of products. Additionally, products are increasing in complexity and customers require higher levels of customization, which hence require the manufacturing companies to increase the flexibility of their production systems (Thomas, et al., 2012; Dombrowski, et al., 2016). As the traditional production lines with a constant flow have limitations concerning flexibility, traditional production lines might not be sufficient in the future with the increased demand on customization (Ren, et al., 2018). However, the flexibility of manufacturing can be increased through using High-Mix, Low-Volume (HMLV) production cells, which are designed to manufacture a wide variety of products with small lot sizes to maximize production flexibility (Irani, 2011; Kocsi, et al., 2020). HMLV production can hence add flexibility to manufacturing, increase customizability of products and perform other production activities such as repairing defected products (Lane, 2020). Additionally, HMLV production cells can help avoid disturbances in the main production flow and avoid high-investment costs otherwise necessary to develop or alter existing production systems (Qudrat-Ullah, et al., 2012).

For productive HMLV production cells, it is essential to manage a high variety of production operations and activities, and the choice of equipment and machinery is therefore critical (Becker, et al., 2015). Generally, a requirement for HMLV production is to maintain flexibility in the equipment (Bengtsson, 2017), whilst maintaining high productivity and utilization, as these performance indicators are directly correlated with profitability (Svancara & Kralova, 2012). Therefore, it is especially important to minimize set-up times in HMLV production, to increase productivity and the company's competitiveness (Andersson, et al., 2015; Singh, et al., 2013). However, HMLV production cells generally cannot be optimized for specific production activities, as the flexibility of equipment needs to be sustained to allow different production activities to be performed (Guan, et al., 2008), which can create difficulties when developing a HMLV production cell (Lane, 2020).

1.2. PROBLEM FORMULATION

Instability of forecasts linked with HMLV production makes production planning difficult (Lane, 2020; Katragjini, et al., 2013; Duggan, 2018). Additionally, machinery set-ups are typically required between different production activities and can be difficult to manage due to the high mix and variance of set-up times of products and production activities of HMLV production (Schaller, et al., 2000; Becker, et al., 2015). Another factor that affects the setup-time is the varying experience of operators, which can cause large variations on the set-up time. Therefore, it can be challenging to predict and plan the time required for HMLV production (Becker, et al., 2015).

Managing the information and material flow of HMLV production cells can be difficult due to high variance of production processes and production time between different products and production activities (Suri, 2010). In addition, there are other challenges relating to short product life cycles and floating bottlenecks in HMLV production (Lane, 2020). Achieving high productivity of HMLV production cells is especially challenging since common features of HMLV production are high levels of inventory, work in progress, long lead times and low utilization, which necessitate proper allocation of resources and the aspects of quality, cost, and deliveries to be prioritized (Pandian, et al., 2010).

Production system development is complex since it involves numerous inputs, i.e., resource utilization and limitations, product variety and characteristics, and market demand (Neoh, et al., 2004). Therefore, production system development is important for HMLV production cells, where a high variety of products are produced in lower volumes (Mahoney, 1997; Lane, 2020). However, production system development is challenging to perform in a systematic and structured way (Bruch & Bellgran, 2013; Rösiö & Säfsten, 2013), e.g. due to the difficulty of predicting potential problems which may result in high costs and increased time-to-market (Ivers, et al., 2016). Furthermore, the resources in HMLV production are usually limited and shared across different routings, which contributes to significant challenges of developing HMLV production cells (Suri, 2010).

To meet difficulties caused by an increased customizability and meet customer demand, companies benefit from developing a HMLV production cell (Wikner, et al., 2007; Bohnen, et al., 2011). However, developing a HMLV production cell is challenging, due to the high mix of products being produced in a single production system and since only a few or none of the products manufactured in a HMLV production cell might have a forecast volume and the order sizes are often unpredictable (Lane, 2020). To be able to develop a HMLV production cell, different tools and methods must be used to achieve the necessary flexibility (Bohnen, et al., 2011; Guan, et al., 2008; Wikner, et al., 2007). It is hence of importance to develop HMLV production cells properly, as poorly planned, and disorganized HMLV production cells could result in e.g., overcrowded work floor (Irani, 2011). In conclusion, it is evident that production system development is challenging for manufacturing companies, and that development of HMLV production cells entails additional challenges. As such, it could be beneficial to support the development of a HMLV production cell.

1.3. AIM AND RESEARCH QUESTIONS

The aim of this study is to support the development of a HMLV production cell.

RQ1: *What are the challenges of developing a HMLV production cell?*
RQ2: *What are the critical factors to consider when developing a HMLV production cell?*
RQ3: *How can the development of a HMLV production cell be supported?*

1.4. SCOPE

In this study, a single case study is conducted at Scania, a global automotive manufacturing company with a production facility located in Södertälje. The selected case is the development of a HMLV production cell in the department of engine machining at Scania, which is planned to perform production activities for various departments of Scania. Furthermore, only the department of engine machining at Scania and departments with direct connection to the HMLV production cell and the production activities to be investigated were taken into consideration in the research design. Production activities to be performed in the HMLV production cell were identified and selected prior to the case study in collaboration with Scania. Some of the production activities are not typical production of products but rather production activities that support the main production lines and can be described as HMLV production and are thus referred to as HMLV production activities in this study.

A literature review will initially introduce the concepts of production system development and HMLV production and subsequently aim to identify the challenges and critical factors identified in previous research. The aim of this thesis is not to practically alter a HMLV production cell, but to support the development of the HMLV production cell. Furthermore, economic factors will be excluded from the thesis work to simplify the analysis and not limit the results of the study.

2. METHOD

In this section, the research design used for this study is initially described. Subsequently, the systematic process used to collect and analyze data to fulfil the aim and answer the research questions of this study is described. Finally, the data collection and a description of what has been done to ensure high reliability and validity is presented.

2.1. RESEARCH DESIGN

The research design is the conceptual structure and logical plan for the data collection and analysis which aims to organize the research project to fulfil the defined research problem and facilitate a smooth research process (Kothari, 2004; Yin, 2018). The research problem of this study was to support development of a HMLV production cell. To investigate this problem, the case study method was used. The case study method is beneficial for historical and in-depth analysis and aids in identifying improvements from the observed case environment and conditions (Kothari, 2004). As such, the case study method was considered suitable for the established research problem.

According to Yin (2018), the primary criteria for selecting a case for a case study is accessibility to data which can illuminate the formulated research questions and that is likely to yield the best data. As such a case was selected at one of the world-leading providers of transport solutions, Scania, which had a HMLV production cell in need of development. The case at Scania was considered especially suitable as Scania provided accessibility to experts knowledgeable within areas closely related to the research problem which could easily be interviewed and provide guidance. The specific case which was studied in the case study is described in detail within section 4.1 - Case description. Finally, flexibility was built into the research design by using an iterative research process which will be described in the subsequent section. An iterative research process is beneficial as it can allow the research problem to be altered as new information is discovered which increases the conciseness of the research problem (Kothari, 2004).

2.2. RESEARCH PROCESS

A clear and structured research process is essential for a research study to be performed successfully (Yin, 2018). The research process involves actions or steps needed to effectively and systematically collect and analyze information to allow reliable conclusions to be made (Kothari, 2004). The research process which was used is based on the sequence of procedures in case study research by Hancock and Algozzine (2017) and is shown in Figure 1 below. The empirical and theoretical data collection was done parallelly; theoretical data was collected to enable the analysis of empirical data as it was collected, which allowed theory and empirical data to be compared iteratively, and collection of supplementary empirical data as new concepts were found.

The topics of interest for the research were the combination of HMLV production and production system development, which were thought to be interesting topics in need of further research. Furthermore, the research process was initiated by a start-up period of two weeks which consisted of exploratory interviews and observations at Scania. At the end of the two weeks, the understanding and scope of the research problem was discussed with the company tutors to ensure a mutual interpretation of the project and its outcome.

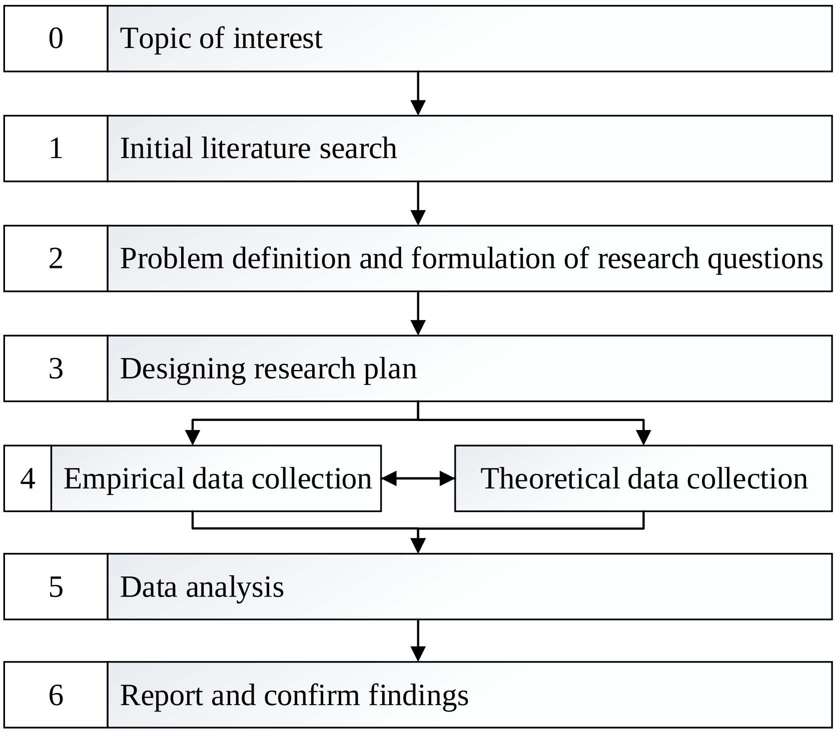

Figure 1 – Research process, modified from Hancock and Algozzine (2017).

2.3. DATA COLLECTION

An important part of the research design is to specify which types and sources of information that are relevant to the research problem as it affects the reliability of the research. Collecting data from all available sources is beneficial as the sources are highly complementary (Yin, 2018; Williamson, 2002). For this study, the primary data was collected through observations and interviews and the secondary data was collected primarily from conducting a literature review but also through documentation from Scania. The data collection methods used are described below.

2.3.1. INTERVIEWS

Interviews as a data collection method are an essential source of information for case studies (Yin, 2018), and are especially beneficial as they allow in-depth information to be obtained as well as the opportunity to restructure questions which provides greater flexibility than other data collection methods (Kothari, 2004). The conducted interviews were semi-structured in character, which refer to asking predetermined questions whilst allowing interviewers to follow up on interesting findings by generating a new question (Williamson, 2002). The structured aspect of interviews increases the comparability of responses from one interview to another which consequently simplifies and reduces the time consumption of the subsequent data analysis (Kothari, 2004). The semi-structured interviews were conducted with key people with different functions at Scania which were selected in collaboration with the company tutors. The criteria used for selecting respondents were that the respondents should have a connection to the prior or current state of the HMLV production cell or the production activities which were planned to be performed in the future state of the HMLV production cell. The interviews were divided into three phases; phase 1 denotes introductions and background information, phase 2 denotes more in-depth questions concerning the research questions, phase 3 denotes generating solutions to support the development of a HMLV production cell.

The interviews of phase 1 used the same interview guide for each respondent, shown in Appendix 1, and were conducted to gain an understanding of the prior, current, and planned use of the HMLV production cell and identify potential challenges and critical factors for its development. Additionally, the interviews helped to identify new sources of information, e.g., additional people to interview and documentation. The interviews were initiated by an introduction phase with a presentation of the thesis work and the case description. Subsequently, the respondents were asked to introduce themselves and describe their connection to the HMLV production cell or the production activities investigated in this thesis. After the introduction phase of the interview, the predetermined questions and follow-up questions were asked as interesting findings with relevance to the case study were found.

The predetermined questions were asked by one interviewer while the other interviewer wrote down the answers to the questions to minimize loss of information and to reduce personal bias. Interesting findings were highlighted in the notes which aided the formulation of follow-up questions, which were subsequently asked by either interviewer to verify answers. Some of the questions were general and identical for all respondents, while others were specific for their function at Scania. The details of the interviews used for empirical data collection are shown below in Table 1 which shows the function of the respondents, topic of the function-specific questions and the duration and location of interviews. For ensuing interviews with respondents, i.e., phase 2, questions were formulated based on the answers from phase 1 and were unique for each respondent. Furthermore, two meetings were performed on a weekly basis with the company tutors where the progress and plans for the project were discussed. The weekly meetings allowed for corroboration of facts, discarding of faulty assumptions and suggestions of respondents to interview to be made to advance the project appropriately.

Table 1 – Interview details

Function	**Topic**	**Phase**	**Duration**	**Location**
Material planner	Order management	1	1 hour	Virtual
Process and tooling developer	The HMLV production cell	1	30 minutes	In person
Workshop technician	The HMLV production cell	1	30 minutes	In person
Operator	The HMLV production cell	1	30 minutes	In person
Tooling specialist	Tool testing	1	1 hour	In person
Process planner	Reparation of core boxes	1	1 hour	Virtual
Logistics planner	Material flow	1	30 minutes	Virtual
Process and tooling developer	Reparation of core boxes Low volume production	1	30 minutes	Virtual
Process planner	Reparation of core boxes	2	1 hour	In person
Process planner	Reparation of core boxes	2	1 hour	Virtual
Tooling specialist	Tool testing	2	1 hour	Virtual
Project manager	Low volume production	1	1 hour	Virtual
Process planner	Low volume production	1	30 minutes	Virtual
Head of advanced engineering	Low volume production	1	30 minutes	Virtual
Method technician	Order management	1	30 minutes	Virtual
Process planner	Reparation of core boxes	2	1 hour	Virtual
Material planner	Low volume production	2	30 minutes	Virtual
Group manager	Low volume production	2	30 minutes	Virtual
Process planner	Reparation of core boxes	2	30 minutes	Virtual
Tooling specialist	Tool testing	2	30 minutes	Virtual
Method technician	Order management	2	30 minutes	Virtual
Method technician	Order management	3	3 hours	Virtual
Tool designer	Development of fixture	3	15 minutes	Virtual
Tool designer	Development of fixture	3	10 minutes	Virtual

2.3.2. OBSERVATIONS

Observations were performed in the initial stages of the research process to gain an understanding of the research problem and the contexts of the case which was to be studied. The observations were primarily of the HMLV production cell, allowing e.g., machining centers, material flow and working operators to be observed. The data collected from the observations aided in identifying potential challenges with the future state of the HMLV production cell and critical factors which would need to be considered in the production system development. Additionally, an observation of the current state of the core box reparation process was performed to better understand the production activity and how it was performed currently. Furthermore, the observations were unstructured in character and were performed in conjunction with visits to Scania, primarily when interviews were done in person.

2.3.3. DOCUMENTATION

Initially, documentation was collected from Scania describing the current state of the HMLV production cell, e.g., the machining centers and supporting equipment and machinery within the HMLV production cell. This documentation was used to identify critical factors which would need to be considered in the development of the HMLV production cell to allow the production activities to be performed in the future state of the HMLV production cell. Additionally, documentation was collected describing the production activities which had been decided to be included in the case study. The documentation of production activities was especially useful due to restrictions of access to the facilities of other departments of Scania due to Covid 19. The documentation of the production activities was collected in cases where the preciseness of data was considered to be critical and was thus requested during or after interviews. Most of the information that was collected from documentation concerned the production activities whilst some documentation was created specifically for the thesis project by Scania.

2.4. LITERATURE REVIEW

A literature review was performed to review manufacturing research relating to the research problem and production system development in general. An extensive literature review plays a crucial role in research (Williamson, 2002) and is beneficial to review the literature connected with the problem within the current research (Kothari, 2004). The theoretical framework was created through a literature review, using the data base of ABI/INFORM Global and snowballing technique to find additional relevant literature from the reference lists of papers included in the literature review. Production system development and HMLV-related literature were searched for separately due to the scarcity of publications, specifically relating to HMLV production. The filter type, description and results of the literature searches is shown below in Table 2 and Table 3.

Table 2 – Production system development-related literature search

Filter type	Description	Results
Inclusion criteria	Search string: "production system" AND ("design*" OR "development*") AND noft("factor"* OR "challenge*") AND noft(manufacturing). Sources: Scholarly journals. Language: limited to English. Limited to full text and peer reviewed.	Retrieved from search: 74 publications
Initial exclusion	Initial exclusion of publications based on screening of titles and abstracts. The exclusion of publications that were considered to have low relevancy to production system development and challenges and factors of developing a HMLV production cell.	After exclusion: 12 publications
Final exclusion	Final exclusion of publication based on reading the publications fully.	After exclusion: 7 publications (Kumar & Singh, 2018) (Kumar, et al., 2018) (Javadi, et al., 2016) (Rösiö & Bruch, 2018) (Bruch & Bellgran, 2014) (Kuzgunkaya & ElMaraghy, 2006) (Choudhari, et al., 2010)

Table 3 – HMLV-related literature search

Filter type	Description	Results
Inclusion criteria	Search string: noft("high mix") AND noft("low volume") AND noft("production"). Sources: Scholarly journals. Language: limited to English. Limited to full text and peer reviewed.	Retrieved from search: 34 publications
Initial exclusion	Initial exclusion of publications based on screening of titles and abstracts. The exclusion of publications that were considered to have low relevancy to challenges and factors of developing a HMLV production cell.	After exclusion: 6 publications
Final exclusion	Final exclusion of publication based on reading the publications fully.	After exclusion: 3 publications (Irani, 2011) (Seth, et al., 2017) (Fritsche, 2011)

2.5. DATA ANALYSIS

The data analysis method which was used for this study is shown below in Figure 2 and described the seven steps which were used to analyze the data and subsequently answer the research questions. The data analysis method is based on the stage model of qualitative content analysis suggested by Hancock and Algozzine (2017). Complimentary to the data analysis model, steps were taken to process and analyze empirical data rapidly by reading through and categorizing notes from the interviews as they were conducted. This cyclical process is depicted in the data analysis method by the arrow pointing back to step 1 as new data is collected. Rapidly analyzing collected empirical data until the aim of the research is fulfilled is beneficial according to Williamson (2002) to reduce the likelihood of unmanageable amounts of data being collected as data collection can be stopped when there is enough data to answer the research questions.

The empirical data that was collected was initially sorted and organized into each of the production activities. Next, the empirical data within each production activity was read through and themed as either a challenge or critical factor to consider for the development of a HMLV production cell. Specific challenges and critical factors were identified and sub-themed, supported by specific challenges and critical factors which had been identified from the theoretical framework. These challenges and critical factors are seen as the headings of the empirical framework. Next, the empirical data within each sub-theme were summarized and subsequently synthesized with the theoretical results. Finally, the analyzed data was summarized and concluded.

The identification of themes and sub-themes from the data that was collected from documentation, observations and interviews was aided by the structured predetermined questions of the semi-structured interviews. The themes and sub-themes were identified from similarities of the empirical data from different sources and data collection methods. The themes that were identified from the empirical data are the subheadings of the empirical findings section of the study, i.e., material flow, information flow and critical factors. Finally, the findings within each sub-theme of empirical data were summarized and synthesized with the theoretical framework to fulfill the aim of the thesis and answer the research questions.

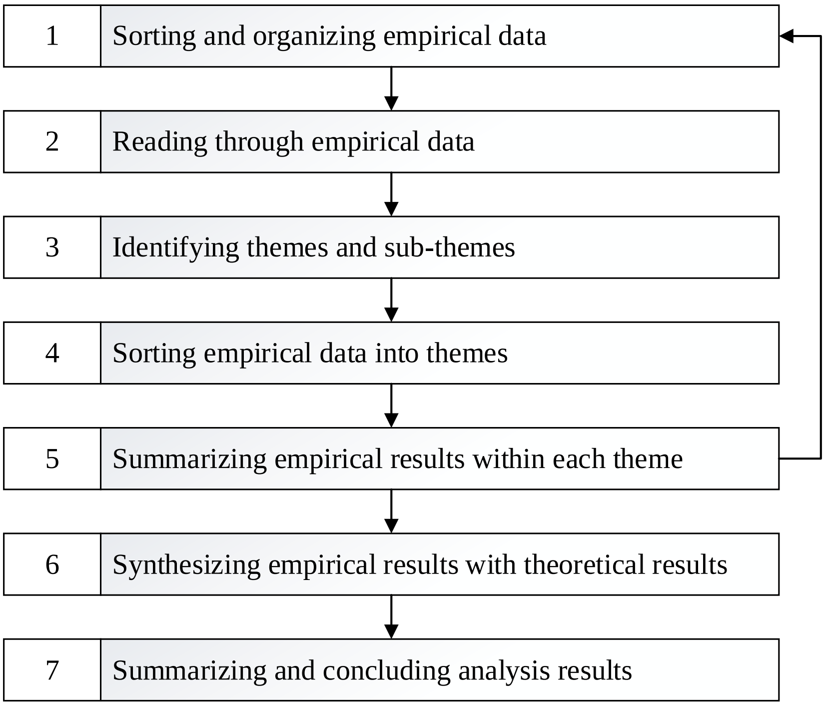

Figure 2 – Data analysis method

2.6. QUALITY OF RESEARCH

The quality of research designs can be evaluated using criteria for the logical set of statements used to make a conclusion within the research design, data collection and data analysis phase (Yin, 2018). The criteria for the evaluation are construct validity, internal validity, external validity and reliability (Kidder & Fine, 1987), although internal validity is associated with explanatory studies and is therefore not relevant for this study. The measures which were taken in the planning of the research design and the research process to ensure high quality of research are described below.

Reliability is a criterion which is concerned with the replicability of research results, aiming to minimize errors and biases and is exemplified by a well-documented research process (Yin, 2018). To ensure high reliability, the study used a well-accepted research process and the use of methods which were selected in the research design was documented continuously and rigorously throughout the study. Also, to ensure high replicability of the research, interview guides were created and used for the semi-structured interviews consisting of questions formulated specifically to answer the research questions.

Validity is the most critical considerations and criterion for research quality and refers to how accurately a method measures what it claims to measure (Kothari, 2004). Construct validity refers to the suitability of the operational measures for the concept that is studied and is especially challenging in case study research (Yin, 2018). As such, the construct validity of this study concerns how properly the data collected from documentation, observations and interviews can be used to support the development of a HMLV production cell. Furthermore, the construct validity of this study was hindered by the restrictions of access to observations and interviews in person at Scania due to Covid 19 as it restricted the use of observations and interviews in person as data collection methods.

Three principles are beneficial to consider for high construct validity, i.e., using multiple sources of evidence, establishing chain of evidence and having key informants review draft of the case study (Yin, 2018). The principle of multiple sources of evidence was used by collecting information from several sources, i.e., documentation, observations and interviews, converging on the same information. Observations of the HMLV production cell were done intermittently to validate and better understand the findings from the interviews. Documentation was also used to triangulate the empirical data that had been collected through observations and interviews and thus increase the reliability of the empirical findings. The principle of chain of evidence was considered throughout the formulating of interview questions and research process aiming to show clearly how the information collected led to the answering of the research questions. Finally, the principle of having key informants review drafts of the case study was done in two ways. Firstly, by sending drafts to the company tutors and university tutor to ensure that the case is progressing in a logical and founded way and to continuously validate inferences made from collected data. Secondly, by updating key people within Scania of progress and the direction the case study was progressing and considering the responses.

External validity refers to defining the domain to which the findings of a study are generalizable and applicable to other cases and increased by generalizing the results to some broader theory (Yin, 2018). As such, efforts to ensure high external validity have been taken firstly by creating theoretical reference by performing a literature review and analyzing the empirical data from the case study with the theoretical framework. Secondly, at the final phase of the research process, i.e., the report and confirm findings phase, the domain in which the findings from the case study are generalizable and applicable was assessed.

3. THEORETICAL FRAMEWORK

In this section, the theoretical framework created from the literature review is presented. Initially, production system development and a process for production system development are presented. Subsequently, the challenges of developing a HMLV production cell and the critical factors to consider when developing a HMLV production cell are presented. Finally, the section is summarized by a synthesis of the theoretical framework.

Production systems can be seen as a process with e.g., raw material and manpower as input parameters, design and production as process parameters and a product or profit as output parameter (Oswald & Munoz, 2008). The output parameters are characterized by variables such as reliability, appearance and cost (Efthymiou, et al., 2012). Production systems are bound by the common flow of material and information (Oswald & Munoz, 2008) and consists of facilities, i.e. manufacturing processes and machinery, human resources and material, and manufacturing support systems, i.e. functions which examine and solve quality and technical problems of organizations (Groover, 2010). Manufacturing companies must continuously develop their production capabilities and consequently their production systems to provide better service for customers and improve customer satisfaction (Li, et al., 2014).

3.1. PRODUCTION SYSTEM DEVELOPMENT

Production system development is the creation of production systems' capabilities and effective production processes and refers to both development of already existing production systems, and of new production systems (Bellgran & Säfsten, 2010). The production system is a critical factor for the performance of manufacturing companies as it positively correlates with profitability (Kumar & Singh, 2018), as such, production system development is essential to enhance the output of manufacturing systems (Malerba, 2002). Production system development is complex as it involves the development of several constituent parts, e.g. organizational structures, information- and material flow, and production technologies, which must interact and synergize (Rösiö, 2012) to transform raw material into products (Rösiö & Bruch, 2018).

The degree of change of production system development projects varies from slight modifications to radical transformations and implementation of highly novel production technologies and processes (Bruch & Bellgran, 2014). Manufacturing companies typically aim to minimize modifications of production systems to preserve the flexibility of production systems (Javadi, et al., 2016). Although, slight modifications of production systems are typically needed as new products or product variants are introduced into the product portfolio, which often involve costly investments such as machinery, jigs, and fixtures (ElMaraghy, 2009). Modifications of production systems are typically considered late in the development process due to a lack of testing and refining of the production system prior to the production ramp-up (Javadi, et al., 2016). As such, it is beneficial to use a systematic production system development process (Bellgran & Säfsten, 2010), which can aid manufacturing companies to manage and coordinate modifications to production systems more effectively (Javadi, et al., 2016).

3.1.1. PRODUCTION SYSTEM DEVELOPMENT PROCESS

The process used by manufacturing companies for production system development is typically greatly influenced by existing production systems and products (Rösiö, 2012), which makes it difficult to look ahead and consider future requirements of production systems in the early phases of development, e.g., to consider what capabilities future products and variants will require of the system (Bruch & Bellgran, 2014). Also, systematic learning from previous production system development projects tends to be limited in manufacturing companies, which increases the likelihood of performing critical activities and considering factors too late in the process (Rösiö & Bruch, 2018). Applying a holistic perspective to production system development tends to be challenging for manufacturing companies, although is crucial to avoid suboptimization, ensure readiness for future changes to the production system and to secure economic feasibility for future product variants and families (Javadi, et al., 2016).

The production system development process can be facilitated by determining which roles and competences to include into the activities of the production system development process (Javadi, et al., 2016). It is critical that production engineering is involved early in the development phases as new products are to be introduced into the production system, as including additional perspectives and competences may improve the manufacturability of the product, reduce lead-time and improve product quality (Bruch & Bellgran, 2014). Although the competence of the production engineering function is especially crucial for production system development (Javadi, et al., 2016), it is important to note that it is beneficial to use cross-functional teams (Adler, 1995) and include other disciplines and functions of manufacturing, such as the logistics function and operators (Bruch & Bellgran, 2014).

Manufacturing companies generally find it challenging to develop production systems so that the production system satisfies functional requirements whilst still being easy to manage and operate (Kuzgunkaya & ElMaraghy, 2006). Manufacturing companies tend to focus on technical subsystems and equipment, and support for other aspects of production system design, such as organizational structures, the preparedness of operators and material- and information flow is often neglected (Rösiö & Bruch, 2018). As such, it can be beneficial to frontload production system development projects, i.e., to dedicate more resources early in the development phases, to ensure that the workload is manageable and that there are adequate resources available to ensure a sound starting point (Bruch & Bellgran, 2014).

A structured process for production system development by Bellgran and Säfsten (2010) is shown below in Figure 3. The first phase, management and control, is concerned with preparatory activities such as preparing investments and planning and preparing the development project to provide a plan for the subsequent phase. The next phase, preparatory design, aims to gather information necessary for creating a conceptual production system design through a background study and a pre-study to result in a requirement specification. The third phase, design specification, develops a system solution from the requirement specification. The fourth phase, realization and planning, is concerned with the implementation and physical realization of the developed system solution to result in a physical production system. The final phase, start up, concludes the development process and hopefully results in an operational and efficient production system (Bellgran & Säfsten, 2010).

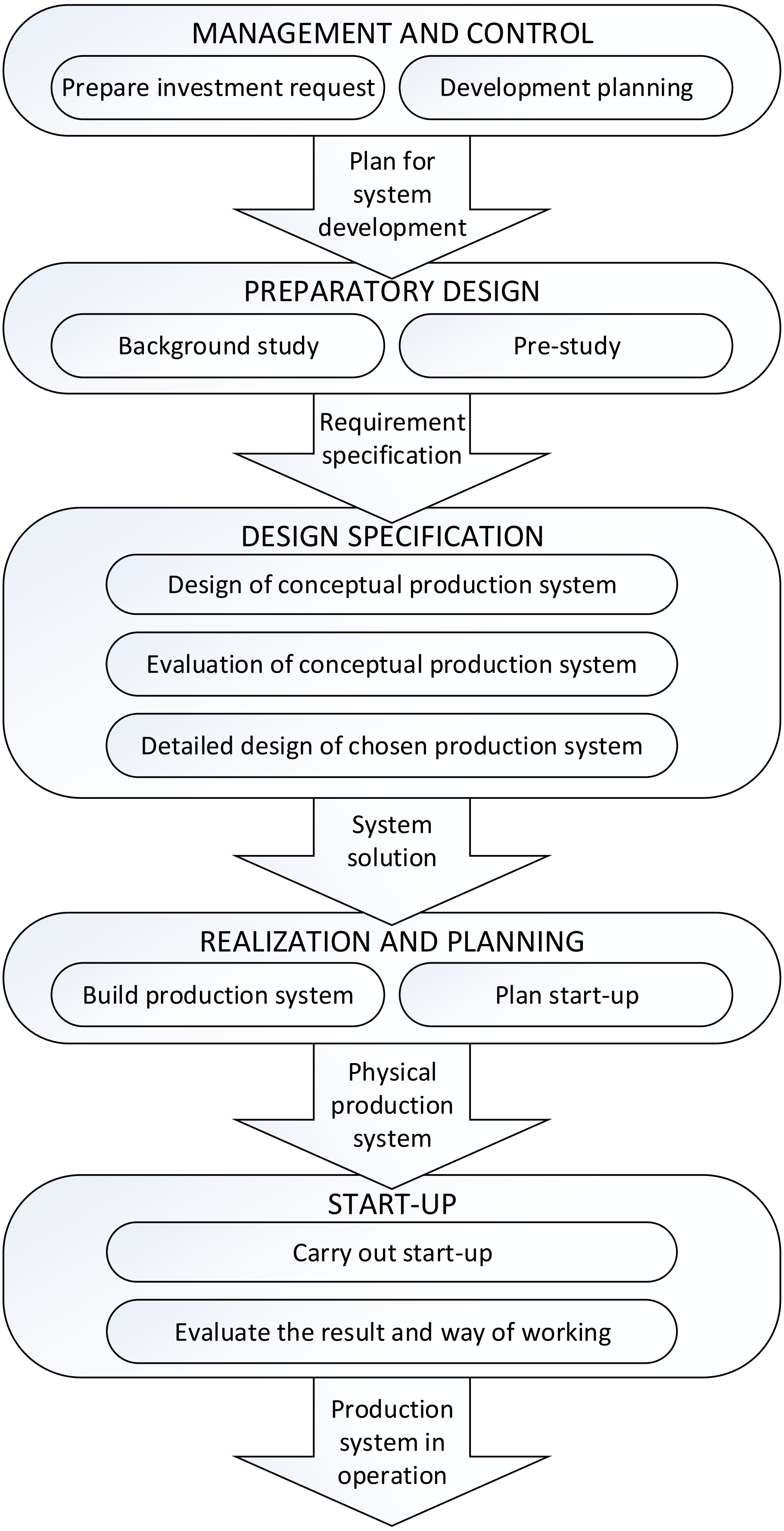

Figure 3 – Production system development process by Bellgran and Säfsten (2010).

3.2. CHALLENGES OF DEVELOPING A HMLV PRODUCTION CELL

The theoretical framework revealed production planning, utilization of equipment, product quality and material flow to be challenges of developing a HMLV production cell. This section will describe these aforementioned challenges.

3.2.1. PRODUCTION PLANNING

Developing an efficient way of planning HMLV production can be challenging due to the need of considering high variation of cycle times (Zennaro, et al., 2019), set-up times, and variability of production operations required to produce different products (Bohnen, et al., 2011; Irani, 2011). When developing a production system, achieving an effective flow of information needed for production planning can be challenging for manufacturing companies, even if the involved functions are at the same company (Bruch & Bellgran, 2014). Furthermore, production planning is especially challenging for HMLV production cells due to the high degree of complexity and uncertainty of customer demand resulting in a short planning horizon (Safizadeh & Ritzman, 1997; Efthymiou, et al., 2014). Also, the demand and delivery dates of HMLV products are usually highly varying and the order sizes are often unpredictable (Irani, 2011). In fact, only a few or none of the products manufactured in HMLV production might have a forecasted demand. Since orders are typically sporadic and highly varied, it is challenging to plan HMLV production (Lane, 2020), as it is typically more complex than for traditional line production (Irani, 2011). Additionally, planning of HMLV production is more turbulent than traditional line production as there might be frequent changes of orders, e.g., changes to the product mix and volume (Jina, et al., 1997) which can lead to sub-optimal performance of the production system (Seth, et al., 2017). Manufacturing companies utilizing the HMLV production strategy typically decentralize decision making and flatten their hierarchies (Nahm, et al., 2003).

3.2.2. UTILIZATION OF EQUIPMENT

It is challenging to ensure high utilization of equipment when developing HMLV production cells, which is reflected in the fact that HMLV production cells typically have low utilization of equipment, partly due to the set-up of machinery required between production of different products (Pachpor, et al., 2017). HMLV production require significantly more machinery set-ups compared to the traditional line production, which decreases the productivity of the production processes (Schaller, et al., 2000). Furthermore, HMLV production cells generally have a high set-up time relative to the cycle time, due to large variability of process parameters and low volumes of each product (Miltenburg, 2005), which negatively utilization of equipment, which is an important factor for making HMLV production cells profitable (Fritsche, 2011). As such, minimizing set-up times is important to be able to increase flexibility and performance of a production system as it results in decreased lead time and reduced idle time, which are potentially problematic for the performance of production systems (Rad, et al., 2014). The set-up time can be reduced by improving the relationship and involvement of suppliers and customers in the design process and optimizing set-up methods such as fixturing of parts (Hendry, 1998).

3.2.3. PRODUCT QUALITY

Key concerns of manufacturing can be improved by focusing on improving product quality, whilst minimizing the cost and process time of production processes (Chen & Huang, 2006; Colledani, et al., 2014). Additionally, product quality improves the financial performance of manufacturing companies (Kazan, et al., 2006) and is thus a competitive advantage (Karim, et al., 2008). Furthermore, product quality in terms of conformance and durability are important in HMLV production cells (Choudhari, et al., 2010). Although, achieving high product quality is challenging for HMLV production cells as there are generally more defected products in a HMLV production cell compared to line production (Hendry, 1998).

3.2.4. MATERIAL FLOW

It is crucial to develop an effective material flow for HMLV production cells as it is directly associated with operational performance (Huo, et al., 2016), and facilitates delivery precision (Choudhari, et al., 2010), inventory control (Jonsson & Mattson, 2008) and the performance of the production system (Eswaramurthi & Mohanram, 2013; Kumar & Singh, 2018). Although, the material flow of HMLV production cells is generally complex, which increases lead time (Irani, 2011) and is thus detrimental as longer lead times reduces the productivity of production systems (Liker, 2021). Thus, improving the material flow is critical for manufacturing companies aiming to reduce lead time (Godinho Filho, 2017). Additionally, the material flow within HMLV production cells generally entails high number of work in progress and raw material to decouple production operations (Hill, 2009), although inventory should arguably be kept low as production volumes of each product are typically low in HMLV production cells (Miltenburg, 2005).

3.3. CRITICAL FACTORS TO CONSIDER WHEN DEVELOPING A HMLV PRODUCTION CELL

The theoretical framework revealed production flexibility, production competence, production technology, pilot production, manufacturing strategy, order management system and standardization to be critical factors to consider when developing a HMLV production cell. This section will describe these aforementioned critical factors.

3.3.1. PRODUCTION FLEXIBILITY

Production flexibility is crucial for the competitiveness of manufacturing companies (Obi, 2013) as it positively impacts production performance (Swink, et al., 2005) and organizational activities (Baykasoğlu & Özbakır, 2008). Furthermore, production flexibility is critical to ensure that the production system is capable and sufficiently scalable to handle uncertainty concerning product mix and customer demand (Javadi, et al., 2016). Uncertainty is a typical characteristic linked with production system complexity and is correlated with the degree of product mix; a high product mix indicates higher uncertainty (Kuzgunkaya & ElMaraghy, 2006). As such, production flexibility is a critical factor to consider when developing a HMLV production cell to ensure that the production system is capable and sufficiently scalable to handle uncertainty concerning future customer demand and product mix (Javadi, et al., 2016).

Production flexibility can mitigate challenges of underutilization, and long set-up times caused by uncertainty and facilitate delivery precision (Khalil & Stockton, 2010). To increase production flexibility, the organizational structure of HMLV production cells tends to be flat, i.e., having few levels of management (Hill, 2009; Miltenburg, 2005), which facilitates quick response to customers (Miltenburg, 2005). Also, manufacturing companies facing a high degree of uncertainty tend to rely less on formal rules and policies to facilitate production flexibility (Nahm, et al., 2003).

3.3.2. PRODUCTION COMPETENCE

Production competence is important for production system development and the resulting performance of the production system (Bellgran & Säfsten, 2010). Furthermore, production competence facilitates return on assets and equity (Nadeem, et al., 2017) and is positively correlated with profit and customer satisfaction (Lun, et al., 2016). Additionally, production competence facilitates effective material and information flow and is a critical factor for HMLV production cells (Godinho Filho, 2017). Highly skilled workers facilitate the necessary production flexibility apt for low-volume manufacturing and to ensure that production is operational and timely (Mohamed & Khan, 2012; Choudhari, et al., 2010; Miltenburg, 2005) without compromising the quality of the product (Lyons, 2005).

Employee development facilitates production capacity and the efficiency of production processes (Lee, et al., 2015) and is significantly linked with manufacturing performance (Sarfaraz, et al., 2015; Agarwal, et al., 2013; Lyons, 2005). General training aiming to better understand the capabilities, limitations and requirements of a production system is particularly beneficial within low-volume manufacturing as the production systems and their characteristics are unlikely to be considerably altered. For example, working with production operators and observing the production system for short periods of time can improve the understanding of the capabilities and limitations of the production system (Javadi, et al., 2016). Organizational support is essential to improve the capabilities of employees (Snell, et al., 2015).

Manufacturing companies commonly use and rely upon equipment suppliers for production system development projects as sources of major innovations and competence for hire (Lager & Frishammar, 2010). In addition, recruiting from outside the company or shifting people within the company may also be required to ensure the requisite competence of new technologies (Kumar, et al., 2018). The downside of relying on outsourcing for production system development tasks is that it impedes the companies’ ability to identify and plan future developments and build internal competence (Bruch & Bellgran, 2014). It is especially challenging to allocate personnel for production system development within low-volume manufacturing industries, due to production personnel and project members being involved in other projects and on-going production activities (Javadi, et al., 2016).

3.3.3. PRODUCTION TECHNOLOGY

The physical and technical capabilities directly affect the capacity of production activities which in turn affect the outputs of the production system, e.g., product quality, reputation, and profit, and is therefore critical to consider in the development of production systems (Kumar & Singh, 2018). Also, advanced manufacturing technology is a critical factor for HMLV production cells to facilitate the degree of product customization required (Zhang, et al., 2006) and production flexibility (Dhinesh, et al., 2005). Additionally, advanced manufacturing technologies such as automatic storage and retrieval systems, CNC machine tools (Raj, et al., 2010), and CAD and CAM systems (Theodorou & Florou, 2008) can be used as a complimentary learning tool and training method to communicate the intricacies of products and processes to production personnel (Malmsköld, et al., 2012). As such, the management of production technologies is directly associated with financial performance, as implementing production technology which improves the tool, method or technique used in manufacturing can increase productivity and profitability (Mandal & Bagchi, 2016). Furthermore, employee training and integration of departments facilitate successful adoption of production technology (Kumar, et al., 2018).

3.3.4. PILOT PRODUCTION

A critical activity to ensure a sound starting point of production system development is the pilot production, which is done to adapt the product and production system together and is especially critical in low-volume manufacturing industries (Javadi, et al., 2016). Pilot production is single- or low-volume production done at an early stage prior to the production ramp-up with the purpose of validating the capability of the production system (Fjällström, et al., 2009), verifying and refining the production system (Winkler, et al., 2007; Fjällström, et al., 2009) and to ensure that a conceptual solution will work well in practice (Thabane, et al., 2010). Furthermore, the pilot production is an opportunity to increase the efficiency of production personnel to produce the new product (Bellgran & Säfsten, 2010) and reduce disturbances (Säfsten, et al., 2006; Bellgran & Säfsten, 2010).

3.3.5. MANUFACTURING STRATEGY

Facilitating factors of the manufacturing strategy to support HMLV production are e.g., emphasizing employee- and customer-driven policies, which are factors associated with high-performing manufacturing companies (Gomes, et al., 2006). In addition, the manufacturing strategy should ensure customer satisfaction as it is crucial to improve customer loyalty and profitability (Helgesen, 2006). Additionally, managerial support is critical for attaining operational benefits to improve the manufacturing output and increasing the efficiency of production systems (Asrofah, et al., 2010; Chung & Lee, 2005). Finally, some of the values and principles of Lean still apply to HMLV production, e.g., developing leaders well acquainted with the company philosophy and increasing internal competence (Irani, 2011).

It is essential to use suitable methods and tools for the utilized manufacturing strategy for good manufacturing output and as the HMLV and traditional line production strategy are significantly different, the method and tools used should differ as well (Irani, 2011). Lean is a well utilized manufacturing strategy to increase productivity and decrease waste in traditional line production, which aims to create a constant flow of production, typically, with low flexibility (Seth, et al., 2017). However, since flexibility is a requirement of the HMLV strategy, Lean is not designed to be utilized for HMLV production, which means that the use of Lean tools must be done thoughtfully (Irani, 2011). As a result, the usefulness of tools and methods used for improving traditional line production system performance can be challenging to apply to HMLV due to the high variability of production volumes and mix of products (Hendry, 1998). For example, it is challenging to use the value stream mapping tool to create a flowchart of the material and information flow within a HMLV production cell due to the high turbulency of the HMLV production environment (Seth, et al., 2017).

3.3.6. ORDER MANAGEMENT SYSTEM

An order management system can act as an organic link and channel of communication for the information flow between customers and production personnel and is critical to sustain flexible production (Okamoto, 2003; Fritsche, 2011). Also, an order management system facilitates feedback and control of information and is beneficial for departmental activities to improve manufacturing performance (Kumar & Singh, 2018) and has a positive impact on customer satisfaction (Karim, et al., 2008).

The most common production strategies utilized for the order management system of HMLV production cells are make-to-order and engineer-to-order, in which production starts after an order is placed (Zennaro, et al., 2019) and therefore it is not necessary to plan the production in beforehand (Arreola-Risa & Decroix, 2002). Make-to-order is typically the appropriate production strategy for low-volume manufacturing companies (Wrobel & Laudański, 2008) and HMLV production cells (Choudhari, et al., 2010) to handle the high complexity and mix of products which distinguishes the low-volume manufacturing industries (Rahim & Baksh, 2003). Make-to-order enables customers to order customized products to their specifications, typically in low volumes and with an unpredictable order pattern, due to the high degree of customized orders (Arreola-Risa & Decroix, 2002). In contrast, engineer-to-order is an appropriate method to handle high product complexity and customer involvement in HMLV production cells, which entails production of unique products according to customer specifications (Seth, et al., 2017). Products with reoccurring orders in relatively high production volume should obtain most of the focus in HMLV production (Lane, 2020).

3.3.7. STANDARDIZATION

Standardized work is a necessity to achieve consistency of high-quality products, even when producing a high mix of products (Irani, 2011; Weber, 2016; Kafetzopoulos, et al., 2015). Standardization of HMLV production cells is beneficial to handle the high complexity of information and material flow caused by a high mix of products and uncertainty (Bohnen, et al., 2011; Irani, 2011). In HMLV production cells, it is critical to ensure visibility and standardization of material, machinery, and tools in the production, which can be done through visible and nearby storage systems to facilitate the removal of obsolete parts and material (Hendry, 1998). Another way to standardize work is to identify similarities of material flow of different product families, which can be done through grouping technology (Irani, 2011), which is a manufacturing technique where products with similarities are grouped together and manufactured at the same location, with the motive to handle each group rather than the individual product types (Weber, 2016; Hendry, 1998). Furthermore, another way of increasing standardization is having information and instructions accessible for product types and operations, which is beneficial to ensure that operations are performed properly for a high mix of product types (Weber, 2016).

3.4. SYNTHESIS OF THE THEORETICAL FRAMEWORK

A synthesis of the challenges of developing a HMLV production cell and the critical factors to consider when developing a HMLV production cell identified from the theoretical framework are shown below in Figure 4.

Challenges of developing a HMLV production cell	Critical factors to consider when developing a HMLV production cell
• Production planning • Utilization of equipment • Product quality • Material flow	• Production flexibility • Production competence • Production technology • Pilot production • Manufacturing strategy • Order management system • Standardization

Figure 4 – Synthesis of the theoretical framework

The theoretical framework revealed four challenges of developing a HMLV production cell: production planning, utilization of equipment, product quality and material flow.

- Production planning is challenging due to e.g., high variation of cycle and set-up times, variability of production operations and uncertain customer demand.
- Utilization of equipment is challenging mainly due to the high set-up time relative to the cycle time.
- Product quality is challenging due to the relatively high number of defects of HMLV production cells compared to line production.
- Material flow is challenging due to the high complexity and high number of work in progress and raw material of HMLV production cells.

The theoretical framework revealed seven critical factors to consider when developing a HMLV production cell: production flexibility, production competence, production technology, pilot production, manufacturing strategy, an order management system and standardization.

- Production flexibility is a critical factor to handle uncertainty concerning product mix and customer demand.
- Production competence is a critical factor to facilitate production flexibility and capabilities.
- Production technology is a critical factor to facilitate production flexibility and increase utilization of equipment.
- Pilot production is a critical factor to ensure a sound starting point of production system development.
- Manufacturing strategy is a critical factor to ensure customer satisfaction and attain operational benefits.
- An order management system is a critical factor to facilitate production planning and the utilization of equipment.
- Standardization is a critical factor to reduce the complexity associated with having a high mix of products.

4. EMPIRICAL FINDINGS

In this section, the empirical findings from the data collection are presented. Initially, the case description and the production activities are described. Subsequently, the challenges of developing a HMLV production cell and critical factors to consider when developing a HMLV production cell are described. Finally, the section is summarized by a synthesis of the empirical findings.

4.1. CASE DESCRIPTION

Scania is a world-leading provider of transport solutions and one of the largest manufacturing companies in Sweden with assembly plants in ten countries, with the headquarters and main production plant is in Södertälje, Sweden. Furthermore, Scania has their own well-defined manufacturing strategy, Scania Production System, which is based on the Lean manufacturing strategy and has structured values and principles to guide manufacturing. Furthermore, Scania has the means, such as technology and competence required to develop a HMLV production cell. At the main production plant, the departments of foundry (DF), engine machining (DM) and engine assembly are used for manufacturing diesel engines for heavy vehicles, marine and general industrial applications. The engine parts are shaped through the casting process in DF and are subsequently machined and processed at DM, where the HMLV production cell is located at.

The HMLV production cell was developed by Scania and consequently conforms to the standards and values of Scania and has primarily been used for low volume production for external customers. The utilization of the HMLV production cell has since been diminished, which potentiates the use of the HMLV production cell for other production activities. In this study it will be evaluated whether it is possible to perform low volume production, tool testing and reparation of core boxes in the HMLV production cell. These production activities will be described in the next subsections. It has been estimated that the HMLV production cell is being utilized ten percent of its past maximum utilization. Scandia's primary goal of performing the production activities in the HMLV production cell is to increase the utilization of the HMLV production cell and increase profitability of the main production lines by minimizing lead-times and ensuring delivery precision. Scania also strives to maintain and improve the internal production competence and believes that the development of the HMLV production cell can facilitate development of internal production competence. As such, the development of the HMLV production cell has managerial support.

The area of the HMLV production cell is approximately 500 square meters and the layout of the of the HMLV production cell is shown below in Figure 5. The layout and machinery within the HMLV production cell were developed for low volume production which is still reflected in the current state of the HMLV production cell. In addition to the two machining centers, the HMLV production cell has an area dedicated to storage and preparation of tools for testing. The HMLV production cell has primarily been used to produce motor blocks and cylinder heads in low volumes, therefore, the fixtures and equipment needed for these two types of products are available in the HMLV production cell. Furthermore, machining centers can perform most cutting operations performed in the production lines at DM; however, the cycle time is considerably longer and is thus not suitable for production of large volumes. Additionally, there is a washing machine which does not conform to the standards of line production and is therefore not included in the investigated production activities. Currently, two employees are assigned to the HMLV production cell to handle the remaining orders that are placed for the HMLV production cell, one of whom is currently undergoing training to use CAM software.

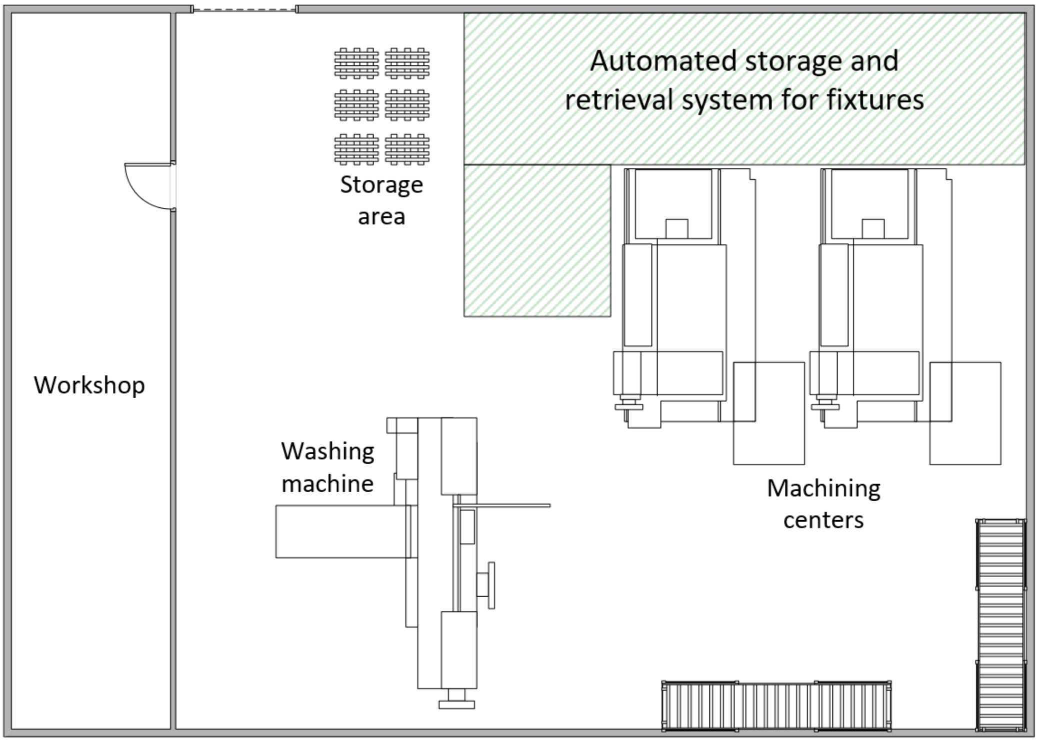

Figure 5 – Layout of the HMLV production cell

4.1.1. LOW VOLUME PRODUCTION

Some of the engine components which are produced at Scania have a low yearly demand and are normally produced in their production lines. The potential customers of low volume production in the HMLV production cell are either internal, i.e., from within DM, or external, i.e., from any other department of Scania. By performing low volume production for internal customers, the productivity of the ordinary production lines can be increased since non-value adding time is removed and disruptions in the ordinary production line can be avoided. Low volume production for external customers has many purposes, e.g., for product development and process optimization.

4.1.2. TOOL TESTING

Using the most suited tool for production processes is critical in achieving the best possible process output as well as saving tooling costs due to a higher life span of the tools. Tool testing is performed to test different factors such as the lifespan of the tool or its suitability for the specific production operation. Different configurations of e.g., tooling, cutting speed and depth, are used for testing the tools and are generated to either try to remedy problems with existing tools in a production line or to identify the more suitable tool for a new production operation or product. Process planners are responsible for assuring that the right tools are used and that the product which is created is within the specified tolerances. Two tooling specialists support the process planners of Scania in Södertälje with tool-related problems. The HMLV production cell is especially suitable to perform tool testing of products made in DM as there generally are fixtures available which are necessary to perform the tool testing. For other customers and products, fixtures may need to be manufactured to enable the tool testing to be performed. Performing tool testing within the HMLV production cell is advantageous as it requires less planning, is less time-consuming and is a cheaper alternative compared to having an external partner perform the tests. The HMLV production cell is capable of performing the tool testing in its current state, as such, no significant modifications are needed to perform tool testing in the HMLV production cell.

4.1.3. REPARATION OF CORE BOXES

The foundry process at DF uses core boxes to create sand cores which are then used to produce the internal cavities of products in the casting process. The core boxes gradually deteriorate due to pressure and friction caused in the process of producing sand cores and must intermittently be repaired and restored for the process to produce perfectly shaped components. For each product group produced in the foundry, two identical sets of core boxes are used, which allows for cleaning and quality control of one set as the other is used in production. The sets of core boxes are swapped on a weekly basis to allow the core boxes to be cleaned; thus, the reparation should preferably be performed in less than a week to allow the core box to be timely swapped back into production. If the reparation of a core box is delayed, DF will be forced to clean the other set of core boxes without having a replacement and will thus entail production downtime. The condition of a full set of eight core boxes is controlled on a fixed schedule based on an historic rate of deterioration, ranging from once a month to once every six months. Scania has built a new foundry facility which is a few kilometers away from the HMLV production cell and is expected to significantly increase production output two- or threefold. As a result, the demand for the reparation of core boxes will increase significantly and will need to be outsourced.

4.2. CHALLENGES OF DEVELOPING A HMLV PRODUCTION CELL

The empirical findings revealed production planning, utilization of equipment, product quality and material flow to be challenges of developing a HMLV production cell. This section will describe these aforementioned challenges.

4.2.1. PRODUCTION PLANNING

Production planning is one of the main challenges of developing the HMLV, largely due to uncertainty of the mix of production activities that would be performed in the HMLV production cell. Also, production planning is challenging as the production activities entail a high degree of uncertainty concerning production lead time and the required set-ups between different production activities and operations. Production planning of new production activities and products is even more challenging due to the uncertainty and difficulty of forecasting set-up and cycle times. Also, high uncertainty concerning customer demand and delivery dates results in a short notice for production planning. Assessing priority for a high mix of production activities can also be challenging; for the HMLV production cell, production activities which directly affect the end-customer is prioritized.

Another challenge of planning HMLV production is that a high mix of material and tools need to be delivered for production and the delivery time is uncertain. Uncertain delivery time has resulted in material arriving unexpectedly before the order information has been received by the employees of the HMLV production cell. As such, ensuring that material is delivered on time for a high mix of production activities is a challenging aspect of production planning for HMLV production cells.

Production planning of the tool testing activity is challenging as the tool tests cannot be forecasted as they are typically triggered by the occurrence of a tool-related problem in a production line. Also, not every tool-related problem requires tool testing as the problem might have been caused by other factors. The tooling specialist needs to investigate the problem and ensure that the tool is the root cause before planning and ordering a tool test. As a result, the order for the tool testing cannot be placed until the root cause of the tool-related problem has been identified. Another challenge concerning tool testing is that it is uncertain whether the tested tool will solve the tool-related problem and may require several tests to be performed.

The challenges of planning the milling operation of the core box reparation process are twofold; if a major defect is found in the scanning operation, the core box must be repaired immediately. Secondly, once the reparation process has been initiated, it must be finished within a week, which entails a challenge of production planning.

4.2.2. UTILIZATION OF EQUIPMENT

The data indicates that the HMLV production cell is an asset for Scania, although the HMLV production cell is costly if the equipment is underutilized. Presently, the equipment in the HMLV production cell is underutilized, which is disadvantageous as the utilization of the HMLV production cell is linked to the utilization of resources, such as personnel and equipment. As such, if the personnel and equipment of the HMLV production cell are not highly utilized for production activities, internal competence may be lost. The potential utilization of the investigated production activities is displayed in Table 4 below, which shows that the utilization of the three investigated production activities is highly varied and uncertain.

Table 4 – Potential utilization of production activities

Production activity	**Low volume production**	**Tool testing**	**Reparation of core boxes**
Utilization	Uncertain	8-16 hours/month	15-725 hours/year Alternatively: 340-1050 hours/year

A challenge of utilizing the equipment in the HMLV production cell for testing of cutting tools is that the demand for tool testing is sporadic and unpredictable, and the aim is to minimize the number of tool tests; therefore, the tool tests are unlikely to constitute high utilization of the HMLV production cell.

Data indicates that the reparation of core boxes is a particularly important production activity for the development of the HMLV production cell, as the production activity can potentially significantly increase the utilization of equipment. However, a challenge of utilizing the equipment in the HMLV production cell for the milling operation of the core box reparation process is that the potential utilization depends on customer trust and satisfaction; a higher alternative utilization of equipment can be achieved based on customer satisfaction. Also, the rate of deterioration of core boxes depends on the age, complexity and robustness of the geometries and there is an increasing trend for the deterioration of core boxes, which means that new core boxes do not have to be repaired as often as worn ones. As a result, the forecasted utilization of the machining centers for the milling operation of the core box reparation process is highly uncertain and will increase with time, which is indicated by the large interval.

A challenge of utilization of equipment is that it depends on the capabilities of the equipment; limitations of the machining centers restrict of what production activities can be performed. For low volume production in the HMLV production cell, the machining centers are not able to perform all operation, which restricts the utilization of equipment. To perform additional operations and increase utilization, potentially costly machinery would need to be purchased. In addition, introducing products into the HMLV production cell which are significantly different than previously produced products to increase utilization of equipment may require investing into new machinery, fixtures, and tools. Another limiting factor of the utilization of equipment is the production part approval process necessary for product activities which directly affect the end-customer, as it is costly and time-consuming and consequently restricts the products which are economically feasible to produce. Furthermore, the utilization of equipment is limited by the machinery set-ups which are required between different production activities. Also, the products are heavy which results in high set-up times which negatively affects the utilization of equipment.

4.2.3. PRODUCT QUALITY

Although the machining centers in the HMLV production cell have high efficiency and precision, and provides high machining quality and reliability, there are challenging aspects of product quality concerning all investigated production activities. The production lines at Scania have been continuously improved and optimized to ensure stable and high product quality; for the HMLV production cell to ensure the same high product quality, significantly more frequent quality controls would be required compared to the frequency of quality controls for line production. As such, product quality is especially challenging for low volume production due to the necessary quality controls to reach the conformity requirements.

Product quality is especially critical for low volume production for internal customers since the products which are produced will be assembled into a truck; the quality of the product directly affect the end-customer. Consequently, the standardized production part approval process, needs to be performed for every product produced for internal customers to ensure that the process can produce conforming products with high quality. However, empirical data indicates that the production part approval process which is required to ensure the conformity of the product quality for low volume production is too time-consuming to perform for a high mix of products. As such, ensuring high product quality for low volume production is a significant challenge.

For tool testing, the product quality does not directly affect the end-customer but does affect the reliability of the results from the tool testing, although, a challenge of performing the tool testing in the machining centers is that the results from the tool testing may be better than what is achievable in a production line and therefore affect the effectiveness of the tool testing activity.

The reparation of core boxes has never been performed in the HMLV production cell, and the capability of the machining centers are uncertain. For the core box reparation process, the resulting condition or product quality of the core boxes is crucial for the performance of the casting process. As such, high quality of the core boxes is a requisite for performing the milling operation in the HMLV production cell. Additionally, the resulting condition or quality of the core box after the reparation process is critical as if a core box is found to be outside of the tolerances in the subsequent scanning operation, the entire reparation process would need to be redone. As a result, DF would not be able to swap the core boxes and would be forced to stop production to clean the core boxes and then use the same core box for another week. Consequently, the HMLV production cell will initially only be assigned a few orders until the capability of the HMLV production cell has been proven, due to the importance of ensuring high product quality of the core boxes.

4.2.4. MATERIAL FLOW

The material flow of low volume production is shown below in Figure 6 and is challenging as it involves coordination between DF, the logistics department and the HMLV production cell. A challenge of performing low volume production for internal customers within the HMLV production cell is to divide the responsibilities, e.g., for the delivery and quality assurance of the products necessary for products which directly affect the end-customer. Furthermore, the process and tooling developer states that the major challenges of performing low volume production in a HMLV production cell is to create the necessary order and delivery structure.

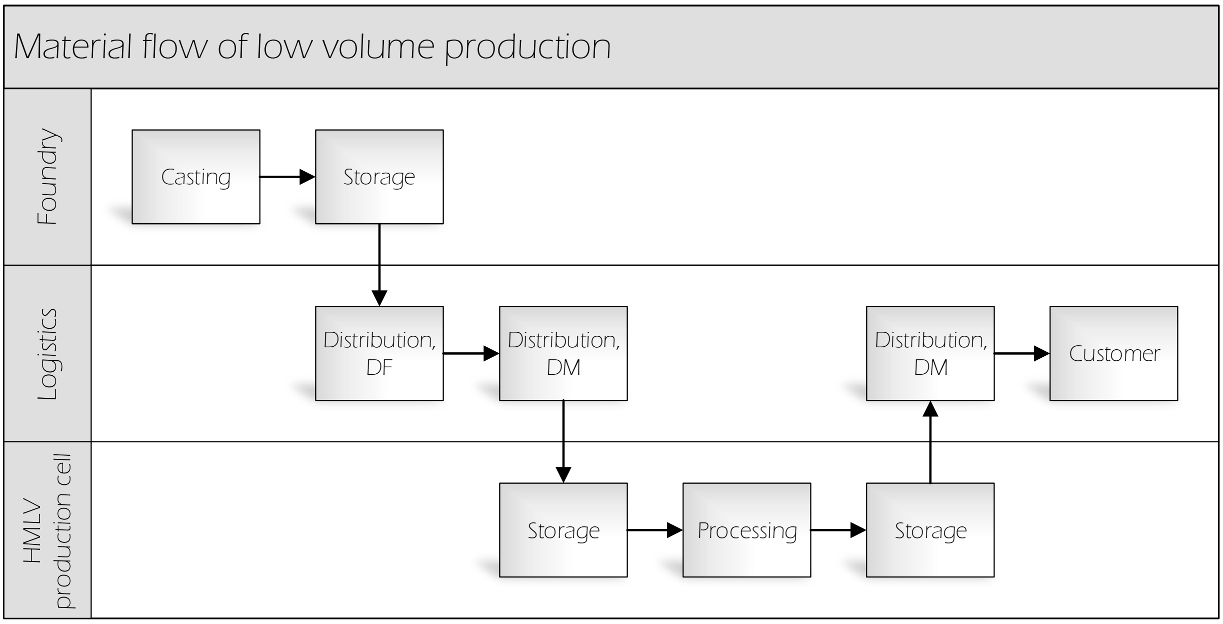

Figure 6 – Material flow of low volume production

The material flow of tool testing is challenging as the HMLV production cell cannot streamline or control the material flow of the scrapped product and the tool required to perform a tool test, since the production planner and the tooling specialist are responsible of the material being delivered. The material flow of tool testing is shown below in Figure 7.

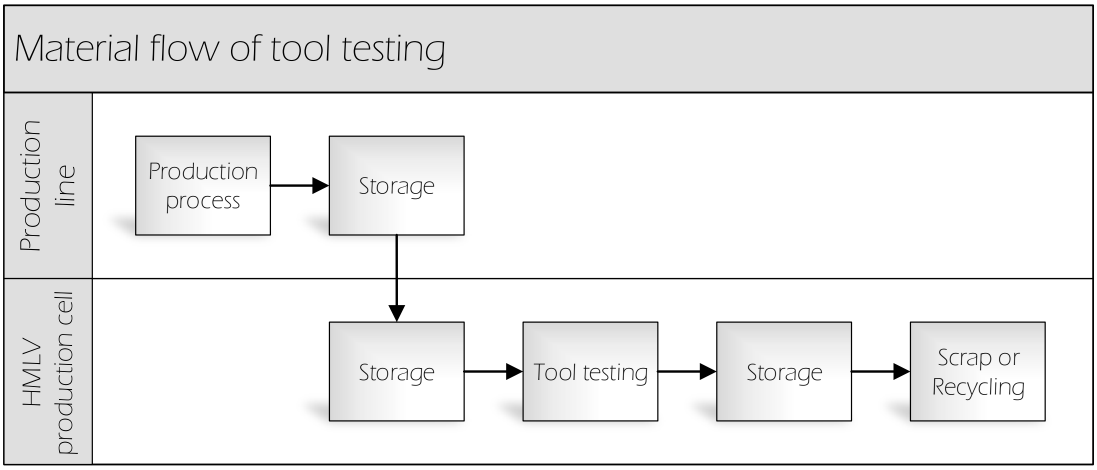

Figure 7 – Material flow for tool testing

The material flow of the core boxes for reparation is challenge due to the newness of the transportation between the new foundry and the HMLV production cell. Furthermore, the deliveries between the HMLV production cell and the new foundry must be timely for the milling operation to be performed as scheduled and for the foundry to receive the repaired core boxes as they are needed in the production. The material flow of core boxes for reparation is displayed below in Figure 8 and process involves a significant number of transportations of the core boxes, as such, the material flow of reparation is complex.

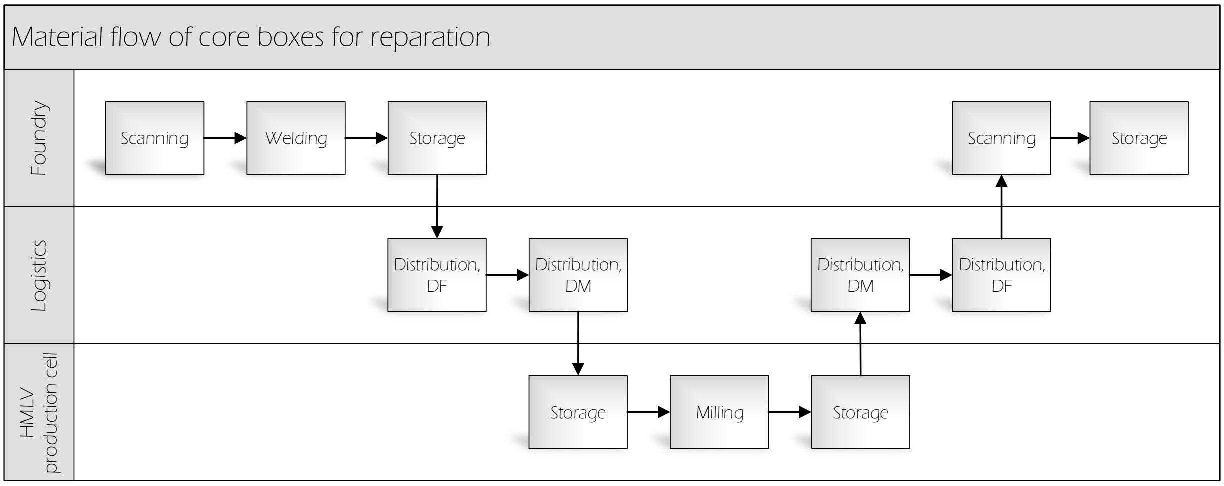

Figure 8 – Material flow of core boxes for reparation

From interviews with a project manager working on developing a similar HMLV production cell at another department of Scania, and the head of advanced engineering at the same department, it was found that the internal material flow of their HMLV production cell is significantly more complex than the material flow of the HMLV production cell at DM. The material flow in their HMLV production cell involved dedicated machinery instead of machining centers which allowed for much lower cycle times to be achieved, and much higher production capacity as a result.

The empirical data indicates that a challenge concerning production activities with external customers is the need to involve the department of logistics as it increases the complexity of the material flow. Furthermore, achieving high delivery precision is especially challenging; the material planner and process planner state that it is common for material and products to go missing in transportation if there is a lack of information and standardization of deliveries.

4.3. CRITICAL FACTORS TO CONSIDER WHEN DEVELOPING A HMLV PRODUCTION CELL

The empirical findings revealed production flexibility, production competence, production technology, pilot production, order management system and standardization to be critical factors to consider when developing a HMLV production cell. This section will describe these aforementioned critical factors.

4.3.1. PRODUCTION FLEXIBILITY

The empirical data suggests that production flexibility is critical for the capability of the HMLV production cell to perform the three production activities effectively, as well as ensure readiness for additional production activities in the future. Furthermore, the HMLV production cell must be flexible to handle the highly varied and uncertain customer demand, especially since the forecasted utilization of the core box reparation process is continuously increasing as core boxes age. Also, production flexibility is needed to perform tool testing and low volume production, which entail a high mix of products that can be significantly different. According to the project manager, internal material flow is a significant challenge due to the combination of using a high number of machines to process products whilst having a high mix of products; dedicated machinery decreases cycle time but increases complexity of internal material flow. As such, production flexibility can facilitate material flow.

The machining centers has four and five degrees of freedom respectively, which allows many different production activities to be performed due to the inherent flexibility of the machining centers. Additionally, the tool change is automatic in the machining centers and many tools can be stored in the machining centers, which increases the flexibility of the HMLV production cell. Furthermore, there are several different fixtures in the HMLV production cell, which will enable processing of different product types. However, data indicates that a universal fixture solution would have a significant importance for the flexibility of the HMLV production cell and to allow many different products to be fixtured, and thus reduce the number of fixtures needed in the HMLV production cell. In conclusion, production flexibility can facilitate the utilization of equipment.

4.3.2. PRODUCTION COMPETENCE

The employees of the HMLV production cell can plan the production themselves as the utilization is so low; higher utilization and number of orders affect the difficulty of production planning. As a result, having the production competence to plan production can facilitate the challenge of planning HMLV production. Also, the empirical data indicates that a certain set of production competence is needed to perform low volume production for external customers within the HMLV production cell, e.g., competence for CAM systems, measuring, order management and billing.

For the core box reparation process, preparatory programming is performed to create machine instructions for the milling operation, and also enables a process time for the milling operation to be computed which more closely pinpoints the actual process time of the milling operation. Production competence is needed for the preparatory programming, e.g., good understanding of the geometries and their significance for the product quality, as well as CAM competence. The preparatory programming can be performed at any location and can therefore either continue to be performed by DF or be reassigned to an employee of the HMLV production cell. If the preparatory programming is going to be performed by an employee of DM, it would be beneficial to teach the employee the intricacies of the core box design which are critical for product quality. The training would include talking to the operator at DF with experience of core box milling and observing the milling operation and could be done in only a week. Furthermore, the preparatory programming can be supported by DF until the required competence has been fully developed.

For the tool testing, tooling competence and years of experience of tools and tool testing is needed to identify an optimal tool, analyze the test results and subsequently solve the tool-related problems. Furthermore, the competence needed for testing of tools is scarce and hard to find as it takes years of experience of tools and tool testing to perform effectively according to the tooling specialist. As a result, it is critical that the tooling competence is kept and developed in Scania.

Finally, milling competence is needed to ensure that the milling operation is done correctly in the HMLV production cell for the various production activities and operations. For example, competence gained from experience of handling the machining centers and milling of products, as well as to know when to alter cutting speeds and settings for optimal results. Milling competence is currently available in the HMLV production cell as it has been used for milling operations for years. As such, the capabilities, and limitations of the HMLV production cell are known to the employees of the HMLV production cell.

4.3.3. PRODUCTION TECHNOLOGY

Production technology is critical to ensure that the capability of production to perform production activities, as some production activities cannot be performed in the HMLV production cell due to limitations of the machining centers concerning e.g., product weight and dimensions. The HMLV production cell utilizes advanced manufacturing technologies such as CNC machine tools, i.e., machining centers, automated storage and retrieval systems for tools and fixtures, as well as CAD and CAM systems. Not all activities are practical to perform in the HMLV production cell due to various factors, such as the high cycle and set-up times of machining centers. Previously produced products or products within the same product family are most practical to be produced in the HMLV production cell, i.e., motor blocks and cylinder heads, due to availability the required of production technologies, fixtures and tools. Furthermore, fixtures are critical for performing production activities in the HMLV production cell, although, a high mix of products results in a high inventory of fixtures. In addition, a fixture must be developed to allow the milling operation of the core box reparation to be performed in the machining centers in the HMLV production cell and is therefore especially critical. Also, the fixture must enable core boxes to be processed horizontally in the machining centers, as opposed to vertically in the milling machine at DF.

4.3.4. PILOT PRODUCTION

Empirical data suggest that performing a pilot production would be advantageous to assess the capability of the machining centers to perform the milling operation of the core box reparation process at an early stage of the production system development. According to the process planner at DF, performing a pilot production for a single core box will be sufficient to assess the capability of the machining centers for all relevant product groups. The feasibility of performing pilot production for HMLV production cells depends largely on the number of product families and variants which are produced. Furthermore, the pilot production can be used to identify and resolve issues concerning product quality and allow information to be collected, such as cycle and set-up times, which can facilitate production planning. Finally, the pilot production would also allow instructions and information concerning the milling operation to be communicated to the production employees of the HMLV production cell.

4.3.5. ORDER MANAGEMENT SYSTEM

When the HMLV production cell was highly utilized, the production of recurring orders was planned monthly by the material planner and the production plan was delivered through email or in person. Also, there has been no structured or standardized method of managing one-time orders for the HMLV production cell; orders have been placed haphazardly, e.g., customers visiting the HMLV production cell and informing operators of operations to be performed. However, the employees of the HMLV production cell consider the unstructured way of managing to be preferred over the dedicated software systems used at Scania for order management for line production, as it lacks flexibility. The complexity of the information flow of the HMLV production cell will increase in the future state due to a higher mix of production activities, products and customers, as such, the process planner believes that it could be beneficial for the HMLV production cell to have a structured order management system.

Comparatively, DF does not use a structured order management system for the core box reparation process since everything is currently performed internally. From interviews with a project manager and a head of advanced engineering it was found that a similar HMLV production cell at another department of Scania is utilizing a custom-made order management system, using the make-to-order strategy, to facilitating production planning. Also, the empirical data indicates that quick response to customers is important for the HMLV production cell. A summary of the necessary information for orders for the production activities is shown below in Table 5.

Table 5 – Necessary information for orders

Production activity	Information	Priority	Customers
Low volume production	Physical characteristics CAD file Process information Order quantity Delivery date	High	Departments of Scania
Tool testing	Duration of test Urgency Material information Processing information	Low	Tooling specialists
Reparation of core boxes	Machine instructions or CAD-file Order quantity Delivery date Pictures	Medium	DF

4.3.6. STANDARDIZATION

Continuous improvements have previously been made by Scania to the HMLV production cell using Lean tools such as 5S, however, the degree of standardization and structure of the HMLV production cell has since decreased due to the decreased utilization of equipment and to facilitate flexibility. There is no standardized way of arranging pallets in the designated areas for storage within the HMLV production cell, which can make it difficult to find a specific pallet or product. From interviews and observations of the HMLV production cell, it was found that there are pallets of material and products in the HMLV production cell with no planned use; the racks are being used by other departments of Scania as temporary storage. According to the material planner, standardization is especially critical for transportation of products to minimize delivery risks, e.g., by having standardized positions for pallets of products within the HMLV production cell and appointing a standardized location at the distribution centers of DM and DF for transportation of core boxes. As such, a standardized way of working with transportations should be developed to minimize delivery risks and should clearly divide the responsibility of the transportation, e.g., for the delivery and quality assurance of the products.

4.4. SYNTHESIS OF THE EMPIRICAL FINDINGS

A summary of the challenges of developing a HMLV production cell and the critical factors to consider when developing a HMLV production cell identified from the empirical findings and is shown below in Figure 9.

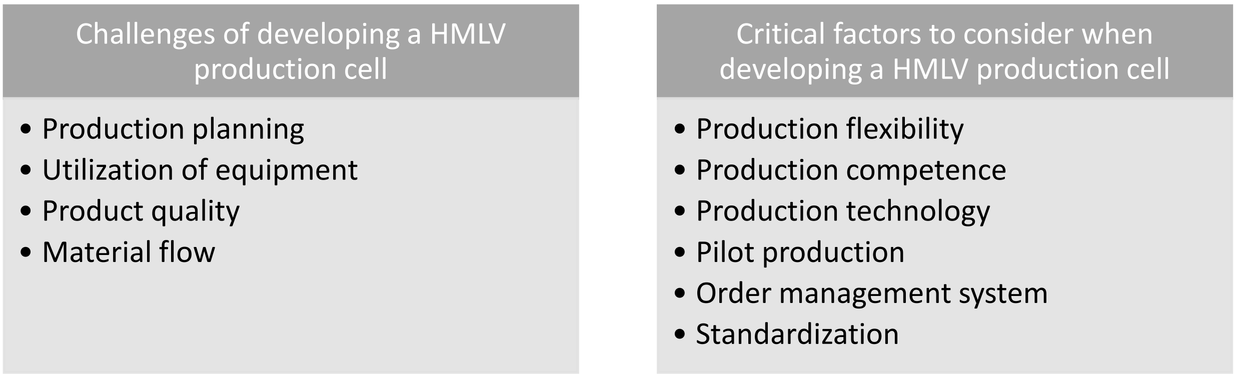

Figure 9 – Summary of empirical findings

The empirical findings revealed four challenges of developing a HMLV production cell: production planning, utilization of equipment, product quality and material flow.

- Production planning is challenging a due to a high degree of uncertainty concerning set-ups, cycle times, customer demand and delivery dates and delivery time.
- Utilization of equipment is challenging as the utilization is highly varied and uncertain and depends on customer satisfaction and production capabilities.
- Product quality is challenging due to the necessary quality assurance and conformity requirements of production activities.
- Material flow is challenging as it is highly irregular, and it is thus not possible to achieve a constant flow of material.

The empirical findings revealed six critical factors to consider when developing a HMLV production cell: production flexibility, production competence, production technology, pilot production, an order management system and standardization. In addition, the empirical data indicates that there needs to be a balance between production flexibility and standardization.

- Production flexibility is a critical factor to perform all three production activities effectively and facilitates utilization of equipment and material flow.
- Production competence is a critical factor to perform all three production activities and facilitates utilization of equipment, product quality and production planning.
- Production technology is a critical factor to perform all three production activities effectively and facilitates utilization of equipment.
- Performing a pilot production is a critical factor for the core box reparation activity and facilitates production planning, utilization of equipment and product quality.
- An order management system is a critical factor to handle the uncertainty concerning production planning.
- Standardization is a critical factor to handle the high mix of products and delivery risk and facilitates material flow.

5. ANALYSIS

In this section, the analysis of the empirical findings and the theoretical framework is done to fulfil the aim of this study and answer its research questions.

5.1. CHALLENGES OF DEVELOPING A HMLV PRODUCTION CELL

Production planning, utilization of equipment, product quality and material flow were revealed to be challenges of developing a HMLV production cell in both the theoretical framework and empirical findings. Furthermore, empirical data indicates that different HMLV production cells have different capabilities, challenges, and therefore also different critical factors. The aforementioned challenges will be analyzed in the following sub-sections of the analysis section.

5.1.1. PRODUCTION PLANNING

The theoretical findings revealed that many factors make production planning especially challenging for HMLV production cells, e.g. the high degree of complexity and uncertainty of customer demand (Safizadeh & Ritzman, 1997; Efthymiou, et al., 2014), highly varying delivery dates (Irani, 2011), lack of forecasted demand and sporadic orders (Lane, 2020). The empirical data indicated there is scarce information concerning forecasted demand for the production activities which are to be performed in the HMLV production cell at Scania, which results in higher urgency of production planning when orders are placed. The production planning thus needs to be performed on short notice, which makes it more challenging to plan the production and to maximize the capacity of the HMLV production cell. Additionally, the mix of production activities increases the challenge of production planning on short notice as some of the production activities require preparation. Furthermore, material and tools might need to be delivered to the HMLV production cell before some production activities can be performed, and the delivery time is uncertain, which can make it challenging to plan production. In conclusion, the mix of production activities, the uncertainty, lack of forecast and the uncertain delivery time make it difficult to plan HMLV production.

Production planning is challenging for HMLV production, due to the need of considering high variation of cycle times (Zennaro, et al., 2019), set-up times, and variability of production operations required to produce different products (Bohnen, et al., 2011; Irani, 2011). The empirical data also suggests that production planning is a challenge for the development of a HMLV production cell, due to e.g., highly varying, and uncertain set-up and cycle times of the production activities. This especially applies when developing a HMLV production cell with new production activities which have not been performed before, as there is a lack of accurate information concerning set-up and cycle times as the cycle time of new production activities and operations are unknown and are difficult to forecast. As such, varying and uncertain set-up and cycle times make it challenging to plan HMLV production.

Planning of HMLV production is more turbulent than traditional line production as there might be frequent changes of orders, e.g., changes to the product mix and volume (Jina, et al., 1997) which can lead to sub-optimal performance of the production system (Seth, et al., 2017). The production planning for the HMLV production cell at Scania needs to handle highly varied volumes of orders, e.g., for the core box reparation process, the number of core boxes in need of reparation can vary significantly. Also, the processing time of the milling operation depends on the condition of the core box and therefore also vary significantly. In addition, the varying mix of low volume production and tool testing can be high and change over time. In conclusion, the varying orders and the order mix make it increasingly challenging to production plan HMLV production.

5.1.2. UTILIZATION OF EQUIPMENT

The utilization of equipment in the HMLV production cell is critical to ensure profitability and to keep production competence in the company, although, ensuring high utilization of the HMLV production cell has been identified as a significant challenge. The empirical data revealed that uncertainty and variation are factors that affects the utilization of the HMLV production cell negatively. This finding is supported by Pachpor et al. (2017) stating that it is challenging to ensure high utilization of equipment when developing HMLV production cells, and that it is reflected in the fact that HMLV production cells typically have low utilization of equipment.

Often when developing a HMLV production cell, an introduction of new production activities is investigated. The empirical data indicated that when developing a HMLV production cell, a challenge of utilization of equipment is that it depends on the capabilities of the equipment; limitations of the machining centers restrict what production activities can be performed. A limitation of the machining centers concerning performing low volume production in the HMLV production cell is that the machining centers are not able to perform all operation, which restricts the utilization of equipment. Also, introducing products into the HMLV production cell which are significantly different than previously produced products to increase utilization of the equipment may require investing into new machinery, fixtures, and tools. In addition, a high mix of products will result in a high inventory of fixtures, which is another challenge which needs to be considered when developing a HMLV production cell.

HMLV production require significantly more machinery set-ups compared to the traditional line production, which decreases the productivity of the production processes (Schaller, et al., 2000). Furthermore, HMLV production cells generally have a large set-up time compared to the run time, due to large variability of process parameters and low volumes of each product (Miltenburg, 2005), which negatively utilization of equipment, which is an important factor for making HMLV production cells profitable (Fritsche, 2011). The empirical data indicates that a set-up will be required between each process, as each production activity that will be performed in the HMLV production cell at Scania is unique. The set-up time is high compared to the actual processing time and the can even be higher than the processing time for some production activities, which is largely due to the low volume of production but also as the products are typically heavy and need to be set-up manually. As such, the set-ups affect the utilization of the HMLV production cell negatively, as the set-ups are non-value adding activities.

5.1.3. PRODUCT QUALITY

Key concerns of manufacturing can be improved by focusing on improving product quality, (Chen & Huang, 2006; Colledani, et al., 2014) and is important in HMLV production cells (Choudhari, et al., 2010). Empirical data indicates that the product quality of the production lines at Scania has been continuously improved and optimized to ensure stable and high product quality. However, for the HMLV production cell to ensure the same high product quality, significantly more frequent quality controls would be required compared to the frequency of quality controls for line production. This aligns well with Hendry (1998) stating that there are generally more defected products in a HMLV production cell in comparison to line production.

The empirical data also indicates that the standardized production part approval process needs to be performed for every product produced to ensure that the process can produce conforming products with high quality. However, the production part approval process is too time-consuming to perform for a high mix of products and therefore reduces the viability of performing low volume production in the HMLV production cell. As such, ensuring high product quality for HMLV production is a significant challenge.

The empirical data revealed other challenges with the HMLV production cell, e.g., that the results from the tool testing in the machining centers may be better than what is achievable in a production line and therefore affect the effectiveness of the tool testing activity. Furthermore, as the reparation of core boxes has previously not been performed in the HMLV production cell, the capability of the machining centers is uncertain. For the core box reparation process, the resulting condition or product quality of the core boxes is crucial for the performance of the casting process. Consequently, challenges of product quality when performing production activities in the HMLV production cell is receiving false results and uncertainty when performing new production activities.

5.1.4. MATERIAL FLOW

According to Hill and Hill (2009), the material flow within HMLV production cells generally entails high number of work in progress and raw material to decouple production operations. The production activities of the HMLV production cell, i.e., tool testing, low volume production and reparation of core boxes, all entail low number of work in progress and raw material. The incongruity may be due to the inherent flexibility and capability of machining centers. Also, the low number of work in progress and raw material in the HMLV production cell should result in low inventories, which according to Miltenburg (2005), should be kept low as production volumes of each product are typically low in HMLV production cells.

Empirical data revealed that the material flow of another HMLV production cell at Scania was considered to be significantly more complex and difficult to manage, due to the use of many dedicated production machines used to reduce the cycle time of products. Comparatively, the machining centers in the HMLV production cell at DM are the only machines needed to process the products for the production activities which are investigated, which indicates that the complexity of the internal material flow is relatively low. The material flow of HMLV production is generally complex, which negatively affects lead time (Irani, 2011) and is detrimental as longer lead times reduces the productivity of production systems (Liker, 2021). As such, reducing the cycle time of HMLV production by having lower flexibility of machinery, i.e., more dedicated production machines, will likely result in higher complexity of the material flow and may negatively affect lead time. Improving the material flow is critical for manufacturing companies aiming to reduce lead time (Godinho Filho, 2017). Additionally, empirical data indicates that the complexity of the material flow seems to correlate with the number of transportations to and from the HMLV production cell and the number of machines used to process the products. These factors affecting the material flow of HMLV production are important to consider, as an effective material flow for HMLV production cells is facilitates operational performance (Huo, et al., 2016), delivery precision (Choudhari, et al., 2010), efficient inventory control (Jonsson & Mattson, 2008) and to improve the performance of the production system (Eswaramurthi & Mohanram, 2013; Kumar & Singh, 2018).

Delivery precision is important for the HMLV production cell as it is essential for the customers to receive their products in time. However, Khalil and Stockton (2010) explain that the uncertainty of HMLV production increases the demand of production flexibility, and that poor delivery reliability could be a challenging outcome. The empirical data indicates that it is not unusual that material gets lost during transportation due to lack of information and standardization. As such, the material flow of the core box reparation activity entails a challenge of developing the HMLV production cell at Scania, as the transportation between the new foundry and the HMLV production cell will increase delivery risk.

The material flow within HMLV production cells generally entails high level of work in progress and raw material to decouple production operations (Hill, 2009), although inventory should arguably be kept low as production volumes of each product are typically low in HMLV production cells (Miltenburg, 2005). Effective material flow is beneficial for delivery precision (Choudhari, et al., 2010). This applies to the HMLV production cell at Scania as well.

5.2. CRITICAL FACTORS TO CONSIDER WHEN DEVELOPING A HMLV PRODUCTION CELL

The synthesis of the theoretical framework revealed that production flexibility, production competence, production technology, pilot production, manufacturing strategy, order management system and standardization are critical factors to consider when developing a HMLV production cell. Additionally, the empirical findings revealed that production flexibility, production competence, production technology, pilot production, order management system and standardization are critical factors to consider when developing a HMLV production cell. The aforementioned critical factors will be analyzed in the following sub-sections of the analysis section.

5.2.1. PRODUCTION FLEXIBILITY

Kuzgunkaya and ElMaraghy (2006) states that a high product mix indicates higher uncertainty and Nahm et al. (2003) states that manufacturing companies facing a high degree of uncertainty tend to rely less on formal rules and policies to facilitate production flexibility. As such, it may be beneficial for the HMLV production cell to rely less on rules and standardization to facilitate production flexibility and mitigate uncertainty. Furthermore, the production personnel of the HMLV production cell can determine which products can be produced in the HMLV production cell and plan the production provided the customer demand is low; the organizational structure is flat, which according to Hill and Hill (2009) and Miltenburg (2005) facilitates production flexibility. Also, a flat organizational structure facilitates quick response to customers (Miltenburg, 2005), which is indicated by the empirical data to be important for the customers of the HMLV production cell.

Production flexibility is critical as the capability and capacity of the machining centers is uncertain for the milling operation of the core box reparation process and potential future low volume production operations, due to the newness of the operations. Although, the inherent flexibility of the machining centers enables many different production activities to be performed in the HMLV production cell, however not all activities are practical to perform in the HMLV production cell due to various factors, such as the high cycle and set-up times of machining centers. As such, the empirical data indicates that production flexibility is crucial to handle the uncertainty associated with HMLV production cells and to enable production activities to be performed effectively.

The theoretical framework supports the criticality of considering production flexibility for the development of HMLV production cells, e.g., to ensure that the production system is capable and sufficiently scalable (Javadi, et al., 2016) and to mitigate challenges of underutilization, and long set-up times caused by uncertainty and facilitate delivery precision (Khalil & Stockton, 2010), all of which are indicated by the empirical data to be challenging for the development of the HMLV production cell. In conclusion, production flexibility is a critical factor to perform all three production activities effectively and facilitates utilization of equipment and material flow.

5.2.2. PRODUCTION COMPETENCE

The theoretical framework indicates that production competence facilitates production system development, production system performance (Bellgran & Säfsten, 2010), return on assets and equity (Nadeem, et al., 2017), profitability and customer satisfaction (Lun, et al., 2016) and effective material and information flow (Godinho Filho, 2017). Empirical data indicates that various production competences are needed to perform the production activities in the HMLV production cell, i.e., CAM, milling, and tooling competence; the HMLV production cell needs highly skilled workers. According to Mohamed and Khal (2012), Choudhari et al. (2010), and Miltenburg (2005), highly skilled workers facilitate the necessary production flexibility apt for low-volume manufacturing and to ensure that production is operational and timely. As such, developing the production competence of employees of the HMLV production cell may be beneficial. Although, the empirical findings indicate that some production competences are hard to find, e.g., the competence needed for testing of tools is scarce and hard to find as it takes years of experience to perform tool testing effectively according to the tooling specialist. As a result, it is critical that the tooling competence is kept and developed in Scania to perform the tool testing in the HMLV production cell. According to Snell et al. (2015), organizational support is essential to improve the capabilities of employees. The fact that an operator of the HMLV production cell is undergoing training to use CAM software, and that DF support the preparatory programming until the required competence has been fully developed, shows that there is organizational support for increasing internal competence.

The efficiency of the milling operation of the core box reparation process can be increased by developing production competence to enable the preparatory programming to be performed by an employee of the HMLV production cell. This empirical finding is supported by Lee et al. (2015) stating that employee development facilitates production capacity and the efficiency of production processes, and Sarfaraz et al. (2015), Agarwal et al. (2013) and Lyons (2005) stating that employee development improves manufacturing performance. Also, empirical data suggests that training an employee of the HMLV production cell can be beneficial to facilitate product quality and would entail observations of the core box reparation process. According to Javadi et al. (2016), general training of employees, including observations of the production system, can facilitate production system development and are particularly beneficial within low-volume manufacturing.

Empirical data suggests that whilst Scania has a significant amount of internal competence, it can be beneficial to use equipment suppliers and shift people with the required competences to the HMLV production cell. The theoretical framework indicates several benefits with outsourcing competence, e.g., as sources of major innovations (Lager & Frishammar, 2010) and to ensure the requisite competence of new technologies (Kumar, et al., 2018). However, the downside of relying on outsourcing for production system development tasks is that it impedes companies’ ability to identify and plan future developments and build internal competence (Bruch & Bellgran, 2014). It is especially challenging to allocate personnel for production system development within low-volume manufacturing industries, due to production personnel and project members being involved in other projects and on-going production activities (Javadi, et al., 2016). In conclusion, production competence is a critical factor to perform all three production activities and facilitates utilization of equipment, product quality and production planning.

5.2.3. PRODUCTION TECHNOLOGY

Empirical data indicates that production technology is critical to consider as it enables production activities to be performed in the HMLV production cell; whilst the capability of the machining centers is high, limitations of production technology can result in high cycle and set-up times. This is supported by Kumar and Singh (2018) stating that the physical and technical capabilities directly affect the capacity of production activities which in turn affect the outputs of the production system, e.g., product quality, reputation, and profit, and is therefore critical to consider in the development of production systems.

The HMLV production cell utilizes advanced manufacturing technologies such as CNC machine tools, i.e., machining centers, automated storage and retrieval systems for tools and fixtures, which facilitates production flexibility and capability. Advanced manufacturing technology is a critical factor for HMLV production cells to facilitate the degree of product customization required (Zhang, et al., 2006) and production flexibility (Dhinesh, et al., 2005), e.g. using automatic storage and retrieval systems, CNC machine tools (Raj, et al., 2010). As such, production technologies, and especially advanced manufacturing technologies are critical to consider for HMLV production cells.

Implementing production technology which improves the tool, method or technique used in manufacturing can increase productivity and profitability (Mandal & Bagchi, 2016) and can be facilitated by employee training and integration of departments (Kumar, et al., 2018). Thus, implementing additional production technologies which improve the performance of the HMLV production cell to perform the production activities may be beneficial and can be facilitated with employee training and integration of departments. Practically, this could imply training employees of the HMLV production cell to improve production competence such as using CAM software and learning from other departments of Scania, which could be done in combination. This is supported by Malmsköld et al. (2012), stating that CAD and CAM systems can be used as a complimentary learning tool and training method to communicate the intricacies of products and processes to production personnel.

High set-up times was revealed to contribute to the challenge of ensuring high utilization of equipment. According to Hendry (1998), set-up times can be reduced by optimizing set-up methods such as fixturing of parts. Also, fixtures have been identified as especially critical for the HMLV production cell as they are necessary for all production activities and enable the machining centers to perform the milling operation of the core box reparation process. As such, a fixture solution was developed with the support of the tool designer to enable a pilot production of the milling operation of the core box reparation process to be performed and is shown below in Figure 10. In conclusion, production technology is a critical factor to perform all three production activities effectively and facilitates utilization of equipment.

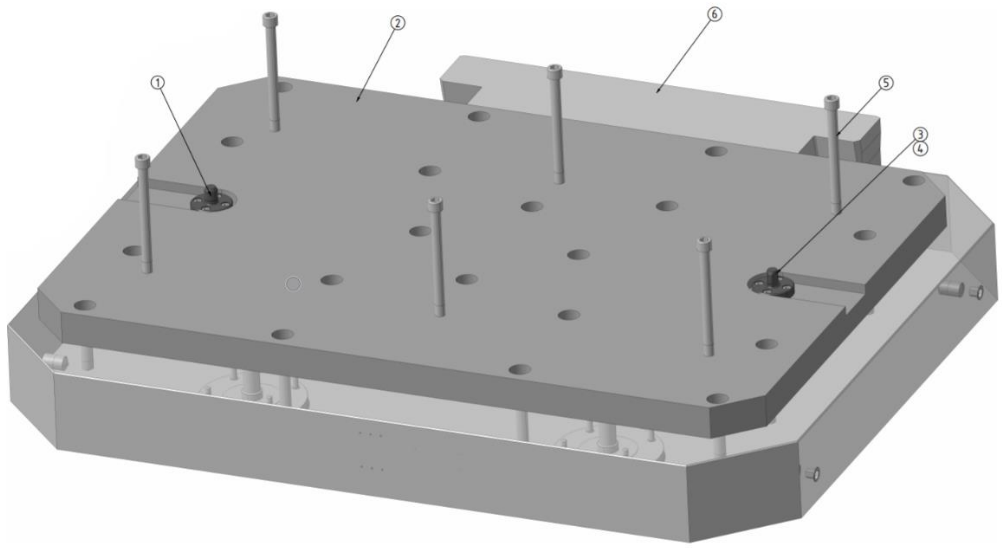

Figure 10 – Fixture solution for core box reparation

5.2.4. PILOT PRODUCTION

Manufacturing companies typically consider modifications of production systems late in the development process due to a lack of testing and refining of the production system prior to the production ramp-up (Javadi, et al., 2016). Also, Bruch and Bellgran (2014) suggests that dedicating more resources early in the development phases is beneficial to ensure a sound starting point. Empirical data indicates that performing a pilot production for a product group of core boxes would be advantageous to assess the capability of the machining centers to perform the milling operation of the core box reparation process at an early stage. Performing a pilot production is a way to frontload the production system development which ensures a sound starting point of production system development (Bruch & Bellgran, 2014), and is especially critical in low-volume manufacturing industries (Javadi, et al., 2016). Furthermore, pilot productions are typically done to verify and refine the production system (Winkler, et al., 2007; Fjällström, et al., 2009) and to ensure that a conceptual solution will work well in practice (Thabane, et al., 2010). The goal of performing a pilot production for the core box reparation process is to ensure the capability of the machining centers to perform the milling operation as the HMLV production cell will initially only be assigned a few orders until the capability of the machining centers has been proven according to the process planner at DF.

Performing a pilot production may also facilitate the efficiency of production personnel to produce the new product (Bellgran & Säfsten, 2010) and to reduce disturbances (Säfsten, et al., 2006; Bellgran & Säfsten, 2010). Performing a pilot production can allow information, such as cycle and set-up times to be collected which can facilitate production planning, which has been identified as a challenge of developing a HMLV production cell. Finally, the pilot production would also allow instructions and information concerning the milling operation to be communicated to the production employees of the HMLV production cell. Also, it is important to note that it is beneficial to use cross-functional teams (Adler, 1995) and include other disciplines and functions of manufacturing, such as the logistics function and operators (Bruch & Bellgran, 2014). Thus, it is recommended that a cross functional team consisting of the customer, in this case DF and operators should be included in the pilot production to ensure customer satisfaction. Additionally, an employee with CAM competence should be involved in the pilot production. In conclusion, performing a pilot production is a critical factor for the core box reparation activity and facilitates production planning, utilization of equipment and product quality. The feasibility of performing pilot production for HMLV production cells depends largely on the number of product families and variants which are produced.

5.2.5. MANUFACTURING STRATEGY

The manufacturing strategy is important for mitigating the challenge ensuring high utilization of equipment caused by high set-up times. For example, set-up times can be reduced by improving the relationship and involvement of suppliers and customers in the design process (Hendry, 1998). The customers of the HMLV production cell are departments of Scania and are therefore integrated and involved in the development of the HMLV production cell. Furthermore, ensuring customer satisfaction is crucial to improve customer loyalty and profitability (Helgesen, 2006). For the HMLV production cell at Scania, customer satisfaction indicates that delivery precision and conforming product quality must be secured. Additionally, the fact that most of the customers of the HMLV production cell are departments of Scania likely contributes to customer loyalty and may thus benefit profitability. Furthermore, the customers of the tool testing and low volume production for internal customers are located in the same building in which the HMLV production cell is located. However, DF is located in another building, as such, it can be beneficial for the HMLV production cell to improve the involvement and relationship with DF concerning the reparation of core boxes activity.

Lane (2020) suggests that products with recurring orders in relatively high volume should obtain majority of the focus in the production. For the HMLV production cell at Scania, the reparation of core boxes activity has the highest forecasted utilization of equipment. Therefore, it could be beneficial for Scania to frontload and prioritize the customer satisfaction of the reparation of core boxes in the development of the HMLV production cell. Customer satisfaction is critical to enable the production activity to be performed but also since DF are willing to outsource all milling operation jobs to the HMLV production cell if they are satisfied with the results, which would lead to an increased utilization of the machining centers.

Empirical data revealed that a challenge of developing the HMLV production cell is that the material flow of the investigated production activities is highly irregular. It is hence not possible to achieve a constant flow of material, which is one of the goals of the Lean manufacturing strategy and entails decreased production flexibility (Seth, et al., 2017). Production flexibility has been identified as a critical factor to consider when developing the HMLV production cell to perform all three production activities effectively and facilitates utilization of equipment and material flow. In addition, the usefulness of tools and methods used for improving traditional line production system performance can be challenging to apply to HMLV due to the high variability of production volumes and mix of products (Hendry, 1998), e.g. the value stream mapping tool (Seth, et al., 2017). This indicates that Lean is not a suitable manufacturing strategy for the HMLV production cell, which is corroborated by Irani (2011) stating that Lean is not designed to be utilized for HMLV production, which means that the use of Lean tools must be done thoughtfully.

Some of the values and principles of Lean still apply to HMLV production, e.g., developing leaders well acquainted with the company philosophy and increasing internal competence (Irani, 2011). The HMLV production cell was developed by Scania and consequently conforms to the standards and values of Scania which align with those of Lean manufacturing. As such, the HMLV production cell follows many of the principles of Lean. Also, facilitating factors of the manufacturing strategy to support HMLV production are e.g., emphasizing employee- and customer-driven policies (Gomes, et al., 2006). These values and facilitating factors are present, as Scania strives to maintain and improve the internal production competence and believes that the development of the HMLV production cell can facilitate internal production competence. As such, the development of the HMLV production cell has managerial support, which is critical for attaining operational benefits to improve the manufacturing output and increasing the efficiency of production systems (Asrofah, et al., 2010; Chung & Lee, 2005). In conclusion, manufacturing strategy is a critical factor to consider when developing a HMLV production cell, although there is insufficient empirical data to confirm which challenges it facilitates overcoming.

5.2.6. ORDER MANAGEMENT SYSTEM

The theoretical framework indicates that an order management system facilitates feedback and control of information and is beneficial for departmental activities to improve manufacturing performance (Kumar & Singh, 2018) and has a positive impact on customer satisfaction (Karim, et al., 2008). The empirical data suggests that an order management system is critical for the HMLV production cell to facilitate production planning and quick response to customers.

Empirical data revealed that the management of one-time orders for the HMLV production cell has been unstructured and done haphazardly, which could result in material and products showing up unexpectedly to the HMLV production cell and the job instructions arriving later. Although, the employees of the HMLV production cell consider the unstructured way of managing orders to be preferred over the dedicated order management systems used at Scania for line production, which does not offer enough flexibility. According to Bruch and Bellgran (2014), achieving an effective flow of information needed for production planning can be challenging for manufacturing companies even if the involved functions are at the same company. Okamoto (2003) and Fritsche (2011) states that an order management system can act as an organic link and channel of communication for the information flow between customers and production personnel and is critical to sustain flexible production. As such, it may be beneficial for the HMLV production cell to have a structured order management system with high flexibility.

From interviews it was found that whilst DF does not use a structured order management system for the core box reparation process since everything is currently performed internally, another department of Scania is utilizing a custom-made order management system, using the make-to-order strategy, which they consider to be facilitating production planning. Furthermore, make-to-order is one of the most common production strategies utilized in HMLV production cells, in which production starts after an order is placed (Zennaro, et al., 2019) and therefore it is not necessary to plan the production in forehand (Arreola-Risa & Decroix, 2002). Make-to-order is typically the appropriate production strategy for low-volume manufacturing companies (Wrobel & Laudański, 2008) and HMLV production cells (Choudhari, et al., 2010) to handle the high complexity and mix of products which distinguishes the low-volume manufacturing industries (Rahim & Baksh, 2003). Make-to-order enables customers to order customized products to their specifications, typically in low volumes and with an unpredictable order pattern, due to the high degree of customized orders (Arreola-Risa & Decroix, 2002). In contrast, engineer-to-order is an appropriate method to handle high product complexity and customer involvement in HMLV production cells, which entails production of unique products according to customer specifications (Seth, et al., 2017). Although, the production activities which are investigated do not entail production of unique products according to customer specification, as such, the make-to-order strategy is recommended.

A structured order management system with high flexibility was identified in section 4.3.5 to facilitate production planning to ensure that the HMLV production cell at Scania is easy to manage and operate. Table 5 in the same section demonstrates the necessary information for orders for the production activities and can support Scania in the development of an order management system. Additionally, having a structured order management system for the HMLV production cell helps to mitigate many of the challenges of developing a HMLV production cell which have been identified. For example, the order management system can help to reduce uncertainty, facilitate production planning and consequently help to increase the utilization of equipment. In conclusion, an order management system is a critical factor to handle the uncertainty concerning production planning.

5.2.7. STANDARDIZATION

Standardized work is necessary to achieve consistency of high-quality products, even when producing a high mix of products (Irani, 2011; Weber, 2016; Kafetzopoulos, et al., 2015). Empirical data suggests that the development of the HMLV production cell will entail a higher mix of products and uncertainty which must be handled. According to Bohnen et al. (2011) and Irani (2011), standardization of HMLV production cells is beneficial to handle the high complexity of information and material flow caused by a high mix of products and uncertainty.

There is no standardized way of arranging pallets in the designated areas for storage within the HMLV production cell, which can make it difficult to find a specific pallet or product. From interviews and observations of the HMLV production cell, it was found that there are pallets of material and products in the HMLV production cell with no planned use; the racks are being used by other departments of Scania as temporary storage. According to Hendry (1998), it is critical to ensure visibility and standardization of material, machinery, and tools in HMLV production cells, which can be done through visible and nearby storage systems to facilitate the removal of obsolete parts and material. As such, it may be beneficial to standardizing the storage systems and removing obsolete parts and material in the HMLV production cell. It may also be beneficial to have process information and instructions accessible to ensure that operations are performed properly for a high mix of product types (Weber, 2016), as the development of the HMLV production cell entails a higher mix of product types and production activities.

According to the material planner, standardization is especially critical for transportation of products to minimize delivery risks, e.g., by having standardized positions for pallets of products within the HMLV production cell and appointing a standardized location at the distribution centers of DM and DF for transportation of core boxes. One way to facilitate the standardization of transportations is through using grouping technology, which is described by Weber (2016) to be a manufacturing technique where products with similarities are grouped together and manufactured at the same location, with the motive to handle each group rather than the individual product types. For the HMLV production cell, this could be done by standardizing the information and material flow of production activities. A structured and standardized way of working with transportations should be developed to minimize delivery risks, especially during transportations of core boxes. Additionally, the standardized way of working with transportations should clearly divide the responsibilities of transportations, e.g., for the delivery and quality assurance of the products. In conclusion, standardization is a critical factor to consider when developing the HMLV production cell, although, there needs to be a balance between production flexibility and standardization. In conclusion, standardization is a critical factor to handle the high mix of products and delivery risk and facilitates material flow.

5.3. SUMMARY OF FINDINGS

A summary of the findings, i.e., the challenges of developing a HMLV production cell and critical factors to consider when developing a HMLV production cell is shown below in Figure 11. The figure shows which critical factors can facilitate overcoming the identified challenged of developing a HMLV production cell.

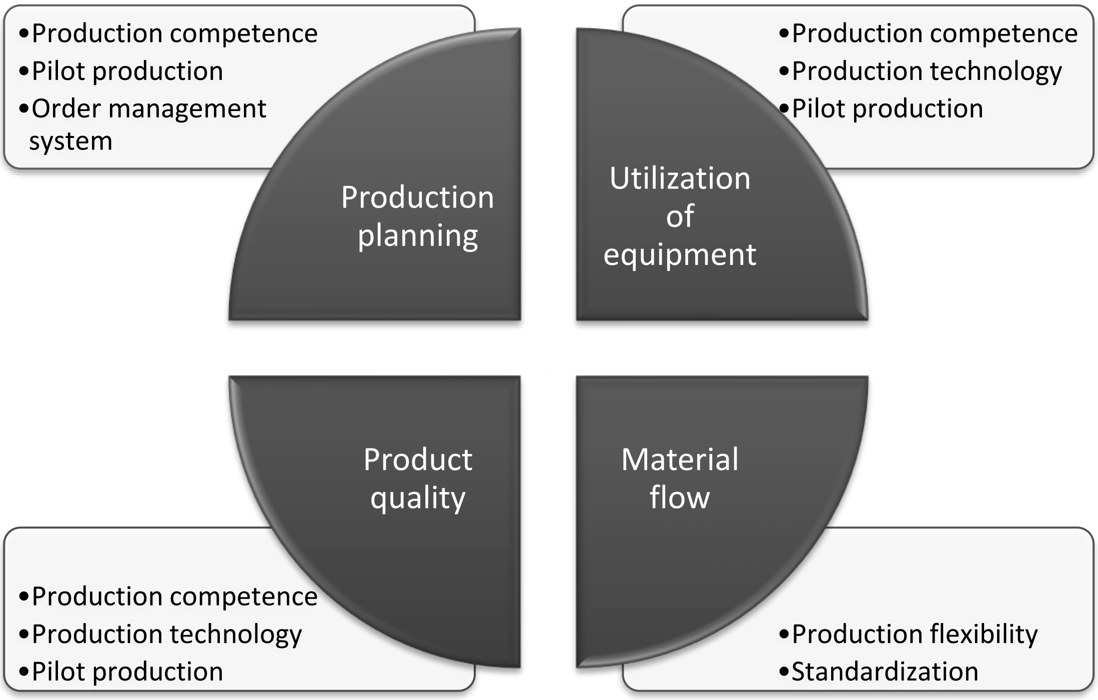

Figure 11 – Summary of findings

6. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

In this section, the results from this study and the contribution to current research are discussed and concluded. Additionally, recommendations for Scania and for further research are presented.

The aim of this study was to support the development of a HMLV production cell. The aim of this study was fulfilled by synthesizing the empirical findings from a case study conducted at Scania in Södertälje with the theoretical framework created from a literature review. Additionally, the following three research questions were answered:

RQ1: What are the challenges of developing a HMLV production cell?

The identified challenges of developing a HMLV production cell are production planning, utilization of equipment, product quality and material flow.

RQ2: What are the critical factors to consider when developing a HMLV production cell?

The identified critical factors to consider when developing a HMLV production cell are production flexibility, production competence, production technology, pilot production, manufacturing strategy, order management system and standardization.

RQ3: How can the development of a HMLV production cell be supported?

The identified challenges of developing a HMLV production cell and the critical factors to consider when developing a HMLV production cell can support manufacturing companies by indicating the challenges to expect prior to developing a HMLV production cell, and the critical factors to mitigate these challenges. This is supported by Rösiö and Bruch (2018) which states that manufacturing companies tend to focus on technical subsystems and equipment, and support for other aspects of production system design is often neglected (Rösiö & Bruch, 2018).

The identified critical factors can support manufacturing companies to develop a HMLV production cell by indicating aspects of the production system design which are critical to consider in the early phases of development. Looking ahead is a facilitating factor for successful production system development according to Bruch and Bellgran (2014), as the process used by manufacturing companies for production system development is typically greatly influenced by existing production systems and products (Rösiö, 2012). The critical factors can also support Scania to achieve a holistic perspective of the development of the HMLV production cell, which tends to be challenging for manufacturing companies, and is crucial to avoid suboptimization, ensure readiness for future changes to the production system and to secure economic feasibility for future product variants and families (Javadi, et al., 2016).

To support the development of a HMLV production cell, two ways of supporting the development of a HMLV production cell are recommended to Scania: creating a structured order management system and performing a pilot production for the milling operation of the core box reparation process, for which a fixture solution was developed. Kuzgunkaya and ElMaraghy (2006) states that manufacturing companies find it challenging to develop production systems so that the production system satisfies functional requirements whilst still being easy to manage and operate. Also, Javadi et al. (2016) states that modifications of production systems are typically considered late in the development process due to a lack of testing and refining of the production system prior to the production ramp-up. The pilot production is recommended as it contributes to ensuring that the HMLV production cell satisfies functional requirements, and to reveal necessary modifications to the HMLV production cell at an early stage of the development process. Additionally, the order management system ensures that the HMLV production cell is easy to manage and operate.

The recommendation to perform a pilot production was revealed from empirical data which suggests that performing a pilot production can facilitate the development of the HMLV production cell at Scania, specifically for one of the investigated production activities which has never been performed in the HMLV production cell previously; performing a pilot production is a way of testing and refining the HMLV production cell. Although, performing pilot productions may not be useful for other manufacturing companies aiming to develop a HMLV production cell, especially if many new production activities and products are to be introduced to the HMLV production cell. In this case, using CAM software and running simulations to test and refine the HMLV production cell are more effective alternatives, as these tools are more appropriate to use for a high mix of products or production activities.

The reliability of the findings of this study was increased by comparing empirical findings to the theoretical framework created from a literature review. Although, a limitation of this study is that only one case was investigated, which limits the reliability of findings and the applicability of the results. Also, the findings of this study are highly linked to the set of production activities which were investigated, and a different set of production activities could result in the identification of other challenges and critical factors. Another limitation of this study is that all empirical data was collected prior to the development of the HMLV production cell, thus, the findings could not be validated from the realization phase of the development of the HMLV production cell.

The results of this study contribute to the scarce research area of production system development of HMLV production cells. Furthermore, empirical findings from benchmarking indicate that different HMLV production cells have different capabilities, challenges, and therefore also different critical factors. As such, a recommendation for further research is to investigate how the development of different types of HMLV production cells can be supported by using a multiple case study research design, and to compare the challenges and critical factors for the development for the different types of HMLV production cells. In addition, another recommendation for further research is to study the realization phase of the development of a HMLV production cell and identify the challenges and critical factors of the realization phase. The findings of such studies can validate the findings of this study.

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8. APPENDICES

8.1. APPENDIX 1 – INTERVIEW GUIDE: PHASE 1

The interview started with a presentation of the thesis workers and the project conducted at Scania. Thereafter the semi-structured interview was initiated with the following questions.

- Vem är du? vad är din roll? Hur länge har du arbetat med detta?
- Vad arbetar du med? Vilka är dina arbetsuppgifter?
- Vilka system använder du i ditt arbete?
- Är du eller har du varit delaktig i cellen?
- Vad har du i sådana fall gjort i cellen?
- Ser du några möjligheter med cellen?
- Ser du några utmaningar för utvecklingen av cellen?

Phase 1 interview with the material planner was initiated with the same questions, but included different questions focusing on the order management for production activities to be performed in the HMLV production cell.

- Hur utförs produktionsplaneringar för cellen?
- Hur hanteras order för cellen?

Phase 1 interview with the employees of DF was initiated with the same questions, but included different questions focusing on the reparation of core boxes.

- Hur utförs reparationer av gravyrer i nuläget?
- Klarar fleroperationsmaskinerna i cellen av att reparera dessa?
- Vad tror ni om möjligheten att utföra reparationer av gravyrer i cellen?
- Hur skulle flödet för transporten av gravyrer till cellen från nya gjuteriet gå till?
- Hur arbetar ni med orderhantering och produktionsplanering?

Phase 1 interview with the tooling specialist was also initiated with the same questions, but included different questions focusing on the tool testing process.

- Hur utförs verktygstester i nuläget? Var? Hur ofta? Hur lång tid tar det?
- Vad innebär ett verktygstest? Vilka egenskaper testas huvudsakligen?
- Vad krävs för att utföra verktygstester?
- Hur sker orderhanteringen för verktygstesterna?