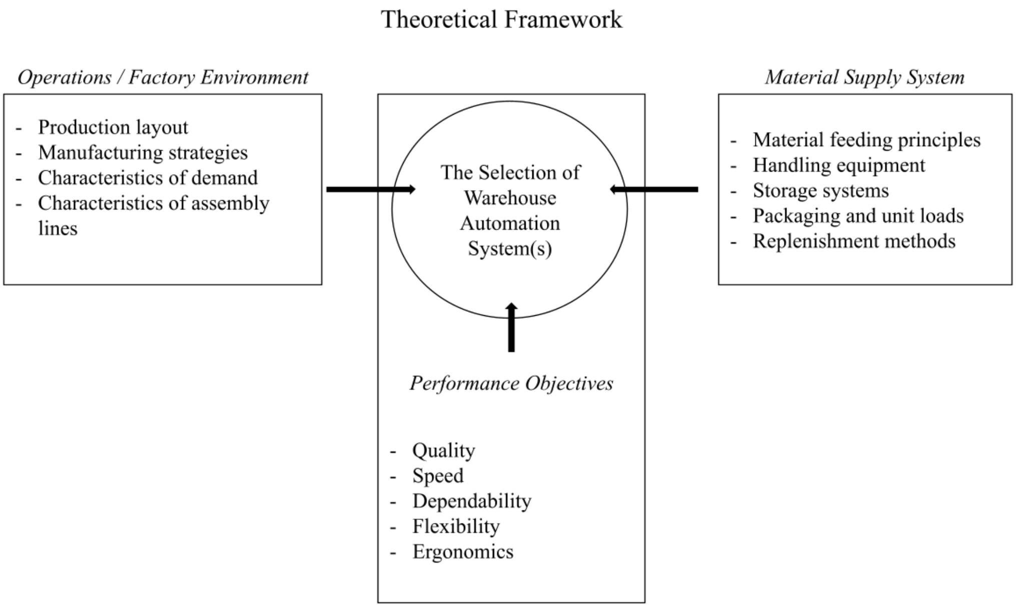

Selection of Warehouse Automation System(s) for component storage

- in a multiple assembly line manufacturing context

Master's thesis in Supply Chain Management

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Cover: The theoretical framework for selection of Warehouse automation system(s) for component storage developed in this master's thesis.

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Selection of Warehouse Automation System(s) for component storage
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Abstract

The purpose of this master's thesis is to explore how the case company, which is a large scale manufacturer, can improve its internal materials supply operation by increasing the level of automation of the component storage systems. This master's thesis contain comprehensive and cohesive recommendations for what performance requirements that are imposed on warehouse automation system(s), which will be used for component storage by a case company within a multiple assembly line manufacturing context. Such performance requirements are imposed by the Operations / Factory Environment, such as: the Production layout; Manufacturing strategies applied; Characteristics of demand (i.e., the Four Vs: Volume; Variation; Variability; and Visibility); as well as the Characteristics of the assembly lines that the stored components are designated for. Further requirements for what warehouse automation system(s) to select for component storage purposes, are imposed by the Material Supply System, like: the Material feeding principles applied; Handling equipment; Storage systems; Packaging and unit loads; and Replenishment methods utilized. In addition, there are requirements imposed by the Performance objectives (i.e., Quality, Speed, Dependability, Flexibility and Ergonomics) for the internal material supply processes, which all should be considered when selecting warehouse automation systems for component storage. A theoretical framework has been developed based on all these requirements imposed, which can be used as a point of departure when selecting warehouse automation system for component storage for any company in a similar manufacturing context. This master's thesis, also include recommendations for what type of warehouse automation system(s) the case company should select for component storage, based on what type of system that best fulfills the performance requirements imposed. Further, market research has been conducted to identify the best suited warehouse automation system(s) based on all the requirements imposed. In this case, the recommendations are that the case company selects the vertical carousel for component storage within the case facility. Further, it is recommended that each assembly line has a dedicated vertical carousel each. These recommendations provides the best solution, considering the performance requirements imposed on the warehouse automation systems for component storage. In addition, the expected consequences for the company's internal material supply operation related to implementing these recommendations are described as well.

Keywords: Warehouse automation, Component storage automation, Automated component storage, Automated storage and retrieval systems, AS/RS, Manufacturing logistics, Internal logistics, Material supply operation, Material feeding processes.

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This master's thesis project was initiated by Parker Hannifin Manufacturing Sweden AB (Pump & Motor Division Europe). Further, this research project has been conducted at Chalmers University of Technology, within the Department of Technology Management and Economics, as a final part of the master program in Supply Chain Management.

We would especially like to thank our supervisor at the case company, Lars Svedung at Parker Hannifin Manufacturing Sweden AB (Pump & Motor Division Europe), who provided us the opportunity to conduct this research project and who have supported us with valuable information and feedback during the project proceeding. Also, we would like to thank Lars Markström and all other members of Parker Hannifin who have supported us in data collection, by agreeing to interviews and site visits, and by providing other necessary information throughout the project.

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Erland Nilsson & Vikraman Jayaraman, Gothenburg, June 2021

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1
Introduction

In this chapter, this master's thesis background, aim, limitations and research questions are presented. First, the thesis background is described in a wider industry context. Thereafter, is the background of the case company's specific situation presented followed by a clarification about how the case company's specific situation is related to the previously described wider context. After that, the aim, limitations and defined research questions of this thesis is presented. Finally, the issue of ethical, societal and ecological aspects are brought up.

1.1 Background

The trend of increased globalization of industrial markets not only provides opportunities for companies in the form of increased sales potential, but it also stiffens the market competition (Rüttimann, 2018). A company's competitive advantage derives from all its performed activities, which make activities the basic unit of competitive advantage (Porter, 1998). The part of a company that creates or delivers its products and services is referred to as Operations (Slack & Lewis, 2015). Since all organizations in one way or another try to add value by producing products and/or services, either for internal or external customers, operations is a function that exists within all companies even though it internally may be called something else (Slack & Lewis, 2015).

Logistics is one such operation that supports the core value-adding processes. Logistics operations can be divided into internal and external logistics, where internal logistics deals with the flow of material within a facility (Groover, 2008; Gupta & Dutta, 1994). Thus, internal logistics includes areas of material supply and material management such as goods receiving, material handling, material feeding, storage and inventory, internal transport and packaging (Granlund, 2014). Even though internal logistics activities in general are considered as a non-value adding activity, it plays an important role in the overall function of organization in terms of business goals (Granlund, 2014). For example, it affects a company's readiness to deliver in a business environment that is ever more characterized by an increasing variety of products, higher ordering frequency of smaller lots, and tougher requirements for shorter delivery times (ten Hompel & Schmidt, 2007). In addition, a major reason for internal stock keeping is to ensure the productivity of expensive production processes by securing the material supply, for example, by buffering semi finished products between processes that differ regarding process time, output quantities, etc. (ten Hompel & Schmidt, 2007). Further, the increased market demand requires an increased focus on internal logistics since it supports operational performance of, for example, efficient material handling solutions and just-in-time supply of materials (Granlund, 2014). Hence the trend of increasing market demand creates a huge pressure and importance of logistics operations (Kartnig et. al, 2012).

Operational effectiveness refers to a company´s relative performance of activities, which are the same or similar as the activities performed by the competitors (Porter, 1996). Even though operational effectiveness is not sufficient to reach or sustain superior performance in relation to competitors, it is a prerequisite for it (Porter, 1996). A company can improve its operational effectiveness, for example by eliminating wasted efforts and implementing more advanced technology, thereby influencing the level of differentiation and its cost position in relation to competitors (Porter, 1996). Though, purchasing top notch technology is not a guarantee for a company to reach or sustain superior performance, instead this is enabled by the ability to perform activities better than what competitors do (Hayes & Upton, 1998).

Automation is one such way to improve competitiveness in operation. For example within the manufacturing industry, automation is known as a means of improving efficiency, productivity, quality and safety as well as lowering costs (Cruz Di Palma and Basaldúa, 2009; Frohm et al., 2006; Groover, 2008; Michalos et al., 2010). Automation has registered a huge mark on the operational areas such as picking, packaging, labeling, replenishment, storage and retrieval (McCrea, 2020). A survey conducted by Peerless Research Group (PRG) in 2020, indicates that there is an increase in respondents who want to increase the level of automation within those areas as compared to 2019 (McCrea, 2020).

The performance of an operation can be measured by comparing how well it reaches the five generic performance objectives (i.e., Quality, Speed, Dependability, Flexibility, and Cost), which both directly and indirectly relates to the fulfillment of customer requirements (Slack & Lewis, 2011). Mediocre operations are usually easy to replicate by competitors, though matching an outstandingly performed operation is often very difficult (Hayes & Upton, 1998). A contributing factor for this, is that management of an operation according to Slack and Lewis (2015) involves handling two interacting sets of issues, namely Processes and Resources.

Operations and processes not only vary in terms of what technologies and skills that are needed to perform them, but also regarding the characteristics of the demand of the produced products and services (Slack & Lewis, 2015). The Four Vs (i.e., Volume, Variety, Variation, Visibility) are considered as four influential characteristics of demand, which each one has implications for how to successfully manage a process (Slack & Lewis, 2015).

When several different products or services, with both different technical and demand characteristics, must be processed within the same operation different implications arise for how to design and manage the operation in the best way. Some previous research indicates that the major problems with automation are not with the actual automation level or a lack of technology, but rather regarding the implementation and difficulty in selection of appropriate automation and the integration of it (Durrani et al., 1998; Sambasivarao & Deshmukh, 1995). The success of automation depends on selecting, acquiring and implementing the right type of automation in consideration to the company's needs, goals and prerequisites (Baines, 2004; Ceroni, 2009; Daim and Kocaoglu, 2008; Spath, Braun, & Bauer, 2009; Säfsten, Winroth, & Stahre, 2007).

At the case company, a manufacturer of hydraulic pumps and motors, the management wants to improve the overall operational effectiveness by increasing the level of automation of the internal material supply operation. These plans are complicated by the fact that there are seven separate assembly lines, within the same production facility, which produces finished products that are assembled by components that differ regarding both technical features (e.g., weight and size) and demand characteristics (i.e, Volume, Variety, Variation, and Visibility).

1.1.1 The case company's situation

The case company is a manufacturer of hydraulic pumps and motors for mobile applications. The company's main customer base consists of manufacturers of heavy machinery and vehicles, from all around the world. This includes manufacturers of trucks, construction machinery and forest machines.

The case company's product portfolio consists of four main product groups: AAA, BBB, CCC and DDD. Each main product group has a certain function and application area and includes multiple models, which in turn are made in several variants. The finished product's weight is between 4.7 kg and about 100 kg. The large variety of finished products entails that there also is a large difference in the required number of input components between different product models and variants. At the case facility, the case company both assembles and tests all manufactured products before delivery. Also, a large share of the input components are manufactured in-house, though input components are also delivered to the case company as finished for assembling. In addition, some in-house manufactured components are shipped to external suppliers for further treatment, before being sent back to the facility.

The goods received have the same manual process for all four main product groups. The case company requests suppliers to ship components in standardized 300x400mm bins, which are owned and provided by the case company. Though, some major suppliers do not fulfill this request and instead ship components in packaging of other sizes. Since the inventory rack system at the case company is adapted to the standardized bins, the case company needs to manually repackage some components to the 300x400mm bins.

At the case facility, there are seven separate assembly lines in total for the four main product groups, which differ regarding volume assembled, assembly complexity, practiced internal material supply methods, etc. The characteristics of the four main product groups are described in Table 1.1. Volume assembled refers to the annual number of finished products assembled, while assembly complexity refers to the number of line items per variant and the number of sellable variants.

Table 1.1: *Characteristics of the case company´s four main product groups assembled within the case facility.*

Main product group / Characteristics	**AAA**	**BBB**	**CCC**	**DDD**
Volume assembled (annual number of finished products assembled)	High ∼[40 000, 100 000]	Medium ∼[20 000, 60 000]	Low ∼[0, 20 000]	Low ∼[0, 20 000]
Assembly complexity A(number of line items) B(number of sellable variants)	Medium A(∼33-40) B(∼1200)	Low A(∼24-39) B(∼300)	High A(∼62) B(∼50)	Very high A(∼86) B(∼500)
Number of assembly lines/assembly stations	3	2	1	1

The case company strives to store all components that are ready for assembling, both in-house manufactured and purchased finished components, in a centralized storage area that is located next to the assembly area. The implementation of this storage strategy has been constrained due to the limited storage floor space. In addition, the use of forklifts within the facility is forbidden due to safety concerns. As a result, all material handling is currently performed manually by personnel. The utilization rate of the total indoor height measuring about 7 m is remarkably low since ergonomic requirements limit the material racks´ height to only 1.6 meters above floor. In addition, some assembly lines are using material kitting as a material supply method which further restricts the height of racks, since the kitting is done manually by picker-to-parts method.

Due to the fairly high complexity, the number of components in the product's variants and limited floor space in the centralized storage area currently drives the case company to store components in multiple storage locations within the facility. This includes components that are both purchased as finished for assembling and in-house manufactured ones. Some in-house manufactured components are, due to constrained space availability, stored both near their respective pre-manufacturing cell and in additional storage locations within the facility. The technical features (i.e. size and weight) of the components is one of the factors contributing to this.

As a result of multiple storage locations, there is an increased internal material handling including transportation between those storage locations and transportation from those storage locations to the different assembly lines. Further, the seven assembly lines at the case company use different material feeding methods, in some cases a combination of several. This also entails increased internal transportation of components from one storage location to another, for instance, from storage locations in the pre-manufacturing area to the centralized storage area where some kitting takes place. These combined problems in the material supply operation, like multiple transportation, storage and handling of components along with the underutilized warehouse space (i.e. height), requires an extensive study in order to improve the overall operational effectiveness.

The case company, views increased automation as a competitive advantage and is now in the initial phase of introducing an automated internal material supply operation. Currently, the company is piloting a project with an Autonomous Mobile Robot that potentially may be used to transport components from the centralized storage area to different assembly lines. The case company sees large potential in better utilizing the available factory space (i.e., height), through increasing the level of automation in the centralized storage area and therefore wants to explore and evaluate implementing warehouse automation system(s). Though, the case company recognizes the importance of a solution that does not sub-optimize the performance of the centralized storage area´s activities at the expense of the effectiveness of the actual material feeding processes. Implementing warehouse automation system(s), at the centralized storage area, will undoubtedly interfere with the currently practiced material supply methods (e.g. the milk-runs and component kitting procedures). Since a main objective with implementing warehouse automation system(s) at the case company is to make the extensive internal material handling more effective, an evaluation of the currently practiced material feeding principles´ compatibility with any warehouse automation system(s) must be conducted. If the warehouse automation system(s) recommended are incompatible with currently practiced material feeding principles, suggestions for new feeding principles are required.

1.1.2 The case company's situation in relation to the wider context

In order to improve the company's competitiveness, the management at the case company plans to increase the level of automation of the internal material supply operation. These plans are complicated due to the fact that there are seven separate assembly lines within the production facility, which all assembles finished products that differ regarding both technical features (i.e., weight and size) and what Slack and Lewis (2015) refer to as demand characteristics (i.e., Volume, Variety, Variation, and Visibility). These differences are transformed into similar differences regarding the input components, which directly influences the internal material supply operation of components and semi finished products. Further complexity is caused in the internal material handling by the case company´s practice of different material supply methods (e.g., kitting, pick-and-place, and milk-run) for different assembly lines. This complex situation, including a large variety in both technical features and demand characteristics of the input components complicates the case company´s selection of warehouse automation system(s) that reaches all performance objectives (i.e., Quality, Speed, Dependability, Flexibility, and Cost) for all seven assembly lines. A further complicating factor for the case company, is the lack of information about what to consider when increasing the level of automation of an internal material storage system, in the company's multiple assembly line manufacturing context.

1.2 Aim

The case company believes that increasing the level of automation of the internal material storage systems will support its competitiveness, but it is unclear for the company what type of warehouse automation system(s) that are suitable. A reason for this, is the lack of recommendations for what a manufacturing company in the case company's multiple assembly line context should consider when selecting warehouse automation system(s) for component storage.

The purpose of this master's thesis is to explore how the case company can improve its internal materials supply operation, by increasing the level of automation of the component storage systems. This includes identifying and analysing important requirements that should be considered by the case company when selecting warehouse automation system(s) for component storage. Further, the purpose of this master's thesis also includes to provide recommendations for what type of warehouse automation system(s) for component storage the case company should select. In addition, the purpose includes identifying and analysing the consequences for the case company's internal material supply operation of selecting the recommended warehouse automation system(s) for component storage. For example, this includes evaluating the compatibility between the case company's currently practiced material feeding principles and the recommended warehouse automation system(s).

Fulfilling the purpose of this master's thesis will support the case company in developing a final detailed solution for an improved internal material supply operation, which involves a higher level automation of the component storage systems. In addition, this master's thesis as a whole is expected to be useful also for other companies that operate in a similar context, which plan to increase the level of automation of their own internal material storage system.

1.3 Research questions

The aim of this master´s thesis is to provide answers for the following research questions (RQs):

RQ1: What are important requirements for the case company to consider when selecting warehouse automation system(s) for component storage?

Answering RQ1 will contribute to the identification and understanding of performance requirements that should be considered when selecting warehouse automation system(s) for component storage, in order to secure a high performing solution when increasing the level of automation of the internal material supply operation.

RQ2: What type of warehouse automation system(s) for component storage, are recommended for the case company to select?

Answering RQ2 will contribute to the identification of what warehouse automation system(s) that are suitable for the case company to select for component storage, taking important performance requirements that were identified when answering RQ1 into consideration.

RQ3: What are the consequences for the case company's internal material supply operation of selecting the recommended warehouse automation system(s) for component storage?

Answering RQ3 will contribute to an understanding of how selection of the recommended warehouse automation system(s) for component storage will affect the case company's current internal material supply operation, for example regarding the systems compatibility with different material feeding principles.

1.4 Limitations

This master´s thesis does not aim to develop a single highly detailed and functional final solution of warehouse automation system(s) for component storage at the case company. Further, financial aspects like investment, operations, maintenance, and liquidation costs related to the selection of warehouse automation system(s) for component storage, are out of the scope of this thesis. In addition, material handling of finished products and raw materials (i.e., materials that will be pre-manufactured in-house before entering the assembly processes), are also out of the scope of this thesis.

1.5 Sustainability - Ethical, societal and ecological aspects

When conducting research, it is important to consider potential consequences for a sustainable development. Accordingly, potential effects on the sustainable development being caused by either the research methods applied or the expected research outcomes should be considered before initiating a research project.

No negative effects related to sustainability (i.e., ethical, societal and ecological aspects), can been expected as a result of the implementation and/or the completion of this master's thesis project. This means, neither the research methods applied (see Chapter 3 - Methodology) nor the answers provided for the asked research questions (see Chapter 7 - Conclusion), are expected to have any negative ethical, societal, or ecological consequences for any stakeholder or third party. Though, since the work environment for the operators within the case company's facility will be effected by an increased automation of the component storage, the aspects of ergonomics has to be considered in the analysis.

2
Methodology

This chapter explains the methodology for how the aim of this master´s thesis has been fulfilled. A case study has been conducted to answer the research questions defined in Chapter 1 - Introduction. A case study is an inquiry-based research strategy that aims to describe, understand, predict, and/or control the individual research object, e.g. a process, organization, or industry (Woodside, 2010). A specific case study can include all, a combination, or just a single one, of these four types of research objectives and case study research can be used for both theory testing and theory building and is not limited to one specific set of research methods, instead, a combination of both qualitative and quantitative research methods within the same study may be advantageous (Woodside, 2010). Though, there exists no research method that is suitable to use in all case study contexts (Woodside, 2010). This case study is based on both qualitative and quantitative research methods.

2.1 Project procedure

In order to get a deeper understanding of this thesis' topic and to enable answering the research questions (RQs) defined, a comprehensive literature review was conducted in the early phase of the thesis project. This involved the study of existing literature and research papers, with focus on different aspects of internal material supply processes and warehouse automation systems. The findings from this literature review conducted, has been summarized in the Theoretical Framework (see Chapter 3). This Theoretical Framework forms the basis for the Empirical data collection (see Chapter 4) and the Analysis (see Chapter 6).

A prerequisite for answering RQ1 (i.e., *What are important requirements for the case company to consider when selecting warehouse automation system(s) for component storage?*), is to understand how the case company's existing internal material supply operation is organized, for example since this enables identifying inefficiencies that should be eliminated, or at least reduced, by future warehouse automation system(s) used for component storage. Further, to understand how the existing internal material supply operation is organized enables comparison between the current and a future state of the internal material supply operation.

How the case company's existing internal material supply operation is organized, has been mapped mainly by conducting interviews with different company stakeholders and through observations in the form of site visits. Examples of case company specific internal material supply operation characteristics that have been mapped, considers the currently applied: storage policies; material feeding principles; storage assignment policies; material replenishment methods; packaging and unit loads; as well as what different types of handling and transport equipment that are used.

In order to answer RQ1, empirical data corresponding to the different parts of the Theoretical Framework has been collected. Analysing this empirical data with support of the Theoretical Framework has allowed identifying and understanding important requirements, for the selection of warehouse automation system(s) for component storage, which are imposed by the case company's: Operations / Factory Environment (i.e., Production layout, Manufacturing strategies, Characteristics of demand, and Characteristics of assembly lines); Material Supply System (i.e., Materiel feeding principles, Handling Equipment, Storage systems, Packaging and unit loads, and Replenishment methods); as well as, Performance Objectives (i.e., Quality, Speed, Dependability, Flexibility, and Ergonomics). Answering RQ1 has allowed identification and understanding of performance requirements that should be considered by the case company when selecting warehouse automation system(s) for component storage, in order to secure a high performing solution.

To provide recommendations for what type of warehouse automation system(s) for component storage that are recommended for the case company to select, requires identification and understanding of important requirements for such selection. This makes answering RQ1 (i.e., *What are important requirements for the case company to consider when selecting warehouse automation system(s) for component storage?*) a prerequisite for answering RQ2 (i.e., *What type of warehouse automation system(s) are recommended for the case company to select for component storage?*)

In order to answer RQ2, a market research has been conducted where the performance characteristics of different types of warehouse automation system(s), which are available on the market, have been mapped. These supplier model specific performance characteristics have been combined with general model performance characteristics data, found in the literature review, of different types of warehouse automation system(s). These findings about the performance characteristics of different types of warehouse automation systems, have then been compared to the requirements that are imposed by the case company's Operations / Factory Environment, Material Supply System, and Performance Objectives, which are found in the answer provided for RQ1. Answering RQ2 has allowed identification of what warehouse automation system(s) for component storage that are suitable for the case company to select, taking important requirements that were identified when answering RQ1 into consideration.

In order to answer RQ3 (i.e., *What are the consequences for the case company's internal material supply operation of selecting the recommended warehouse automation system(s) for component storage?*), the strengths and weaknesses related to implementing the warehouse automation systems recommended, in the answer for RQ2, with respect to how well the performance objectives, defined in the answer for RQ1, are reached and how well the main recommendations are compatible with the requirements imposed by the Operation / Factory Environment and the Material Supply System, which also are defined in the answer for RQ1. Answering RQ3 has contributed to an understanding of how selection of the recommended warehouse automation system(s) for component storage, will affect the case company's current internal material supply operation, for example regarding the systems compatibility with different material feeding principles.

2.2 Empirical data collection

In the Analysis (see Chapter 6), both qualitative and quantitative data are used. The non-numerical qualitative data has been collected through primary sources in the form of multiple structured, semi-structured, and unstructured stakeholder interviews, conducted with different managers within the case company, as well as by observations, through several site visits, where non-numerical data mainly about the existing material supply operation has been collected. To interview managers with different responsibility areas within the case company, has brought different perspectives into the analysis, which strengthens the viability of the answers for the research questions. In addition, some managers have also been interviewed multiple times. Further, that several managers have been interviewed and partly been asked the same questions strengthens the reliability of the collected empirical data since answers perceived as divergent have been followed up and either rejected or confirmed by other interviewees. This has also reduced the risk of biased answers, from individual stakeholders, influencing the empirical data collection and in turn the Analysis.

The numerical quantitative data has almost exclusively been collected through secondary sources in the form of the case company's Enterprise Resource System (ERP system), Plan For Every Part files (PFEP files), and Bill-of-Materials (BOMs). The data extracted from these secondary sources has in the Analysis been combined in order to enable the numerical calculations required, for example regarding throughput requirements and storage volume capacity requirements imposed on the selection of warehouse automation system(s). The specific sources for each type of quantitative data is provided, where the focal data is presented in this thesis. Further, that almost exclusively secondary data has been used for the numerical calculations, increases the reliability and validity of the analysis. This since risks related to mistakes or errors in data collection and data transferring has been minimized.

The qualitative and quantitative empirical data are used in an integrated approach in the analysis, where the theoretical framework is applied on all the empirical data collected. This further strengthens the validity of the answers for the defined research questions.

3

Theoretical Framework

Due to the lack of cohesive frameworks for the selection of warehouse automation system(s) for component storage, within a material feeding context where multiple assembly lines are the direct customers of the stored components, this chapter summarizes aspects of an internal material supply operation that, through reviewing literature and previous research, have been identified as important to consider when selecting warehouse automation system(s) for component storage in the case company's situation. This theoretical framework forms the basis for the empirical data collection (see Chapter 4) and for the Analysis (see Chapter 6).

3.1 Operations / Factory Environment

In this section, first the main characteristics of the customer order decoupling point and related manufacturing strategies are described. Next, what implications the characteristics of demand have on a material supply process are provided. Then, different process performance objectives and the importance of fit between such objectives and the design of a production system are described, as well as, the importance of monitoring processes with the support of performance measurements. Here, the importance of making ergonomic considerations within manual material handling are brought up. Also, examples of important performance measures within internal manufacturing logistics are provided. The following subsection describes how performance objectives can be reached by improving internal manufacturing logistics processes, through reducing process variability and applying Lean Six Sigma logistics. Thereafter, several main characteristics of different assembly lines and what implications such differences have for material feeding processes are described. This is important for the scope of this thesis since there are seven assembly lines, with different main characteristics, within the case company's facility being in focus. After that, different aspects of material supply strategies are described, followed by a description of the area of automation of internal logistics.

3.1.1 The Customer order decoupling point & Manufacturing strategies

The case company applies different manufacturing strategies, which affect the internal material supply operation. It is important to consider the customer order decoupling point (CODP) when designing a manufacturing operation, both on the strategic, tactical and operational level (Olhager, 2010). What manufacturing strategy that is practiced within a company has implications for how to manage the material supply and production processes, for example when the degree of information about the final product is low at the customer order decoupling point the following processes must be more flexible than when the degree of information is high (Jonsson & Mattsson, 2009).

A manufacturing company can according to Jonsson and Mattsson (2009) be classified regarding how customer order initiated its operations are, in other words, how integrated its production functions are with the customer orders received. This means that the customer order point (i.e., the BOM-level from which the product design is customer order specific) or the similar customer order decoupling point (i.e., the BOM-level from which material supply and value-adding activities needs a customer order to be initiated) can be used for categorizing a manufacturing company (Jonsson & Mattsson, 2009). Before the customer order decoupling point all material supply and value-adding activities are initiated by forecasts, while afterward, customer orders received decide the initiation (Jonsson & Mattsson, 2009). From a supply perspective, the degree of order information according to Wikner and Rudberg (2005) concerns four mutually independent supply issues: What product does the customer want?; How much of that product is wanted?; When is delivery wanted?; and Where is delivery wanted?, which all must be specified to make a customer order fully defined. Since the production lead time often is longer than the delivery lead time demanded by customers (see Figure 3.1), decisions regarding the four aforementioned supply issues must be taken before full information is available about the demand requirements (Wikner & Rudberg, 2005). In addition, there is no sure relationship between the level of information certainty between the four different supply issues (Wikner & Rudberg, 2005).

Based on the customer order decoupling point five manufacturing strategies can be separated (see Table 3.1), which all differ regarding: the level of customer order integration within material supply and manufacturing activities; where the stock point(s) is located within the material flow; and the degree of information at order receipt (Jonsson & Mattsson, 2009). Figure 3.2 shows the relationship between different manufacturing strategies and the CODP. Most companies produce a mix of make-to-stock and make-to-order products, which affect the design of the production system (Olhager, 2010). In an assemble-to-order environment, it is necessary to design different parts of the supply chain according to either make-to-stock or make-to-order strategy (Olhager, 2010).

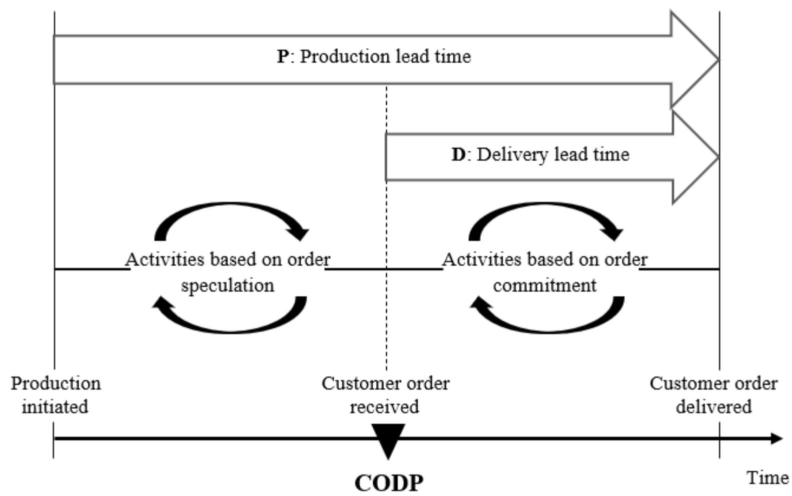

Figure 3.1: *The Customer Order Decoupling Point (CODP) in relation to production and delivery lead time. Adapted from Wikner and Rudberg (2005).*

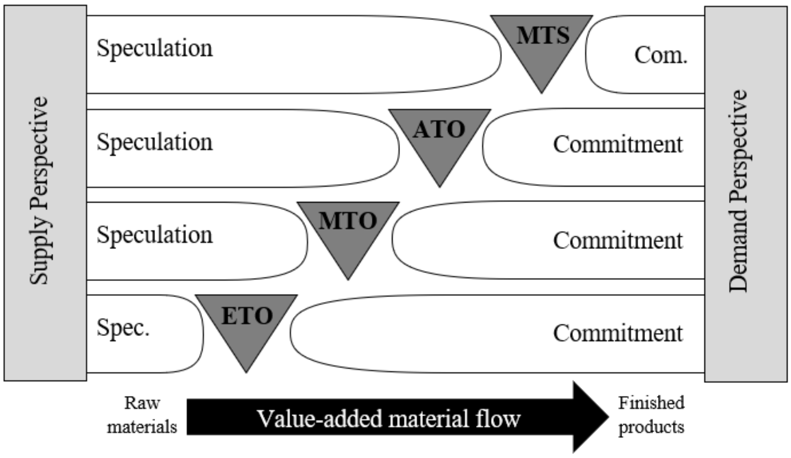

Figure 3.2: *The Customer Order Decoupling Point (CODP) in relation to four manufacturing strategies. Adapted from Wikner and Rudberg (2005)*

Table 3.1: *Main characteristics described by Jonsson and Mattsson (2009) of five different manufacturing strategies.*

Manufacturing Strategy	The level of customer order integration within material supply and manufacturing activities	The degree of information at order receipt	Location of stock point(s)
Engineer-to-order (ETO)	All activities from product design, material supply, to final assembly is customer order initiated.	Very low	There is only one stock point, which is located between the procurement and fabrication processes.
Make-to-order (MTO)	Parts of the material supply and manufacturing activities involving input-components and products are executed based on forecasts, i.e., they are not customer order initiated.	Low to average	There is a stock point located both between the procurement and the fabrication process and within the fabrication process.
Assemble-to-order (ATO)	All material supply and pre-manufacturing activities of standardized input-components are executed based on forecasts, i.e., they are not customer order initiated. Only the final composition of input-components and the assembling activities are specified and initiated by customer orders received.	Average to high	There is a stock point located both between the procurement and the fabrication process and between the fabrication and assembly process.
Make-to delivery-schedule (MTDS)	Products are either completely standardized or customer specific for certain customers, though material supply and manufacturing activities are not customer order initiated but instead executed based on forecasts, stock levels, or a delivery schedule.	High	As for the ATO-strategy, there is a stock point located both between the procurement and the fabrication process and between the fabrication and assembly process.
Make-to-stock (MTS)	Product specifications are completely known before customer order is received and the company manufactures standardized finished products, which are stored in stock until a customer order initiates delivery. All material supply and manufacturing activities are as for MTDS executed based on forecasts, stock levels, or a delivery schedule.	High	In addition to the stock point locations within the MTDS-strategy, there is also a stock point between the assembly and delivery process.

3.1.2 Characteristics of demand - influences material supply processes

The case company's product portfolio includes a large variety of products, which have implications for the assembly operation and consequently for the related material supply processes. Operations and processes not only vary in terms of what technologies and skills that are needed to perform them, but also regarding the characteristics of the demand of the produced products and services (Slack & Lewis, 2015). The Four Vs (i.e., Volume, Variety, Variation, and Visibility) are four influential characteristics of demand (see Table 3.2), which each one has implications for how to successfully manage a process (Slack & Lewis, 2015).

Table 3.2: *Summary of implications described by Slack and Lewis (2015) for an operation with High respective Low level of the Four Vs .*

Characteristics of demand (the Four Vs)	**Implications for an operation with High level of focal "V" (OBS: Low level for Volume)**	**Implications for an operation with Low level of focal "V" (OBS: High level for Volume)**
Volume (i.e., demanded volume)	Low degree of repetition, Labor intensive, Low level of specialization, Low grade of systematization, High cost per unit.	High degree of repetition, Capital intensive, High level of specialization, High grade of systematization, Low cost per unit.
Variety (i.e., variety in characteristics of products and services)	High degree of flexibility, High level of complexity, Match customer needs, High cost per unit.	Low degree of flexibility, Routine, High level of standardization, Regular, Low cost per unit
Variation (i.e., variation in demanded volume)	Varying capacity needs, Anticipation, High degree of flexibility, In touch with demand, High cost per unit.	Stable capacity needs, Predictable, Routine, High utilization rate, Low cost per unit.
Visibility (i.e., how exposed the operation´s value-adding is to customers)	Short waiting tolerance, Customer perception is important, Customer contact skills are required, High cost per unit.	Time discrepancy between production and consumption, High level of standardization, High utilization rate, Low cost per unit.
	HIGH UNIT COST	**LOW UNIT COST**

3.1.3 Performance Objectives - fit production system design with manufacturing objectives

It is crucial that implementation of warehouse automation system(s) improves the case company's operational performance. According to Devaraj, Hollingworth, and Schroeder (2004) manufacturing performance is enhanced when manufacturing design choices fit with the manufacturing objectives.

3.1.3.1 Five generic performance objectives

In practice, the five generic performance objectives (i.e. Quality, Speed, Dependability, Flexibility, and Cost), which are applicable to all operations, form the basis for a reasonably well-defined set of required performance objectives (Slack & Lewis, 2011). All these five generic performance objectives are related to the underlying business task of fulfilling the customer needs (Slack & Lewis, 2011). These five performance objectives are often interlinked and even if any of them happens to be of low direct importance for meeting customer requirements, it may still be valuable for the operation´s overall performance due to the internal benefits it creates (Slack & Lewis, 2011). In Table 3.3, descriptions and examples of internal and external benefits of the five generic performance objectives described by Slack and Lewis (2011) are presented.

Table 3.3: *Descriptions and examples of benefits with the five generic performance objectives described by Slack and Lewis (2011).*

Generic performance objective	**Description**	**Examples of potential internal benefits**	**Examples of potential external benefits**
Quality	Quality often refers to the specification of the produced products or services but can also refer to how well the produced products or services are fit for purpose. Quality is multidimensional and several aspects of specifications are required to describe the desired features of the produced products or services. In addition, conformance quality regards how reliably and consistently the focal operation itself reaches the defined product or service specifications.	Fewer errors in processes, less complexity and disruption, higher internal reliability, less processing costs	Fewer errors in products/services, highly specified products/services, increased reliability of products and services
Speed	Speed refers to elapsed time and in its most basic form concerns the time from start to the end of a process in an operation. It may involve external happenings, like the customer order lead time that may include both order-handling, core processing, queuing, delivery, installment, though speed may also refer, more narrowly, to only an internal process´ throughput time.	Faster throughput times, less inventory, less overhead costs, less processing costs	Shorter delivery times, faster response to customer requests

Continued on next page

Continuation of Table 3.3			
Flexibility	Flexibility has two different meanings: the process´ range flexibility, e.g. the ability to produce different variants of products or services, or produce with varying output levels; and the process´ response flexibility, i.e. how fast, smoothly, and cheaply the process can change between different production states. Examples of different kinds of flexibility, which may influence an operations competitiveness are: product and service flexibility, i.e. how easily modifications to existing products/services are made and how easily novel products are introduced; mix flexibility, i.e. how easily the produced variety of products/services is changed; volume flexibility, i.e. how easily the aggregated output level is changed; and delivery flexibility, i.e. how easily planned delivery dates are changed.	Increased responsiveness to unforeseen events, increased responsiveness to required changes in activities, less processing costs	Frequent new product/service introductions, wide range of products/services, adjustable volumes, adjustable deliveries

Continued on next page

Continuation of Table 3.3			
Dependability	Dependability refers to keeping delivery promises regarding the delivery time, i.e. deviations between due delivery time and actual delivery time, which often makes it linked with the speed performance objective. In addition, fast throughput times often facilitate high dependability due to the related increased level of process control.	Increased trust in the operation, fewer contingency plans required, increased internal stability, less processing costs	Increased on-time delivery to customers
Cost	Cost refers to any financial input that is required for enabling the focal operation to produce the assigned products or services. In general, an operation requires: operating expenditures; capital expenditures; and working capital.	higher margins	Lower prices
End of Table 3.3			

3.1.3.2 Ergonomics - the importance of human well-being for high performing material handling

Since any changes to the case company's internal material supply operation will affect the employees work conditions, ergonomic aspects must be consider when selecting warehouse automation system(s) for component storage. Internal logistics activities involve both movement of materials as well as handling of equipment and the discipline of ergonomics is used to improve the execution of such activities, by simultaneously acknowledging the importance of both good human and physical work conditions as well as effective and efficient performance (Loos, Merino & Rodriguez, 2016). For a company to reach its organizational objectives, it is crucial to create conditions that support human well-being, followingly, ergonomic factors must be taken into consideration when designing processes (Loos, Merino & Rodriguez, 2016). This includes evaluating both explicit physical loading and psycho-social aspects, with support of defined ergonomic goals and related indicators (Neumann, Winkel, Medbo, Magneberg & Mathiassen, 2006). Further, to consider ergonomic factors early in the design phase of a production system have a major impact on the ergonomic quality of the final system (Neumann, Kihlberg, Medbo, Mathissen, & Winkel, 2002). For example, when re-designing a production system through increasing the level of automation, it is important to consider both what work tasks should be removed as well as the remaining work tasks since also the removal of specific repetitive monotonous activities, which are unwanted from an ergonomic perspective, can reduce operators overall load variation and consequently increase the workload concentration to fewer body parts (Neumann et al., 2002). Main ergonomic risk factors within manual material handling, which according to Rossi, Bertolini, Fenaroli, Marciano and Alberti (2013) all are related to fatigue and physical injuries, are: static or awkward work postures; repetitive motions; forceful exertions; and pressure points.

The International Organization for Standardization (ISO) provides a three-part framework (i.e., ISO 11228) for ergonomic evaluation of manual material handling, with the primary objective of making design improvements to manual handling operations (Rossi et al., 2013; ISO, 2003; ISO, 2007a; ISO, 2007b):

1. The first part of ISO 11228 provides ergonomic recommendations for manual lifting and carrying of objects with a weight of at least 3 kg and for normal walking speeds between 0.5-1.0 m/s on plane surfaces (ISO, 2003). Related risk factors are presented in Table 3.4. An ideal posture for manual handling is to: stand upright and symmetrically; keep a horizontal distance of less than 25 cm between the centre of mass of the operator and the object handled; and keep a vertical distance of less than 25 cm between the hand grip and the knuckle height (ISO, 2003).

2. The second part of ISO 11228 provides risk-assessment methods for whole-body manual pushing and pulling, as well as proposes limitations for such work tasks (ISO, 2007a). This includes tight restrictions of manual pushing and pulling of heavy objects, which can be avoided by automation, mechanisation, or through design adaptations of the work task or workplace (ISO, 2007a). Risk factors related to manual pushing an pulling are presented in Table 3.4.

3. The third part of ISO 11228 provides a risk-assessment model for high frequent repetitive work tasks involving manual handling of low loads, as well as proposes restrictions for such work tasks (ISO, 2007b). Examples of factors that, alone or in combination, are associated with ergonomic risks related to handling of low loads at high frequency are presented in Table 3.4. Such risk factors can be reduced by automation, mechanisation, work task enlargements, or job rotation (ISO, 2007b).

Table 3.4: *Provides examples of risk factors provided in ISO 11228, which are associated with manual material handling.*

Work tasks	Examples of risk factors (alone, or in combination)
Lifting and Carrying	object position, working posture, mass and size of objects handled, frequency of execution, and exposure duration, etc (ISO, 2003).
Pushing and Pulling	used force, working posture, frequency of execution, exposure duration, distance, object characteristics, environmental condition, individual characteristics, work organization, etc (ISO, 2007a).
Handling of low loads at high frequency	working posture and movement of body parts, used force, exposure duration, frequency of executions, training level, quality and precision requirements on output, work organization, etc (ISO, 2007b).

An additional positive effect of improving ergonomic work conditions for material handling operators, is that by removing work tasks that involve heavy lifting, which excludes many potential employees, a company can broaden the possible worker pool as well as improving productivity and quality by reducing worker fatigue (Baudin, 2002). Further, since the preferable work height from an ergonomic point of view is between the shoulders and hip, which is a range that differs between individuals, the height of workstations or used fixtures should preferably be adjustable (Baudin, 2002). In addition, the material exposure at an assembly line strongly affects ergonomic conditions, for example, using small containers for material exposure reduces the ergonomic risk factors of shoulder elevation and trunk flexion (Finnsgård, Wänström, Medbo & Neumann, 2011).

3.1.4 Performance measurement systems - monitoring performance within manufacturing logistics

The case company has a flow oriented production system, which according to Stricker, Echsler Minguillon, and Lanza (2017) generally are prone to disruptions, and especially lean practices like inventory, time and capacity buffer reductions make such a system´s performance immediately affected by such disruptions. Further, the probability of disruptions increases due to the general growing range of product variants and the increasing distribution of production processes (Stricker et al., 2017). Consequently, the costs of disturbances are rising due to the increasing need for process control and flexibility, which in turn raises reliability and consistency requirements on utilized equipment (Jonsson, 2000). In order to monitor and detect changes in a production system´s performance a well-developed multi-dimensional performance measurement system is needed (Stricker et al., 2017). To measure and follow-up the performance of manufacturing logistics processes enables a company to take adequate actions that allows it to reach performance objectives determined (Jonsson Mattsson, 2009). In addition, performance measures can be used for sizing the logistics system and for delegating responsibilities for logistics activities (Jonsson & Mattsson, 2009).

3.1.4.1 Criteria for a performance measurement system

A performance measurement system should be process oriented and designed with customer value-adding in focus and should be designed so it highlights improvement potential and increases the effectiveness and efficiency of actions (Dörnhöfer, Schröder, Günther, 2016). Process performance indicators are seldom independent, instead, they are commonly in some kind of conflicting or complementary relationship with one another (Kueng, 2000). It is important that there exists a balance between performance measures for individual process steps and performance measures that covers the whole process (Dörnhöfer et al., 2016). Since logistics often involves a complex set of interlinked activities there is according to Caplice and Sheffi (1995) a need for several complementary and supportive performance metrics to provide the management a comprehensive view of the logistics performance. Such performance measurements should support the company's competitiveness and be aligned with its objectives and the overall business strategy (Jonsson & Mattsson, 2009).

It is also important that a well-balanced set of financial and non-financial measures are used (Gunasekaran, Patel, & McGaughey, 2004). A well designed performance measurement system that is both complementary, comprehensive, and cohesive, in which performance metrics are evaluated both individually and on a system-wide level, will improve the management's decision making (Caplice & Sheffi, 1995). A performance measurement system should fulfill all six criteria that are described in Table 3.5 (Caplice & Sheffi, 1995).

Table 3.5: *Description of the six criteria a performance measurement system should fulfill, according to Caplice and Sheffi (1995).*

Criteria	Description
Comprehensive	all relevant stakeholders for the process should be captured.
Causally Oriented	activities and indicators that affect both the current and future performance should be tracked.
Vertically Integrated	the overall business strategy should be translated to all relevant decision makers in the company.
Horizontally Integrated	all relevant activities, functions and departments along the process should be included.
Internally Comparable	potential trade-offs between different performance aspects (not between evaluation criteria) should be recognized and allowed.
Useful	decision makers should be able to understand and use the performance measurement system as a tool for decision making.

3.1.4.2 Three types of logistics performance variables

Logistics performance variables can regarding their influence be divided into three types (see Table 3.6), i.e.: Revenue influencing logistics variables; Cost influencing logistics variables; and Asset influencing logistics variables (Jonsson & Mattsson, 2009). The largest part of a manufacturing company's current assets often consist of tied-up capital in raw-material, semi-finished items, and purchased components located both in different inventories and within the actual material flow, though, also accounts receivable is affected by the logistics procedures through the company's delivery capacity, for example by the share of customer orders that are delivered in full (Jonsson & Mattsson, 2009). Since tied-up capital costs significantly influence a company's profitability, in terms of return on capital employed (ROCE), the logistics performance of a company has a major impact on the overall financial results (Jonsson & Mattsson, 2009). More detailed descriptions of a selected number of revenue, cost, and asset influencing logistics variables, used within manufacturing logistics, are provided in the next subsection.

Table 3.6: *Examples of three types of manufacturing logistics performance measurements described by Jonsson and Mattsson (2009).*

Performance measure	Description	Examples
Revenue influencing logistics variables	Includes customer-oriented performance variables.	E.g., delivery precision, delivery reliability, delivery lead time, stock service level and flexibility.
Cost influencing logistics variables	Includes performance variables related to both production and the material flow.	-Production (e.g., capacity costs, costs for changing rate of production, and set-up costs). -Material flow (e.g., transportation and handling costs, packing costs, inventory carrying costs, shortage costs and delay costs, and administrative costs)
Asset influencing logistics variables	Includes performance variables related to both fixed and current assets.	-Fixed assets (e.g., the rate of capacity utilization, i.e., the quota between the produced volume and the nominal capacity). -Current assets (e.g., share of full deliveries, the amount of tied-up capital in monetary values, inventory turnover rate, and run-out time).

3.1.4.3 Key performance indicators within manufacturing logistics

The case company uses several key performance indicators (i.e. measures), to control the assembly operation and related material supply processes. Within logistics, it is crucial to use logistics performance indicators to quantify the current state and potential improvements (Dörnhöfer et al, 2016). The choice of performance measures is crucial for a company's success since these affect: planning and control, on both strategic, tactical and operational level; evaluation of performance; and what future actions that should be taken (Gunasekaran et al., 2004). All companies have individual performance measurement needs and the chosen set of performance measures must reflect a company's unique operations and its business context (Gunasekaran et al., 2004). The number of performance measures a company uses tend to accumulate over time, though generally it is better to use a few performance measures that cover areas that are most important for the company's success (Gunasekaran et al., 2004).

Financial performance measures are often valuable for external reporting and when making strategic decisions, while non-financial performance measures generally are more valuable for the control of day-to-day manufacturing operations (Gunasekaran et al., 2004). The performance of production operations has a great influence on both quality, flexibility, speed of delivery, delivery reliability, and product cost (Gunasekaran et al., 2004). In addition, the use of non-financial performance measures has a statistically significant direct positive effect on company profitability, but it also has a statistically significant mediating function for the indirect positive effects that lean management practices have on company profitability (Fullerton & Wempe, 2009). Descriptions of a selected number of performance measures used within manufacturing logistics, are presented in Table 3.7.

Table 3.7: *Description of a selected number of performance measures within manufacturing logistics*

Performance measure	Definition	Relevance & Implications
Order lead time	The time elapsed between a customer makes an order and the customer receives the ordered product or service (Gunasekaran et al., 2004).	Is a source of competitive advantage since it affects a company's response time for meeting customer needs (Gunasekaran et al., 2004).
On-time parts availability / On-time-in-full (OTIF)	The right part should be delivered at the right time, in the right quality, in the right location, and in the right packaging (Dörnhöfer et al., 2016).	On-time parts availability is crucial for ensuring high capacity utilization of an assembly line (Dörnhöfer, et al., 2016).
Productivity / Throughput	Is defined as the quota between outputs and inputs used, which refers to effectiveness of a system, where inputs are resources such as time, labor, or money, while examples of outputs are line items, the number of finished orders, or transactions (Park, 2012).	Throughput decreases: as queue capacity between work stations decreases; as product and process variation increases; and as the number of sequenced work stations increases (Crandell & Burwell, 1993). Productivity may imply wrong decisions and behaviors if used in isolation (Goldsby & Martichenko, 2005).
Capacity utilization / Utilization rate	Can be defined as the ratio between produced volume and the nominal capacity, where nominal capacity refers to the capacity that is available under normal conditions (Jonsson & Mattsson, 2009).	Has direct impact on a company's response time for meeting customer needs since it influences lead time, flexibility, and deliverability (Dörnhöfer et al., 2016). Decreases as: que capacity decreases; the number of workstations increases; and product and process variation increases (Crandell & Burwell, 1993). Influences both the average and the variability of lead time through factory, see Figure 3.3 (New, 1993). May imply wrong decisions and behaviors if used in isolation (Goldsby & Martichenko, 2005).
Cycle time deviation	Cycle time is the time available, at each station, for each work cycle (Boysen, Fliedner, & Scholl, 2008). In other words, the time span between a workpiece´s two entries into two successive workstations (Boysen et al., 2008).	If the cumulated task time for any station (i.e. the station time), in a paced line, exceeds the fixed common cycle time that work station becomes a bottleneck and the fixed common cycle time is not feasible (Boysen et al., 2008). If the cumulated task time for any station is shorter than the fixed common cycle time that workstation has idle time (Boysen et al., 2008).
Takt time deviation	Takt time is a measurement of production pace, which relates available production time to customer demand (Linck & Cochran, 1999). It determines the time available, at each workstation, for producing a single product, and is calculated as the ratio between available production time and the average customer demand per time period (Linck & Cochran, 1999),	Deviation from takt time leads to either overproduction or underproduction in relation to customer demand (Linck & Cochran, 1999). Logistics processes should be timely in line with the manufacturing lines takt time (Dörnhöfer et al., 2016)
Line fill-rate	A measure of the probability that an assembly line will not have any disruptions, between successive component-storage replenishments, that is caused by component shortage (Bukchin & Meller, 2005).	To maximize the line fill-rate is a main goal when designing an assembly line operation since it equals minimizing the probability of component shortage, which causes line stoppages (Bukchin & Meller, 2005). Large positive financial effects can be caused by even small increases in line fill-rate, since a single component shortage may cause major disruptions and idleness costs (Bukchin & Meller, 2005).
Line efficiency	A measure of an assembly line´s productivity that is calculated by the ratio between the sum of the cumulated task time , i.e. station time, for all workstations (t,sum) and the product of the number of station (n) and the common cycle time (c), i.e. Line efficiency = t,sum/(nc) (Boysen et al., 2007).	Is used for evaluating the quality of the assembly line balance, by measuring the productive fraction of the total operating time (Boysen et al., 2007).
Throughput efficiency	Measures productivity of time and is defined as the ratio between work content and the elapsed time taken (New, 1993). Does not measure efficiency of the actual work tasks, though is measured for a given set of work methods and shift patterns (New, 1993). On item level, throughput efficiency = 1-Balance Delay loss, where Balance Delay loss equals (cycle time x number of stations - work content of unit)/ (cycle time x number of stations) (New, 1993).	High levels can lead to: reduced customer order lead time in make-to-order environments; shorter forecast horizons and consequently the reduced exposure to forecast errors in make-to-stock environments; lower WIP-inventory levels; improved responsiveness to changes in demand; improved service levels with lower inventory levels; reduce a company's risk exposure; and facilitate timely introductions of new products; (New, 1993). Though, improved throughput efficiency of an individual process does not automatically lead to improved overall company throughput efficiency (New, 1993).
Work in Process (WIP)	Inventory of unfinished products that are located in and between production processes (Jonsson & Mattsson, 2009).	WIP provides buffers against process variability, which facilitate high machine utilization rates (Crandell & Burwell, 1993). Reduced average WIP may reduce throughput, i.e, the number of units processed per time unit (Crandell & Burwell, 1993). Increased WIP increases both the average and the variability of lead time through factory, i.e. the sum of process and waiting time (New, 1993; Crandell & Burwell, 1993).

3.1.4.4 Conflicting and complementary relationships between performance measures

Figure 3.3 and Figure 3.4 show examples of conflicting and complementary relationships, which according to Kueng (2000) commonly exist between different performance measures. Figure 3.3, which summarizes findings by New (1993), shows that high throughput efficiency shortens customer lead times, in a make-to-order environment, though it reduces the capacity utilization. In addition, Figure 3.3 shows that WIP-congestion causes capacity utilization, after a certain level, to fall (New, 1993). Figure 3.4 show that both average work-in-process, work pieces´ average time in system, average utilization, and average throughput increases as the queue capacity increases (Crandell & Burwell, 1993). The data in Figure 3.4 show that it is possible to both reduce work-in-process and shorten lead times, while preserving resource utilization and throughput, by reducing process variability (Crandell & Burwell, 1993). The importance of process variability for production systems performance is further described in the next subsection about process improvements.

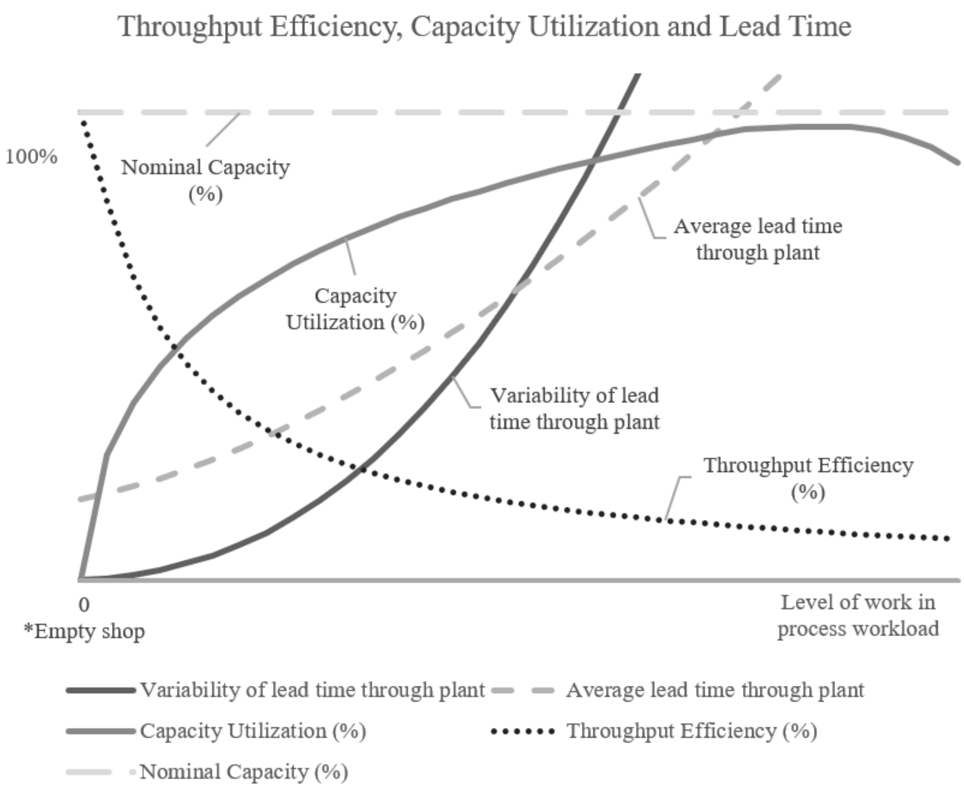

Figure 3.3: *Describes the relationship between Throughput efficiency, Capacity utilization and Lead time. Adapted from New (1993).*

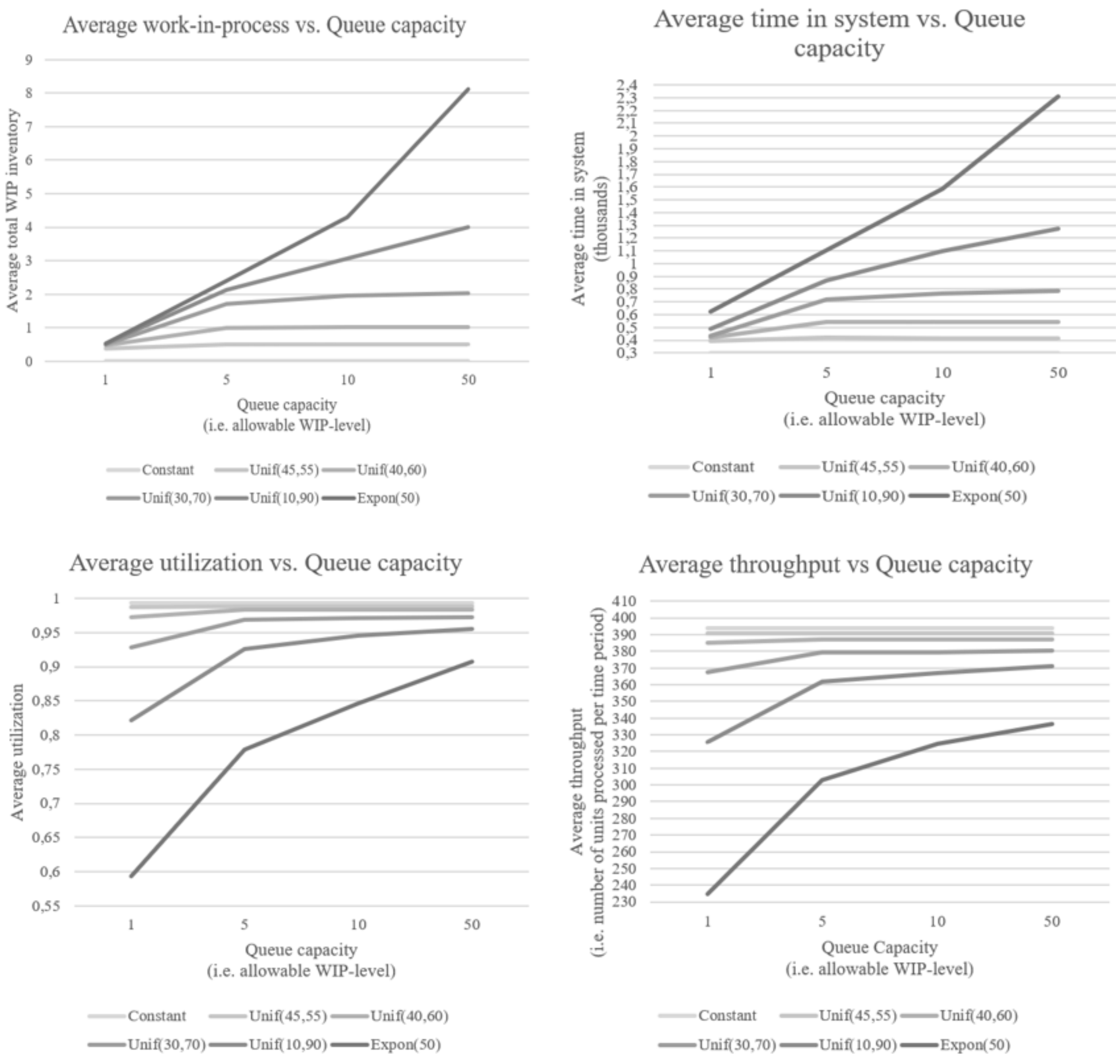

Figure 3.4: *The relationship between Queue capacity and average work-in-process, average time in system, average utilization, and average throughput, respectively. Adapted from Crandell & Burwell (1993).*

3.1.5 Process Improvements - reaching performance objectives

It is important that future warehouse automation system(s) at the case company does not sub-optimize the component storage processes, instead, it should enable and facilitate excellent performance of all interlinked processes, not at least the assembly processes. This subsection describes different aspects and concepts of how internal manufacturing logistics processes can be improved.

3.1.5.1 Designing a production system - three ways to handle process variability

A production system must be designed so internal variability in production throughput does not affect the company's ability to satisfy customer needs (Mierzejewska, Castaneda-

Vega, Cochran, 2002). Such internal variability can be handled by: decoupling of processes, through implementing buffers in-between; excess capacity, by capital investments in equipment and labour; or by reduction of variation, which often is the most cost-efficient alternative even though it requires both skills and endurance (Mierzejewska et al., 2002). Buffers between processes in a production flow can be either visible, in the form of WIP material, or invisible, such as flexible distribution of work tasks, reduced worker concentration (i.e. fewer operators in relation to the number of products), and assigning operators additional work tasks that are not directly linked to the production flow (Engström, Jonsson & Medbo, 1996; Engström & Karlsson, 1982).

3.1.5.2 Process variability - an underlying driver of manufacturing performance

All performance measures are not drivers of a manufacturing plant´s operating performance, instead, several are only intermediate measures that are influenced by what actions the company previously has taken (Mapes, Szwejczewsk, New 2000). Especially actions that increase the stability and reliability of operating systems can be considered as underlying drivers of plant performance since such improvements reduce both manufacturing lead times and the need for inventories, which in turn shortens customer lead times, increases delivery reliability, improves quality consistency, and raises productivity (Mapes et al., 2000). Thus, reducing process variability and process uncertainty leads to several plant performance improvements (Mapes et al., 2000). This is supported by Crandell and Burwell (1993) which found that low levels of process variability reduces both work pieces average time in system and average WIP inventory levels, but also that it increases the average workstation utilization and the average throughput, see Figure 3.4.

Reducing process time variability facilitates coordination of different manufacturing stages and reduces the need for WIP-buffers to protect downstream manufacturing stages from idle time that is caused by unexpectedly long processing times in previous manufacturing stages (Mapes et al., 2000). Reducing process output variability (i.e. increasing the share of throughput that fulfills specifications) lowers scrap and rework costs, reduces the number defective products that are shipped to customers, and increases both average delivery reliability and average throughput rates since there are fewer delays that are caused by rejected components (Mapes, et al., 2000). Figure 3.5 shows the relationship between process variability and manufacturing plant performance.

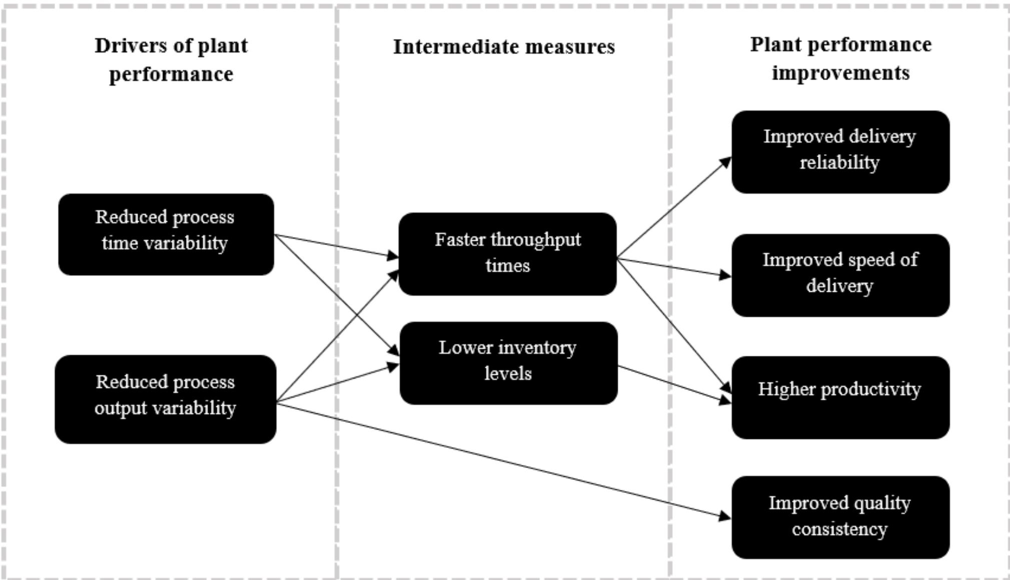

Figure 3.5: *Show the relationship between process variability and manufacturing plant performance. Adapted from Mapes et al. (2000).*

3.1.5.3 Four main sources of process variability

The different sources of process variability can be divided into four categories: Time, for example low coordination of internal logistics and bad production scheduling; Equipment, like machine reliability, variation, and scrap rate; Material, such as inconsistent material quality and related variations in processing times; and People, as human errors, variation in operators task time, and effects of fatigue (Mierzejewska et al., 2002). There naturally exists inter-operator variation (i.e. differences between operators) and intra-operator variation (i.e. individual differences between work cycles) regarding the work pace and efficiency of executed repetitive work tasks (Engström et al., 1996).

3.1.6 Lean logistics - reducing non value-adding wastes within internal logistics processes

The case company's operations management is oriented towards the concept of Lean, which has implications for what performance improvements that are prioritized when implementing warehouse automation system(s) within the company's facility. This subsection describes the concepts of Lean and Six Sigma within a logistics context.

3.1.6.1 Waste - activities that add cost but no value

From a customer perspective, the only justification for a company's existence is its value creation (Jones et al., 1997). Though, within a company many activities, from the order receive to product delivery, add no or only little customer value (Jones et al., 1997). Such activities are Waste, which can be defined as "activities that add cost but no value" (Jones et al., 1997). Lean is a concept in which the overall objective roughly is to improve the velocity and flow within the supply chain and eliminate non value-adding activities, i.e. waste, from all processes (Goldsby & Martichenko, 2005). Optimally, all activities should be organized in such a way that an uninterrupted flow is created, which exactly corresponds to the customers pull-demand rate (Jones et al., 1997).

In general, it is more difficult to identify waste than the activities that are value-adding (Jones et al., 1997). Regarding activities within a factory, in general, about 60 percent do not add any value at all and about 35 percent are necessary to perform but do not add value either, which leaves only about 5 percent of all activities actually being value-adding (Jones et al., 1997). The highest potential to improve performance lies in focusing on eliminating the about 60 percent of all activities that are not value-adding at all (Jones et al., 1997).

Originally, seven common forms of waste were defined: excess stock; excess transport; excess movement; excess processing; waiting; and rectification of mistakes (Jones et al., 1997). Regarding logistics specifically, seven potential sources of waste can be defined: excess inventory; transportation; space and facilities; time; packaging; administration; and knowledge, see Table 3.8 (Goldsby & Martichenko, 2005). Though, obviously each one of these sources of waste within logistics are also necessary for planning and executing the logistics operations (Goldsby & Martichenko, 2005). Other examples of non value-adding activities within internal logistics are: moving; counting; finding; chasing; storing; reworking; batching; inspecting; recalling; and recording items (New, 1993). There are three different focus areas of waste elimination, which are described in the next subsection.

Table 3.8: *Descriptions and Implications described by Goldsby and Martichenko (2005) for seven sources of logistics waste.*

Logistics waste	Description	Implications
Excess Inventory	Is often the most visible form of waste. Inventories normally constitute between 5 and 30 percent of manufacturers total assets.	Increases average annual inventory carrying costs by raising capital costs, inventory service costs, inventory risk costs, and storage space costs, etc. An optimal level, based on customer requirements, must be determined.
Transportation	Is often the largest single cost within logistics. Normally constitute about half of a company's logistics costs.	Major contributor to variance in order cycle time and reduction in both average time and variance is desirable. Further, often has a non-normal frequency distribution curve with an open-ended right tail but a closed left tail representing a definitive minimum.
Space and Facilities	All activities within a warehouse consume valuable resources, but often about half of the activities are neither value-adding nor contribute to customer satisfaction. Fixed warehouse costs are independent of the volume stored, but many warehouse operation costs are variable, i.e. they correspond to the volume handled.	Better service is not necessarily reached by increasing inventory and even if stored SKUs is demanded, it can be difficult to locate specific items when a facility is filled up with inventory. A paradox in warehousing is that bad designed and ineffectively executed warehouse processes tend to result in more warehouse space.
Time	Is a crucial metric within logistics. Both short order lead time and reliability of on-time delivery support competitive advantage.	Time waste can exist within all steps of the order cycle: Order transmission; Order processing; Order filling; Order staging and verification; and Order shipping and delivery. Time waste can be observed in both absolute numbers and in variance and time wastes, within an order cycle step, are rooted in either poor performance or due to error/miscalculation in other order-cycle steps.
Packaging	Includes all forms of containerization at the bundle or individual item level as well as all forms of conveyance and shipping platforms, such as pallets, racks, and bins. The packaging itself can be waste, but also the failure of capitalizing on its ability to transfer information in the supply chain.	Is the fundamental physical unit of analysis in a logistics system because the packaging both influences and is influenced by manufacturing and logistics activities at both the focal company, customers, and suppliers. Further, packaging can be used to control material supply and manufacturing activities and packaging may influence the flow efficiency, goods damage, material wastes, other cost savings, and the control of operations in the supply chain.
Administration	Is not value adding, but still necessary for order fulfillment. Waste occurs when administration, instead of the involved processes, is used for coordinating flows of physical products, information, and cash.	The more steps there are in the administration, the more are the opportunities for errors and delays to occur. Further, EDI, Internet, and other communication technologies can minimize costs, errors, and delays rooted in administration. The IT-systems enable better, faster, and more accurate handling of information and removes the human factor, though, IT-systems may also create wastes since the specialized competence needed to run them may not be required full-time, which may create partly idle technicians.
Knowledge	Is possibly the most commonly wasted resource within a company. Competitive advantages that are rooted in the performance of operations, like manufacturing and logistics, are achieved by tapping accessible knowledge.	To improve the utilization of knowledge and creativity should be encouraged and rewarded. Further, a company must have procedures for information and knowledge-sharing to avoid "islands of knowledge" and lessons from made mistakes must be communicated to avoid unnecessary repetition, as well as best practices must be communicated to other functions to be fully utilized.

3.1.6.2 Waste elimination - three strategic focus areas

Waste elimination has according to Goldsby and Martichenko (2005) three strategic focus areas, where Quality at the Source is the most relevant for the scope of this thesis.

The other two focus areas are Continuous Improvement, which refers to the importance of creating an organizational infrastructure and processes that enables a flow of continuous improvements through all parts of the organization, and Execution that refers to the importance that effective implementation of improvements have on organizational performance (Goldsby & Martichenko, 2005).

Quality at the Source refers to the importance of isolating design and operational errors, which occurs because people and machines are involved in the processes, and not allow them to become customer defects. Consequently, processes must have mistake-proofing mechanisms that enable detection and handling of errors before they become defects, either for internal or external customers (Goldsby & Martichenko, 2005). Quality issues must never be transferred to downstream processes since the negative consequences of a quality issue increases as it moves through processes (Goldsby & Martichenko, 2005). Successful implementation of mistake-proofing processes leads to several benefits: reduced rework; reduced scrap; reduced risk; reduced variation; and reduced complexity. Regarding logistics specifically, Quality at the Source is about the realization of perfect orders, i.e. fulfilling the five rights by delivering (Goldsby & Martichenko, 2005): the right part; in the right quantity; at the right time; in the right quality; and at the right cost. Similarly, according to Dörnhöfer et al. (2016) perfection in logistics performance is about fulfilling customer requirements for: the right part; at the right time (e.g. delivering the part according to the takt time where it is required); in the right quality, in the right location; and in the right packaging (e.i. both the right load carrier and the right packaging itself), which all can be transferred upstream through all processes.

3.1.6.3 Lean Six Sigma logistics - a combination of two process improvement methods

Six Sigma is a management concept that focuses on understanding and eliminating variability and improving accuracy and reliability of processes based on customer expectations (Goldsby & Martichenko, 2005). By understanding and controlling variability in processes the need for buffers between the processes is reduced (Goldsby & Martichenko, 2005). By identifying process-influencing variables Six Sigma methodologies facilitate a better understanding of the root causes to problems (Antunes, Sousa, & Nunes, 2013). This is important since the process of developing improvement actions becomes complicated when problems´ root causes are unknown (Antunes et al., 2013).

The combined use of the Lean and Six Sigma management concepts supports managers to improve operations, increase quality, and reduce costs within logistics and consequently contribute to the overall business success (Goldsby & Martichenko, 2005). Applying the Lean and Six Sigma concepts in an integrated approach provides a high potential for successful improvements of internal logistics processes (Antunes et al., 2013).

3.1.7 Assembly lines - the internal customers of stored components

The configuration planning of an assembly line is of great importance since both installing and redesigning an assembly line implies large capital investments (Boysen, Fliedner, & Scholl, 2007; Boysen, Fliedner, & Scholl, 2008). The most important factor for an assembly line's productivity is the performance of the related part supply system (Baudin, 2002). The case company´s seven different assembly lines all have unique characteristics that influence the material supply processes and in this subsection typical characteristics of different assembly lines are described. A general description of an assembly line is that it is a flow-line production system where work pieces successively are processed in productive units (i.e. workstations), which are aligned in a specific sequence that the work pieces commonly are transported in-between by a transportation system (Boysen et al., 2007; Boysen et al., 2008).

3.1.7.1 Single-model, mixed-model, and multi-model assembly lines

Classification of assembly lines can be done with respect to the number of different models that are assembled and how the line pace is controlled (Bukchin & Meller, 2005; Scholl, 1999). In a single-model line, as the name suggests, only a single product model is assembled, while in a mixed-model line there are several different , but similar, models assembled simultaneously (Bukchin & Meller, 2005; Scholl, 1999). Even though the similarity between models assembled in a mixed-model line makes rearrangement of the assembly line unnecessary, a mixed-model line is more complicated to both design and operate (Bukchin & Meller, 2005). For example, it is necessary to decide what quantity to store by the assembly line, for each component type that is included in the different models (Bukchin & Meller, 2005). This decision, together with decisions about component replenishment policies and component area allocation, is closely related to the risk of a component stock-out at the assembly line, which may stop the whole assembly operation and consequently entail exceptionally high costs (Bukchin & Meller, 2005). Van Zante-de Fokkert and de Kok (1997) further distinguishes between mixed-model lines, in which produced lot sizes equal one unit, and multi-model lines, which produces different product models in batches larger than one unit. In mixed-model lines are set-up times and set-up costs assumed to be insignificant, while this is not the case for multi-model lines (Van Zante-de Fokkert & de Kok, 1997). Though, when each work task always needs to be performed at the same workstation and when lot sizes are small, a multi-model line can be balanced using line balancing methods for mixed model lines (Van Zante-de Fokkert & de Kok, 1997).

3.1.7.2 Line balancing - smoothing workloads between process stages

There is an important, but often neglected, interdependence between material supply and line balancing problems that in practice may be crucial to consider simultaneously (Boysen et al., 2007). Line balancing is the procedure of assigning work tasks to workstations in such a way that the cumulated task time, called station time, is the same for each workstation, i.e. all workstations should have the same common cycle time (Boysen et al., 2007). The workstation with the longest station time is the assembly line´s bottleneck, which sets the throughput pace for the whole process (Johnsson & Mattson, 2009). In an unbalanced system will the differences in cycle time between workstations cause accumulation of WIP-inventory (Linck & Cochran, 1999). Workstations with a task time shorter than the common cycle time will from time to time have unproductive idle time (Boysen et al., 2007). Consequently, transferring work tasks from the bottleneck workstation to workstations with a lower station time will increase the assembly line´s productivity (Boysen et al., 2007). The difference between a balanced version and an unbalanced version of the same assembly line is shown in Figure 3.6, which are adapted from Baudin (2002). Observe that some of the workstations in the unbalanced assembly line in Figure

3.6 exceed the takt time, while this is not the case for any workstation in the balanced version of the same assembly line.

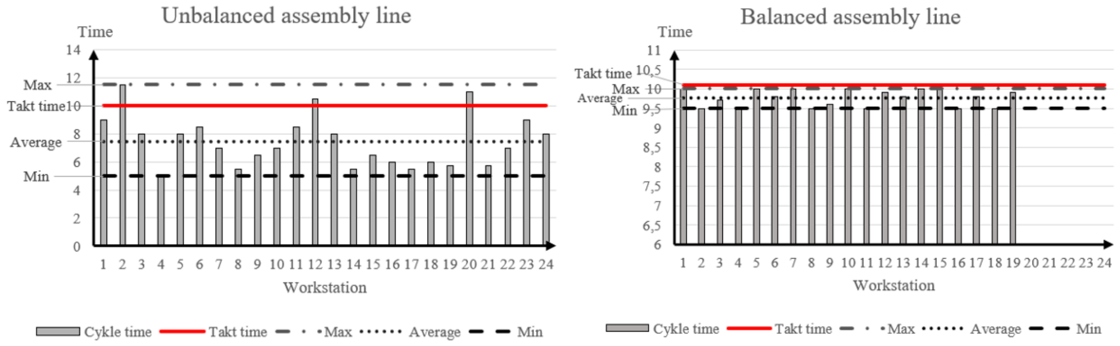

Figure 3.6: *Example of an unbalanced vs. balanced assembly line. Adapted from Baudin (2002)*

3.1.7.3 Takt time and level production - matching production processes with customer demand

Takt time, which is closely related to line balancing, guides the design-configuration of a production system by being a measurement of production pace, which relates available production time to customer demand (Linck & Cochran, 1999). Thus, takt time is a crucial factor for both determining long-term capacity requirements during the design phase of a production system and for short-term production pacing of the finished system (Mierzejewska et al., 2002). The takt time determines the time available, at each workstation, for producing a single product and is calculated by dividing the available production time by the average customer demand per time period (Linck & Cochran, 1999). The customer demand can be calculated either for individual customers, which facilities customer focus and management across product lines, or for the aggregated customer demand, which complicates customer focus and reduces followability of components (Linck & Cochran, 1999). How the customer demand is defined directly affects the takt time and consequently how production subsystems can be configured (Linck & Cochran, 1999). If a production system is line-balanced according to a common cycle time that deviates from the takt time it will lead to to overproduction, i.e. when the common cycle time is shorter than the takt time, or underproduction, i.e. when the common cycle time is longer than the takt time (Linck & Cochran, 1999).

Takt time is also used to level production, i.e. for leveling the cycle time mix, which is necessary to keep up the production pace and avoid WIP-inventory build-up when several products, which have different cycle times, are produced within the same system (Linck & Cochran, 1999). Though, leveling the cycle time mix requires low set-up times (Linck & Cochran, 1999). See Figure 3.7 for a comparison between a cycle time mix that is unbalanced and balanced respectively.

The second aspect of level production concerns leveling the product mix, which refers to the importance of producing each customer product in a time interval that corresponds to demand (Linck & Cochran, 1999). Leveling of product mix may not be necessary to satisfy customer demand, but it improves the response time to changes in demand and reduces inventories of finished goods (Linck & Cochran, 1999). See Figure 3.8 for a comparison between a product mix that is unbalanced and balanced respectively.

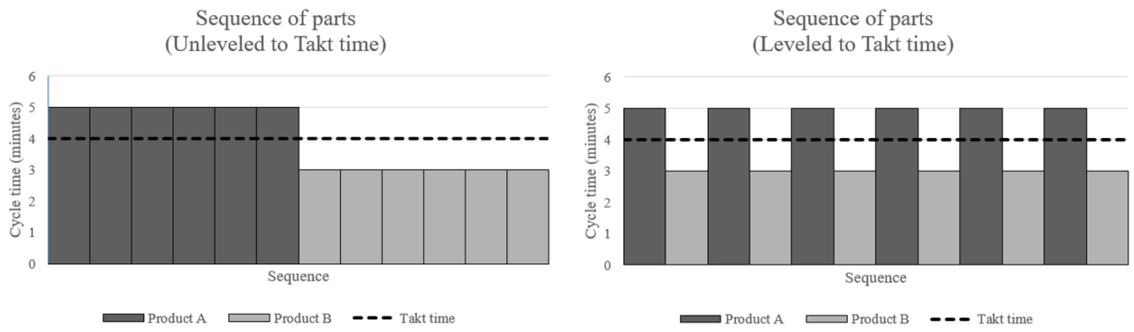

Figure 3.7: *Example of a cycle time mix that is unleveled vs. leveled to Takt time. Adapted from Linc & Cochran (2000).*

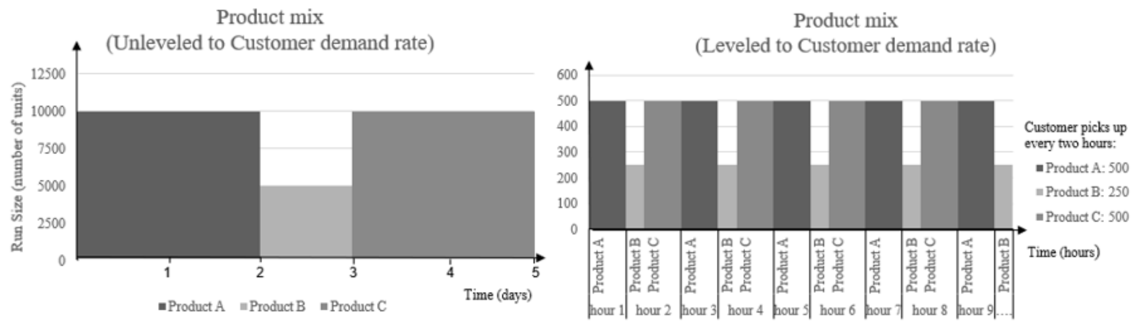

Figure 3.8: *Example of a Product mix that is unleveled vs. leveled to Customer demand rate. Adapted from Linck & Cochran (1999).*

3.1.7.4 Paced line vs. Unpaced asynchronous line vs. Unpaced synchronous line

Regarding the line pace control, assembly lines can be divided into three categories: Paced lines; Unpaced asynchronous lines; and Unpaced synchronous lines. In paced lines the process times at each workstation is restricted and there is often a common cycle time for all stations (Boysen et al, 2007). Work pieces can either be continuously moved forward, e.g. by a conveyor belt, or intermittently transported between workstations at fixed time intervals that correspond to the determined cycle time (Boysen et al, 2008). In unpaced asynchronous lines the transfer of work pieces between workstations are not restricted to a given time interval, instead, each workstation transfers the work pieces to the subsequent station whenever the assigned work tasks are finished (Boysen et al, 2007). If there exist deviations in task time, work piece buffers can be used between workstations to minimize the time each workstation has to wait for the successive workstation to complete the work on the previous work piece (Boysen et al, 2008). Though, a work piece buffer is of no use if there are general differences in task time between two workstations since the buffer in-between then will lose its effect as a result of being filled up (Boysen et al, 2008). Consequently, line balancing is crucial to enable a smooth long term workstation workload also for an unpaced asynchronous line (Boysen et al, 2008). In unpaced synchronous lines there is no need for work piece buffers between workstations since the work pieces in each station are transferred to the successive workstation at the same point in time, which is when the workstation with the longest cycle time has completed all its assigned work tasks (Boysen et al, 2008). Since it is the slowest workstation that initiates the transfer of work pieces, an unpaced synchronous line with deterministic task times can be managed almost identically as a paced line that uses intermittent transports between workstations (Boysen et al, 2008). Though if work task times instead are stochastic, an unpaced synchronous line can provide a higher throughput than a paced line since work pieces can be transferred to successive workstations independent of any predetermined time-intervals, which happen when assigned work tasks in all workstations have been completed faster than expected (Boysen et al, 2008).

3.2 Material Supply System

Material supply systems should according to Johansson and Johansson (2006) be designed and developed around six areas: materials feeding; storage; transportation; handling; packaging; and manufacturing planning and control, for the production system to function effectively. When introducing any support system, such as automation, to enhance the overall system performance, it is reasonable to consider factors affecting any of these areas. This to ensure that the introduced support system does not sub-optimize any individual area performance and consequently diminish the overall performance.

3.2.1 Material feeding - how components reach the assembly line

This section describes how materials can be fed to and displayed at an assembly station. These principles or methods play a crucial role in determining the performance of the system (Hanson, 2012). Johansson (1991), presents three different material feeding principles: continuous supply; batch supply; and kitting supply, see Figure 3.9 and those are categorized based on conditions such as whether a selection of items or all items are displayed at the assembly stations and whether the components are sorted by part numbers or the assembly object.

	Selection of part numbers	All part numbers
Sorted by part number	**Batch**	**Continuous**
Sorted by assembly object	**Kitting**	

Figure 3.9: *Categorization of material feeding principles. (Source: Johansson, 1991).*

3.2.1.1 Continuous Supply - a material feeding principle

With continuous supply, all items or materials required for producing all product variants are presented or displayed at the assembly stations all the time (Johansson, 1989). With the part consumption taking place, the materials are being replenished continuously (Hanson, 2009). This principle has a drawback of consuming more space, as all the part numbers are presented at the assembly stations and not preferable when a product has many variants, since it requires more space and high capital cost (Hanson, 2009). Furthermore many variants bring the risk of the operator picking the wrong component (Medbo, 2003). However, the advantage is that this feeding principle requires less material handling at the supply phase, since some of the supplier packages at arrival to the facility, directly can be transported to the assembly stations that require them (Johansson, 1991).

3.2.1.2 Batch Supply - a material feeding principle

For batch supply, only a selection of part numbers are displayed at the assembly stations which are determined based on the assembly object (Johansson, 2006), sometimes in the required quantity and sorted by part numbers (Johansson, 1991). Thus according to Hanson (2009), the contents of the components racks may change from batch to batch, which is achieved through either removing of partial quantities at the end of the batch or by balancing the next replenishment based on the inventory. The advantages with batch supply is that it requires less space at the assembly and produces lower risk of operators picking the wrong component, while the disadvantages involve more handling which is in contrast to continuous supply characteristics (Medbo, 2003).

3.2.1.3 Kitting Supply - a material feeding principle

Kitting supply means that the materials are supplied to the assembly stations in kits, where each kit contains only the materials required for one assembly object (Johansson, 1989). Thus kits contain more than one component and need to be put together before it is required in the assembly station (Medbo, 2003). Kitting is beneficial when the total number of components, including variants, per assembly object is increased (Johansson, 1991). One of the benefits is that kitting saves space in the assembly stations, as the components are not stored near the assembly (Hanson, 2009). Furthermore product changeovers are, according to Bozer and McGinns (1992), facilitated by having more space through elimination of components racks and improves the productivity and quality, since the components are readily available for the operator to assemble at workstation rather than to pick from the racks. Kits should, according to Medbo (2003), be designed in a manner that facilitates the sequence of assembly operation. Further kitting supply can facilitate the training of operators, which results in higher efficiency and quality in assembly operations (Medbo, 2003). However, kiting possesses certain disadvantages too. For example, kit preparation requires additional time and space (Bozer & McGinns, 1992). Also the incomplete or defective kits cause delay at the assembly station and require additional handling (Bozer & McGinns, 1992).

There are two types of kitting. Travelling kit is one type, where the kits are delivered at the first station of the line and continues to move along as the product progresses through the assembly stations, whereas the other type is the stationary kit or individual kit where a separate kit is prepared and delivered to each assembly station (Caputo, Pelagagge &

Salini, 2015). According to Hanson (2012), a kit contains several part numbers, so a fixed structure in a kit can help to orient and arrange a part in a manner that aids the assembly operations. However this type of kits has limited flexibility (Brynzér and Johansson, 1995). If the kits structures are specific to assembly stations, then the flexibility in re-balancing the assembly station is limited unless the kits are redesigned (Hanson, 2012).

3.2.1.4 Sequencing - to coordinate material supply with the sequence of material demand

In sequencing, the materials are supplied in the same sequences as they are to be assembled in the station (Hanson, 2009). This sequencing can be carried out either as single components or in kits (Hanson, 2009). The advantages of sequencing is that it saves the space in the assembly station and this approach is used when there are more variants available for each component since it is nearly impossible to store all variants with continuous supply method (Johansson & Johansson 2006). However, sequenced supply requires extra handling for picking the materials in sequence (Hanson, 2009). Further this often requires a lot of space, not in the assembly, but in other locations where the materials are picked (Hanson, 2009).

3.2.1.5 Hybrid feeding policy

According to Caputo & Pelagagge (2011), hybrid policy could perform better than applying single policy to an assembly line when considering overall performance such as capital investment, WIP cost, labour cost, space requirement, handling requirement and so on. Further authors suggested that higher the number of different components to be handled and higher the economic value of those components, kitting could be preferred for those types of components. Considering the varying characteristics of economic value of components and possible different variants that could be produced in an assembly line, applying a single feeding policy may not be a cost efficient solution (Caputo & Pelagagge, 2011).

3.2.2 Material handling and Transportation

Material handling is defined by Kulweic (1985), as *"a system or combination of methods, labour, facilities, and equipment for packaging, moving and storing of materials towards a specific goal"* (p.4). Based on the needs and necessity of the conditions, different kinds of equipment are used within material handling, however, partly manual handling by operators might be involved too in most cases (Hanson, 2009). Different transportation equipment that can be used inside a facility are for example forklifts, push carts, pallet jacks, tugger trains, conveyor and automated guided vehicles (AGVs) (Baudin, 2004). Further, facilities do not use different types of transport equipment based on their various needs, but instead stick to a few that might give inadequate service for their varied needs where those equipment are poor fit (Baudin, 2004). In addition to transportation, there are some equipment which are exclusively used for handling within the facility. Examples of such handling equipment according to Bagadia (1985), are different types of hoist, cranes and lifts. Based on the specificity of use of such equipment, some are classified as transportation equipment according to Baudin (2004) and handling equipment according to Bagadia (1985). According to Hales and Anderson (2001), the selection of material handling equipment should consider factors such as distance of transport and intensity of use, as depicted in Figure 3.10.

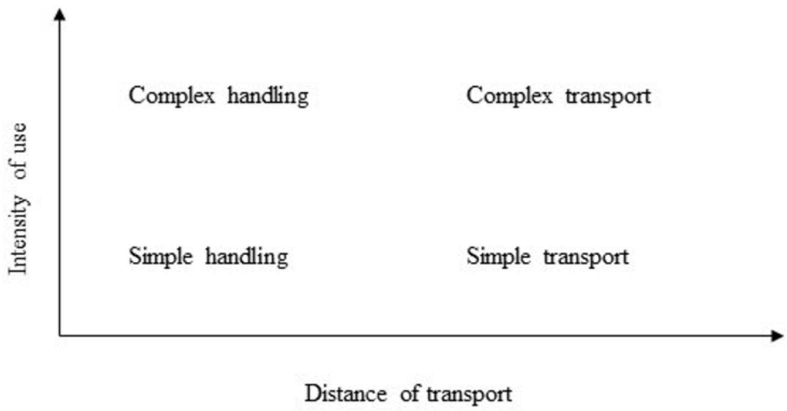

Figure 3.10: *Selection of equipment based on use (Source: Hales and Anderson, 2001).*

With most of the lean production system, milk run is the commonly used in-plant transportation method which can provide frequent deliveries of various materials from common or central storage area to their point of use (POU) (Klenk, Galka & Günthner, 2015). Kanban is used for signalling the demand for the milk run which is operated by material handlers using tugger trains. According to Klenk et al., (2015) for larger production systems, the preparation of milk run tours are often separated from actual deliveries and complemented by an AS/RS system but there could be possibilities for other demand signals and storage design also within the industry. The challenge lies with the milk run in determining the routes and intervals. Container demand at POU, factory layout and allowable inventories are to be considered and the designing of such milk run systems is even more difficult with variation in demand and unknown production schedules which affect the number of containers each tour requires (Klenk et al., 2015).

Further the authors propose three distinctive strategies to handle if the number of containers for a tour exceeds the milk run capacity. Those were (i) Strategy 1-Exception Transport: In this strategy, the excess containers are handled by separate transport which delivers those containers individually to their POUs. This exception transport is mostly quicker than the regular milk run since they are handled separately but this is “expensive” in terms of cost of operation. (ii) Strategy 2-Exception Tour: In this strategy, in contrast to strategy 1 which is delivered individually, the excess containers are accumulated and organized in a separate tour by milk run. This exception tour does not have a fixed schedule, however collects the container for all routes and delivers to their respective POUs. (iii) Order Shifting: In this strategy, in order to utilize the regular milk run schedules, the orders are shifted to the next scheduled tours if possible without causing the material shortage at the POU. The authors in their study concluded that order shifting strategies perform best in terms of total transportation cost if the lead time is not critical.

3.2.3 Storage and inventory

Storage is one of those activities which requires to be effective for a manufacturing setup to be efficient from the view of material supply strategies (Hanson, 2009). This involves storage of parts or components in places such as buffers, inbound warehouses, etc.

3.2.3.1 Centralized versus Decentralized storage - benefits and disadvantages

Inside a facility, a storage can be classified as centralized or decentralized based on the material feeding strategies. Centralized storage can offer advantages such as large control over inventory, high space utilization since the components are stored in a single place rather than in multiple places, and possibility to use automated equipment (Hanson, 2009). Decentralized storage, instead, offers advantages such as less travel time and distance for the components within the plant (Hales and Anderson, 2001). Both centralized and decentralized storage brings disadvantages. Those are high inventory and multiple material handling for decentralized storage (Bennett & Forrester, 1993). For centralized storage, the equipment for effective handling is costly, for instance, automation setup for high racks with high space utilization (Hales & Anderson, 2001). Baudin (2004) lists three types of storage devices within the warehouse: manual systems; automated storage and retrieval systems; and carousels.

3.2.3.2 Grouping strategies inside a warehouse

There are, according to Baudin (2004), different types of grouping strategies inside warehouses for storage: grouping by source; grouping by destination; and no grouping. Grouping by source is used in situations with mixed sources or suppliers, for instance when the incoming materials are from both local suppliers and international suppliers, which differs in lead time, lot quantities as compared to local suppliers, or for quality reasons, in order to monitor the source at certain conditions (Baudin, 2004). Grouping by destination is suitable where the parts from the same source may go to different destinations and this provides one stop-shopping for the material planning department in parts retrieval or replenishment (Baudin, 2004).

3.2.3.3 High space utilization versus easy material handling - a storage design conflict

There is a conflict between the space utilization and facilitating handling during the storage design (Hales and Anderson, 2001). For high space utilization, high racks are used whereas handling is facilitated when there is ease of access to material which is often the case with wider aisle (Hanson, 2009; Kulweic, 1985). Six ways to improve warehouse storage visibility, according to Baudin (2004), are through: location labelling on the warehouse floor; dock identification; zone identification; rack identification; slot separation; and rack orientation.

3.2.3.4 Warehouse main activities - from receival to shipping

According to de Koster, Le-Duc & Roodbergen (2007), there are six main activities within conventional warehouse: receiving; transfer and put away; order picking/selection; accumulation/sortation; cross-docking; and shipping. Receiving activity involved with unloading of items from inbound transport, updating inventory details, inspection to find the discrepancy; transfer and put away involves the transport of incoming materials to its assigned storage location, which may sometimes include repacking of items; accumulation and sorting activity is required for individual (customer) orders which needs to sorted and accumulated based on the destination (customer), if the picking activity is done in batches; cross docking and shipping activity means transfer of incoming materials directly to shipping areas for customer destination, often requires little or no order picking (de Koster et al., 2007). Order picking is the most important process within the warehouse activities since it constitutes 55% of the operation cost of the distribution centre (Hinz, 2013). This activity involves the process of picking the order lines or items from the storage locations and disposal of the picked items to the required destination (de Koster et al., 2007). Order picking can be manual, for instance low level picking from aisle by operators (picker-to-part); hybrid, for instance end-of-aisle picking by operators using parts-to-picker system (AS/RS, VLM, Carousel) and completely automated, for instance A-framing dispenser and picking robots (de Koster, et al., 2007).

3.2.3.5 Storage Assignment methods - determining the location of items stored

Items need to be stored in an optimal position before being retrieved or picked. A storage assignment method is a set of rules, which determine the storage locations for the items (de Koster et al., 2007).

- **Reserve versus Forward storage - separating bulk from pick area:**
  To speed up the picking process and to be efficient it is, according to de Koster et al (2007), important to separate the reserve (bulk) storage from the forward (pick) area. Also, the size of the forward pick area influences the average travel time of pickers, where a smaller area will entail lesser average pick time (de Koster et al., 2007). Further, multiple inventory of the same SKU may lead to regular internal replenishment from reserve to forward area (de Koster et al., 2007). The replenishment from reserve to forward area is restricted to the time when there is no picking activity, which is a constraint (de Koster et al., 2007). Dynamic storage is an extension of forward-reserve allocation, which tries to keep the forward area as small as possible to make it easier to pick by automated crane, vertical lift module, or carousel (de Koster et al., 2007). In this dynamic storage method, forward areas usually have less storage area than the available SKUs (de Koster et al., 2007).

- **Storage assignment policies - rules for assigning items storage location in the racks:**
  Storage assignment policies are a set of rules to determine where the packages can be stored within forward-reserve allocation (de Koster et al., 2007). There are according to de Koster et al. (2007) five different types of storage assignment methods: random storage; closest open location storage; dedicated storage; full turn over storage; and class based storage. In random storage, every incoming package gets randomly

assigned with equal probability (de Koster et al., 2007). This random storage assignment method has high space utilization at the expense of increased travel distance (Sharp, Choe and Yoon, 1991). A computerised control environment is a prerequisite for this random storage method (de Koster et al., 2007). In closest open location storage, the package gets assigned manually to the nearest free location encountered by the operator (de Koster et al., 2007). This method may lead to filling up of racks closer to the depot and may have empty racks at the back, if there is an excess of racks capacity (de Koster et al., 2007). In dedicated storage, a location is reserved for each product and the disadvantage of this method is that each location cannot be used by other types of items than the designated one (de Koster et al., 2007). This method creates low space utilization, however, order pickers get familiar with the items storage locations that can be an advantage (de Koster et al., 2007). Though, by using this dedicated storage method only at the forward pick area and using other storage methods, such as random storage, at the reserve area for that same item can reduce the disadvantage of low space utilization (de Koster et al., 2007). Further, this dedicated storage method can be helpful when handling products with different weight ranges, for example, heavy products can be stored at the bottom and lighter products at the top (de Koster et al., 2007). This method of storing and routing the pickers, gives a good stacking sequence for the operator without any additional effort (de Koster et al., 2007). In the storage method full-turnover storage, the packages are stored based on their turnover, where the products with a high sales rate are stored at the easiest accessible location, mostly near the depot (de Koster et al., 2007). Further, when demand varies and the products need to be reshuffled to different locations, is a disadvantage of this method (de Koster et al., 2007). With this kind of scenario full-turnover storage may lead to inefficient storage operations (de Koster et al., 2007).

- **Class based storage - organizing items based on volume demanded:** ABC classification is one of the ways to organize items in inventory management (Blackstone and Cox, 2004). According to de Koster (2007) the class based storage method, which may combine some of the storage assignment policies explained above, involves storage classification based on item popularity. Fast moving items are classified as A-class items, the next fast moving items are classified as B-class items and rest as C-class items (de Koster et al., 2007). Further the number of classes defined in the warehouse can increase, instead of only 3 classes, provided the trade-off shows additional gains with the travel time (de Koster et al., 2007). The location allocation or storage strategy for the different classes are based on the routing policy, warehouse size, and number of picks per route (de Koster et al., 2007). Jarvis and McDowell (1991), suggest that each class should be stored in a separate aisle for effective storage in a low-level picker to part system. Whereas Le-Duc and de Koster (2005), claims that the across aisle storage is optimal for the class based storage, based on their study in optimising the storage-class positioning of items. However, according to de Koster et al., (2007) there is no firm rule in warehousing literature for class partitions such as number of classes, percentage of items per class.

- **Family grouping - organizing items based on customer orders content or destination:**
  Family grouping is another type of storage policy in which the stored items, according to de Koster et al. (2007), are grouped based on items on customer orders

or, according to Baudin (2004), are grouped based on their destination within the facility. Family grouping can be combined with other storage policies, for example with class based storage, however, the decision to locate the products in a specific class should be based on the combination of properties of all the products in that group (de Koster et al., 2007).

- **Zoning - an alternative to single order picking:**
  Zoning is an alternative to single order picking, as the picking is divided into zones. One advantage of zoning is that each picker has to transverse only for a smaller distance, which reduces traffic congestion (de Koster et al., 2007). Further zoning is divided into two types: progressive picking / pick and pass; and parallel picking / synchronized picking. In progressive picking/ pick and pass, one picker starts the picking and passes the unfinished order to another picker in another zone until it is finished, whereas in parallel picking / synchronized picking, all pickers start the same order at the same time and consolidate it at the end (de Koster et al., 2007). With progressive zoning uneven workload between pickers could be an issue (Brynzér & Johansson, 1995).

3.2.4 Packaging - implications on a material supply operation

The packaging serves, according to Rushton & Croucher (2006), multiple functions such as containing the product, to preserve or protect it, provide information, facilitate storage and handling. According to Johansson, (2006) there are three functions of packaging units: flow function; market function: and environment function. Flow function is concerned with protecting, identifying and facilitating handling operations within the facility (Johansson, 2006). The flow function is most relevant for this thesis scope since it encompasses the material handling activities.

Unit load is a term sometimes used in relation to packaging within the logistics system. Tompkins, White, Bozer and Tanchoco (2003), define unit load as *"single item, a number of items or bulk material which is arranged and restrained so that the load can be stored, and picked up and moved between two locations as a single mass"* (p.186). Being the key element of the logistics system, the choice of packaging influences the wide range of activities within the material supply system such as material handling and storage efficiency, product protection, handler safety and ergonomics (Goldsby & Martichenko, 2005). According to Wänström and Medbo (2009), it is important to consider the assembly operation when selecting packaging which materials are fed to the assembly stations in. Wänström and Medbo (2009) found that Japanese plants use packaging which facilitates and supports the assembly operation through use of small packaging units, designed to suit the material characteristics and assembly requirements, whereas, in Swedish plants overall costs considering transportation is the most influencing factor, for example, this entail the usage of large packages like pallets that are not optimal to present at the assembly stations. Further, varying requirements of packaging at different positions within the materials supply system causes additional costs and delays in accessing materials, for instance, repacking that causes extra administrative costs (Johansson & Mathisson-Öjmertz , 1996).

3.2.5 Manufacturing Planning and Control

Manufacturing planning and control refers to all activities involved with the planning and controlling of all aspects of manufacturing, which includes scheduling of machines and materials (Vollmann, Berry, Whybark & Jacobs, 2005). Planning and control activities which encompass the material feeding, such as inventory control, and replenishment method, are interesting for the scope of this thesis. The manufacturing planning and control, according to Jonsson and Mattsson (2009), ensures that the demand is matched with the supply in a cost efficient way. Further matching the demand and supply should be carried out considering two aspects, i.e. time and quantity, where the time aspects of synchronization of demand and supply is a bigger problem since early synchronization can cause large tied up capital and late synchronization can cause shortage problems (Jonsson & Mattsson, 2009). To address this problem, several material planning methods are used, where some widely used planning methods are material requirement planning (MRP), kanban, reorder point system, run-out time planning and order based planning (Jonsson & Mattsson, 2009). MRP (Material requirement planning) is one of the material planning methods which determines the scheduling for new deliveries at a time point based on the calculation of when a new net requirement arises (Jonsson & Mattsson, 2009). Several factors such as lead time of delivery, planning horizon, time fences are considered to calculate the net requirement. Primarily used in the dependent demand situations, established bills of materials in ERP (Jonsson & Mattsson, 2009). Kanban is another method used for signalling new deliveries or new production planning in a pull environment. The number of kanban used in a setup is calculated using demand during lead time, safety stock and number of pieces in the container used (Jonsson & Mattsson, 2009). In the reorder point system, a new material planning or replenishment is planned when the stock falls below the reference quantity which is referred to as reorder point (Jonsson & Mattsson, 2009). This reorder point quantity covers the expected consumption during the lead time for replenishment and includes some safety stock to negate the variations in demand. Primarily used for finished goods, low value items, frequent and continuous demand, short lead time items (Jonsson & Mattsson, 2009). Run-out time planning is similar to reorder point system in determining the new replenishment, however run-out time uses time as a unit rather than quantity as in the reorder point system (Jonsson & Mattsson, 2009). Run-out time indicates the time that is available until the stock (including both stock on hand and scheduled receipt) is depleted. Primarily used in finished goods and environments where capacity flexibility is good (Jonsson & Mattsson, 2009). Material planning is characterised as either pull or push. Material planning is considered as pull if production and replenishment are initiated by the consumer downstream and as push if production and replenishment are initiated by the central planning team (Jonsson & Mattsson, 2009).

3.3 Automation of internal logistics

Granlund (2014) has summarized a list of possible automation systems and equipment that can be used to improve internal logistics processes: Automated loading and unloading system; Automated guided vehicle (AGV); Automated storage and retrieval system (AS/RS); Automatic forklift truck for mechanised handling; Carousels; Conveyor belts and conveyorized sorting system; Industrial robots/robotics; Item picking devices; Screening and/or sorting system.

In addition to the mechanised system for automation, different forms of automation for communication, data handling, monitoring etc., are available. For instance barcodes and RFID technologies for automatic identification, various IT systems (e.g. WMS) for planning, managing operations, etc (Granlund, 2014). Custodio and Machado (2020), categorizes flexible automation options that can be applied in warehouse and distribution centres as: automated equipment; data collection technologies; and management solutions.

3.3.1 Automated Equipment

In this subsection, some of the automated equipment that are used within storage, robotics and transportation systems are described. Robotics, according to Custodio and Machado (2020), is the most studied area (i.e. 85% of papers analysed in their research) within automated equipment. According to Custodio and Machado (2020), there is: (i) a necessity to have a flexible gripper in automated equipment to handle products with different characteristics; (ii) a need of flexible robots which can be adapted quickly to mass customization needs; (iii) a lack of robot-human collaborative environment due to safety reasons. Automation within storage and transportation were discussed in only 15% of papers analysed by Custodio and Machado (2020).

3.3.1.1 Automation with Robots

Robots are used to perform uniform repeated activities or processes within the warehouses, however mass customization is a challenge and requires flexible robots, which means (i) ability to swiftly change the task for long period of time without shutdown; (ii) ability to assess the situation, for instance when a item is dropped, and act accordingly to go through and complete the task; (iii) ability to be compatible with different manufacturers and their environment (Custodio & Machado, 2020). Packaging is the one application area for robots within the warehouse, however this needs a proper detection or item identification (Custodio & Machado, 2020). Automated picking is another possibility, for example, Kang & Kim (2017) developed a robotic vision system to assist the random bin picking. However, the major challenge lies within the gripping of random and vulnerable objects. Liu, Chiu, Chen, Pai, Hsu and Chen (2018), developed a compliant finger for better robotic grasping application through topology optimization method and proved its effectiveness with general industrial robots arms such as SCARA robots or six-axis robots.

3.3.1.2 Automation in transportation

According to Oleari, Magnani, Ronzoni and Sabattini, (2014), AGVs can be utilized for "automatizing movement of goods among different locations within an industrial environment" (p.233). Horizontal movement of goods is the prime functionality of AGV and those movements of goods between specific locations are often referred to as a mission, which is communicated and controlled by the WMS (Nilsson & Elmar Merkle, 2018). Usually AGVs do not plan their own route, instead they follow orders/missions from the WMS which often has a predetermined map to avoid collisions (Granlund, 2014). The difficulties with implementation of AGVs are less in newly designed warehouses, rather than in the existing ones (Oleari et al., 2014). The problems, when introducing AGVs in an existing warehouse, could be often within the safety concerns and space utilization (Nilsson & Elmar Merkle, 2018). If multiple AGVs are used, it is important that they should be connected to each other apart from the surrounding area, otherwise safety could not be guaranteed when collision avoidance support data is connected only to a specific AGV (Carderalli, Digani, Sabattini, Secchi, & Fantuzzi, 2017).

There is a difference between AMRs (Autonomous Mobile Robots), which can navigate to any accessible and collision free point within a defined area, and AGVs, which can navigate only in a fixed and predefined path (Fragapane, de Koster, Sgarbossa & Strandhagen, 2021). AGVs take significant time to adjust to small changes made in the working environment, whereas AMRs adapt quickly which is advantageous (Fragapane et al., 2021).

3.3.1.3 Automation of order picking system

This subsection describes different types of order picking systems and implications of automated order picking systems within warehousing activities. Also, selection criteria for the automated order picking system are presented, particularly in detail for AS/RSs.

Types of order picking system:
There are several order picking systems (OPSs) available or discussed within the warehousing literature. Dallari, Marchet and Melacini (2009), classify OPSs into five different groups based on four factors: (i) who/what picks the goods; (ii) who/what moves in the picking area; (iii) usage of conveyor within the picking area; and (iv) picking policy deployed, as illustrated in Figure 3.11. The five main groups are: picker-to-parts; pick-to-box; pick-and-sort; parts-to-picker; and completely automated picking (Dallari et al., 2009).

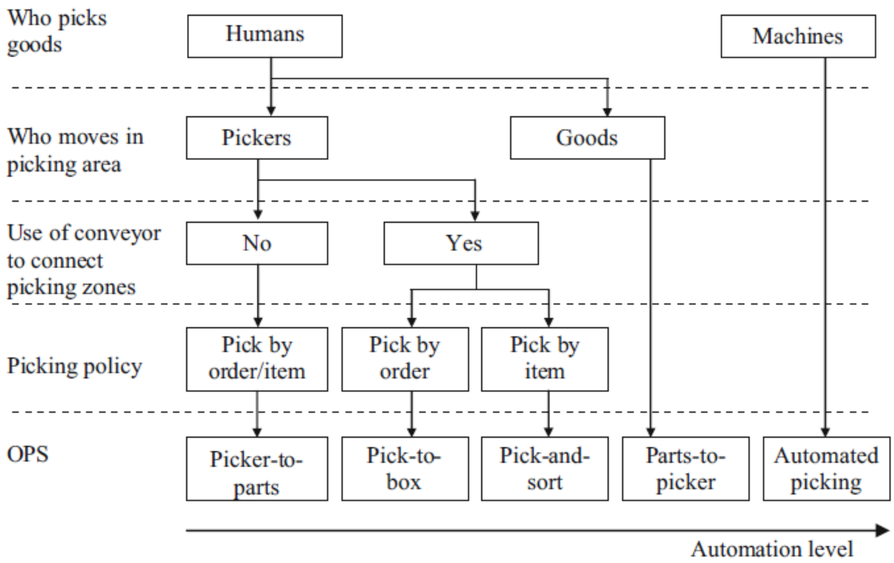

Figure 3.11: *Classification of order picking system (OPS). (Source: Dallari et al., 2009)*

Picker-to-parts system is one of the widely used setups in warehouses (de Koster et al., 2007). In this type, the picker drives or walks along the aisle to pick the items in order to complete a single order or batch of orders depending on picking policy (Dallari et al., 2009). Picker-to-parts systems can be further divided in two types: low level order picking, in which the items are picked from gravity flow racks, along with racks and bins maintained at lower level, while moving along the aisle; and high level order picking, which involves picking from high storage racks using man on board pick vehicles usually done in the front storage area (Dallari et al., 2009).

Pick-to-box is another type of OPS, in which picking areas are divided into different zones that each are allocated with one or more pickers (Dallari et al., 2009). A conveyor that carries boxes are connected to all zones, in which the partially or completely picked customer orders are transported (Dallari et al., 2009). This picking order system corresponds to the storage assignment policy called zoning, which is described in subsection 3.2.3.5

Pick-and-sort is another type of OPS, in which the pickers retrieve a certain amount of each single item where the accumulated quantity is based on batching of multiple customer orders (Dallari et al., 2009). A conveyor that is connected to the forward pick area transports the material to the sort area, where a computerised system determines the destination of single items based on separate customer orders (Dallari et al., 2009). Further accumulation of different sorts of items, based on the separate customer orders, are done and packed for delivery (Dallari et al., 2009). The picking productivity is higher for this pick-and-sort system, compared to the pick-to-box system, since a component rack is visited only once. Trade-offs between the picking benefits and packaging activities should be considered when designing such a system (Dallari et al., 2009).

Parts-to-picker is another type of OPS, where an automatic setup brings the unit load from storage and an operator picks the required quantity (Dallari et al., 2009). Potential setups for this parts-to-picker system are: carousels; vertical lift modules (VLM); automated storage and retrieval (AS/RS); and mini-loads. This type of OPS is advantageous for conditions with large numbers of SKUs, low picking volume, and small orders (Dallari et al., 2009). Though, drawbacks with parts-to-picker systems is the high risk of developing bottlenecks in feeding picking bays, as well as reduced picker utilization and picker productivity (Dallari et al., 2009).

Automated storage and retrieval (AS/RS) is one of the automation possibilities within storage that corresponds to a parts-to-picker OPS. According to Manzini, Gamberi and Regattieri (2006), AS/RS is a system which stores and retrieves items with accuracy and speed with the help of automated equipment. AS/RS reduce labor requirements and avoid capital expenditure by utilizing unused vertical space (Custodio & Machado, 2020). There are different types of AS/RS available, which differ regarding the weight and handling features equip-med in them. According to Custodio and Machado (2020), conventional AS/RS, which can move horizontally and vertically simultaneously, can only be suitable for environments with high throughput and low variety. Kuan-Yu and Chang (2010), proposes a three dimensional AS/RS, which provides more accurate travel time calculation than others, for designing a more flexible AS/RS. To implement RFID technology along with the AS/RS, according to Wang, Guo, Zhang and Liang (2015), significantly improve the efficiency of storage and retrieval, replenishment operation and warehouse flexibility.

3.3.1.4 Selection and design of an order picking system

The selection of a suitable OPS is a key decision within warehousing for a company since it has considerable impact on logistics and customer service levels (Marchet, Melacini, & Perotti, 2014). Maximizing the service levels within constraints such as labour, machine and capital is the main objective of an order picking system (Goetschalckx & Ashayeri, 1989). Also, minimizing the average travel distance is one of the main objectives of the order picking system (de Koster et al, 2007). This, since travel time is the most dominant activity within order picking (Dekker, de Koster, Roodbergen, van Kalleveen, 2004; de Koster et al., 1999). However, de Koster et al. (2007), list other objectives which are often taken into consideration in overall warehouse design and optimization:

- minimizing the throughput time of the order
- maximizing the use of space
- maximizing the use of equipment
- maximizing the use of labour
- maximizing the accessibility to all items.

The design of an OPS is complex, since it involves different internal and external factors which impact the design choices (de Koster, 2009). According to Goetschalckx and Ashayeri (1989), customer demand, supplier replenishment pattern, marketing channels, inventory level and overall demand of the products are the external factors. Whereas internal factors include system characteristics, organizational and operational policies of order picking (de Koster et al., 2007). System characteristics of an OPS involve information availability, warehouse dimension and mechanisation level, while, OPS operational and organisational policies include factors such as order release mode, zoning, batching, storage, and routing, see Figure 3.12 (de Koster et al., 2007). Dallari et al., 2009, identifies three parameters for selection of an OPS: the number of order lines; the average order size; and the number of items (SKUs).

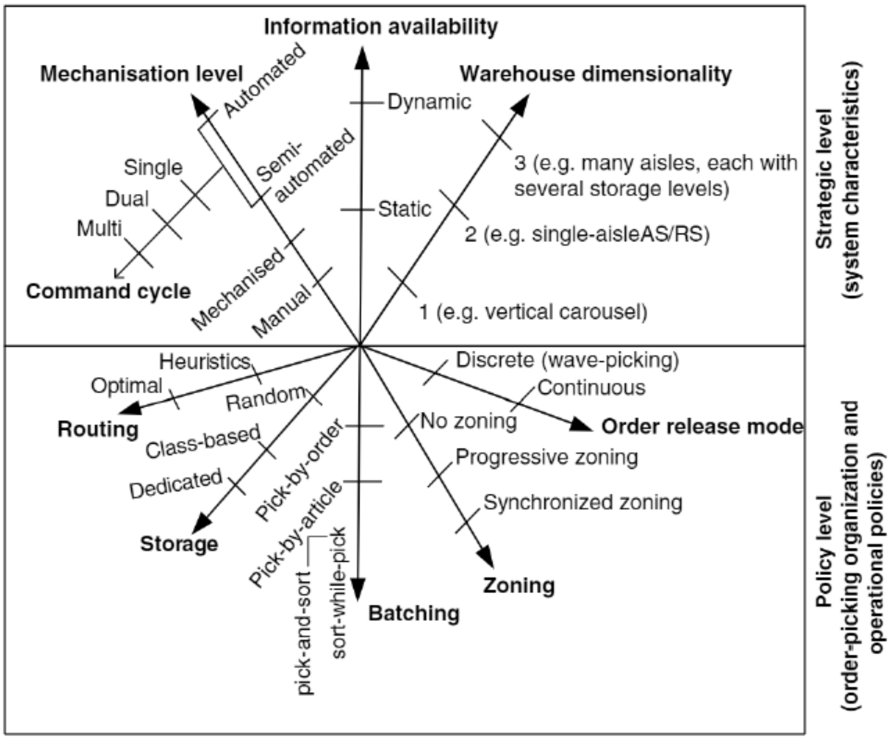

Figure 3.12: *Complexity of order picking system (Source: de Koster et al., 2007)*

3.3.2 Automation within data collection technologies

The motives behind automation in data collection are: (i) reducing the time in picking activities; (ii) enabling inventory management on a real time basis; (iii) enabling item position identification for better and faster decision making (Custodio & Machado, 2020).

3.3.2.1 Labelling technologies

To control inventory and manage a warehouse effectively, it is important to know the precise location of items stored (Custodio & Machado, 2020). Earlier conventional inventory control processes include the manual reading of labels for different products, which often is time consuming and sometimes can be wrong due to operator error (Custodio & Machado, 2020). Labelling technologies, such as barcodes, 2D data codes and radio frequency identification (RFID), aids automatic reading that collect data swiftly (Custodio & Machado, 2020). One drawback with the barcode, is that it requires scanners or sensors to be in a certain range to read the labels, whereas RFID tags can be read in long distances (Custodio & Machado, 2020).

3.3.2.2 Picking technologies

To manage an OPS effectively, the exact location of every item stored should be collected (Custodio & Machado, 2020). Simple physical labelling can give a unique location to every item stored in a warehouse, which should be communicated to the picker in an effective way to assist the picking process (Custodio & Machado, 2020). There are multiple ways of communicating the picking instructions, such as pick-by-voice and pick-by-light solutions (ten Hompel & Schmidt, 2006). Pick-by-voice system is the most sophisticated and error free approach, which allows the operator to use their both hands freely for picking activity, in addition, this enhances the order picking accuracy and safety for operators (Custodio & Machado, 2020; Hompel & Schmidt, 2006). Pick-by-light is another approach assisted by light, which improves order fulfilment performance by reducing the travel time (Custodio & Machado, 2020). Further this pick-to-light system is most suitable for zone picking and improves the pick rate productivity, accuracy and cost efficiency of labour intensive order picking process (Custodio & Machado, 2020).

3.3.3 Automation in Information, Communication and Technology (ICT)

According to Marchet et al. (2014), ICT techniques used for warehousing related activities which improve the picking productivity are routing algorithms, items allocation policies and retrieval policies. The combination of one or more ICT systems, for example Warehouse Management System (WMS), are widely dealt with optimizing and coordinating picking activities, managing inventories, and tracking customer orders (Marchet et al., 2014). Within a WMS, ICT tools like pick-to voice and pick-to-light were used for assisting picking activities and barcodes were widely used for item identification (Marchet et al., 2014). Information Technology (IT) integration with existing systems, according to Nilsson and Elmar Merkle (2018), is perceived as one of the major challenges while implementing automation within warehouses.

Most ICTs are implemented along with OPS to enhance the traceability of items, improve picking accuracy and timing and reduce picking errors (Marchet et al., 2014) . According to de Koster and van de Velde (2002), WMS can be distinguished into three types:

1. Basic WMS - supports stock and location control. Scanning tools can be used in this basic WMS to identify and register the information of incoming materials. This type of WMS is simple and mainly focuses on throughput.

2. Advanced WMS - in addition to the features of basic WMS, this advanced WMS can be used to plan resources and activities for goods. This type of WMS is focused on throughput, stock and capacity analysis.

3. Complex WMS - this type of WMS can be used to optimize the warehouse or a group of warehouses. A complex WMS provides information on the item's whereabouts (i.e. tracking and tracing), where it is headed and why (i.e. planning and execution). Furthermore this complex WMS can interact with different kinds of technical systems, such as AS/RS, AGV, sorter, RF robots and data collection systems, to enable planning and optimizing the warehouse in whole.

3.4 Application of the Theoretical Framework

The literature review summarized in this main section, has described the different areas in silos. Figure 3.13 depicts a view for how the theory will be applied in the analysis. The left part of Figure 3.13 refers to section 3.1 that describes the process related characteristics of Operations / Factory Environment such as Production layout, Manufacturing strategy, Characteristics of demand and Characteristics of assembly lines, which should be considered in the selection of warehouse automation system(s). The right part of Figure 3.13 refers to section 3.2 that describe the design areas of the Material Supply System such as Material feeding principle, Handling equipment, Storage, Packaging and unit loads, and Replenishment method, which also should be considered in the selection of warehouse automation system(s). Further, the mid-lower part of Figure 3.13 refers to section 3.1.3.1 that describe the Performance objectives such as quality, speed, dependability, flexibility, cost and ergonomics, on which the selection of warehouse automation system(s) also should be based on.

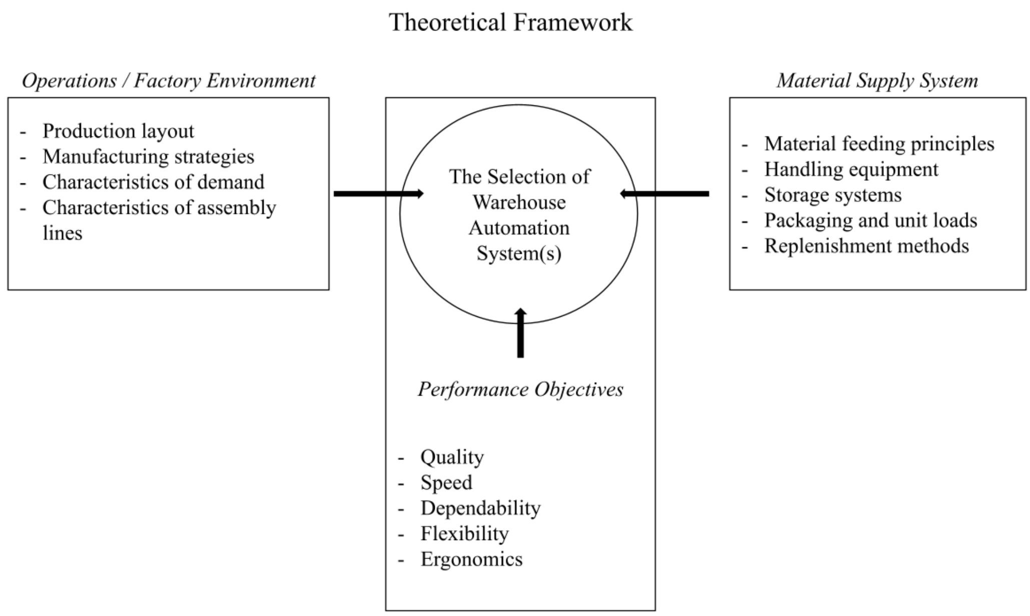

Figure 3.13: *Outline of the theoretical framework, for selection of warehouse automation system(s) for component storage - in a multiple assembly line manufacturing context, that is developed in this section.*

4
Empirical data

In this chapter is the empirical data that have been collected at the case company presented. The theoretical framework summarized in section 3.4 is in the analysis sections applied on this empirical data collected. The qualitative data presented in this section have been collected through interviews and observations, while the quantitative data presented mainly has been extracted from annual production data, PFEP-files, and Bill-of-materials.

This section include descriptions of: the case company background; the four main product groups; the existing production layout; goods receiving; the rack system and load carriers used; storage areas; component inventory build up before summer leave; storage replenishment methods; the assembly lines; equipment/automation used; and logistics performance measurements.

4.1 The case company's background - a large scale manufacturer

The case company, which is a global supplier of motion and control technologies for industrial and aerospace markets, is organized in about 100 divisions with over 300 manufacturing facilities spread over 50 countries. The production facility in focus of this thesis is part of the company's Pump and Motors Division Europe, which have production facilities in five European countries, that produces hydraulic solutions, systems and services for global industrial and machine manufacturer markets.

4.1.1 Four main product groups - hydraulic pumps and motors

In the case facility, input components are manufactured and final assembly and testing of four main product groups, which all are based on hydraulic technology, takes place. These are: AAA; BBB; CCC; and DDD. Inside the facility, the material supply for these four main product groups are divided into the three value streams that are referred to as: AAA; BBB; and CCC:DDD, which includes both CCC and DDD.

Table 4.1 summarizes the main characteristics of the four main product groups regarding; Value stream, Main models; Volume assembled; Label of assembly line(s); and Complexity of assembly. The assembly lines, in which the product groups are assembled, are described in detail in Section 4.6. In addition, Spare parts are also manufactured within the focal facility and customer orders of supplementary accessories for the main product groups are picked and packaged there as well.

Table 4.1: *Summary of the main characteristics of the four main product groups, which are assembled in the case facility.*

Main product group / Characteristics	***AAA***	***BBB***	***CCC***	***DDD***
Value stream	*AAA*	*BBB*	*CCC:DDD*	*CCC:DDD*
Main models	*AAA:1, AAA:2*	*BBB:1, BBB:2*	*CCC:1*	*DDD:A, DDD:B, (DDD:C)*
Volume assembled (approximate annual volume assembled per product group)	High ∼[40 000, 100 000]	Medium ∼[20 000, 60 000]	Low ∼[0, 20 000]	Low ∼[0, 20 000]
Assembly line(s) (approximate annual volume assembled per assembly line)	-AAA:1 ∼[20 000-40 000] -AAA:2 ∼[20 000-40 000] -AAA:3 ∼[0, 20 000]	-BBB:1 ∼[20 000-40 000] -BBB:2 ∼[0, 20 000]	-CCC:1 ∼[0, 20 000]	-DDD:1 ∼[0, 20 000]
Complexity of assembly	Medium	Low	High	Very high
A(approximate number of line items per finished product)	A(∼33-40)	A(∼24-39)	A(∼62)	A(∼86)
B(approximate number of sellable variants)	B(∼1200)	B(∼300)	B(∼50)	B(∼500)

4.2 The existing production layout - an overview of the case facility

The current production layout of the case facility is shown in Figure 4.1. The seven assembly lines, in which the four main product groups are assembled, are represented by different colored areas in the lower half of the figure. In addition to these seven assembly lines, the facility also has designated areas for: Component manufacturing; Centralized storage / Kitting area; R&D, Maintenance, and Service; Goods receiving; and Shipping (including packaging of spare parts and accessories). Areas where component manufacturing takes place are colored grey, while areas that contain R&D, Maintenance and Service functions are colored black. The orange area represents a rack storage that internally is referred to as 803, which is shared between several assembly lines. The dark yellow area in the upper part of the figure represents a rack storage, which is used for storing components that due to a lack of space in the Central storage /Kitting area cannot be stored there. The white corridors between the colored areas are used for transporting raw materials, components and finished products. The inward pointing black arrow, at the Goods receiving, shows where all inbound goods (i.e., both raw material, as well as, purchased and externally treated components) are entering the facility. The outward pointing black arrow, at the Shipping, shows where all finished products are leaving the facility. Figure 4.1, is approximate in that sense that some of the color marked areas also contain storage racks that are used by several assembly lines.

Figure 4.1: *Approximate production layout of the case facility*

4.2.1 A potential future state production layout

There are early plans of a larger reshuffle of the existing production layout where the BBB:1 and BBB:2 assembly line will be relocated to the Maintenance area, between the AAA:2 assembly line and the Shipping area. The factory floor that is freed up by relocating the BBB:1 and BBB:2 assembly line is planned to be used for kitting activities for the AAA:1, AAA:2, AAA:3 and DDD:1. This potential alternative of a new production layout, hereinafter will be referred to as the Potential Future State Layout (PFSL).

4.3 Goods receiving

All inbound goods (i.e., purchased components, in-house manufactured components that have been further processed at external suppliers, and raw-material for the in-house component manufacturing processes) enter the facility at the Goods receiving. Two work shifts are used at the Goods receiving department, a morning shift that consists of three operators and an afternoon shift that includes one or two operators. There are always more operators working in the morning shift than in the afternoon shift, due to the increased volume of inbound goods during the morning hours.

The inbound goods arrive at the facility by truck, mainly loaded on either standard EU-pallets, half-pallets, or special plastic pallets that are adapted for the case company´s standard bins. A single forklift is designated for unloading the arriving trucks and for putting the delivered load carriers just inside the ports to the Goods receiving. An external milk-run, internally referred to as “Slingbilen”, is used for collecting goods from local suppliers in the Gothenburg area and this truck has a special unloading dock, which uses roller floor technique. A few number of arriving load carriers are temporarily stored in pallet racks just inside the Goods receiving. Otherwise, pallet jacks are used for moving the load carriers from the entry hall, through an air sluice, into the control and repackaging area. Here, the operators at Goods receiving control so the quantity and quality of each inbound delivery corresponds to the attached delivery declaration. Most inbound goods that do not arrive in the case company’s own standard bins, are repackaged into such bins by the operators at Goods receiving. Though, a few number of components are directly moved to their respective designated location inside the facility in other types of load carriers, such as EU-pallets or half-pallets. Still, the vast majority of components are either delivered to the facility in the case company´s own standard bins or are repacked into such bins at arrival.

When the operators at Goods receiving has controlled the delivery, registered the arrival by using a barcode scanner, and if necessary repacked the inbound goods, the load carriers are transported to their respective designated location inside the facility. Accordingly, there is no deliberate intermediate storage of components at the Goods receiving, except for a very few types of large components that due to space limitations are stored in pallet racks in a separate “heated storage”. It is the operators at Goods receiving that executes all transports of load carriers from the Goods receiving to each load carrier’s designated location in the rack systems inside the facility.

4.4 The rack system and load carriers used

The main rack system used for storage of components within the facility is a flow rack system (see Figure 4.2), which allows replenishment with full load carriers on the opposite side to where the component picking/kitting operator retrieves the components (see Figure 4.3). This enables replenishment of load carriers to take place without the replenishing operator interrupting the component picking/kitting operator, or the other way around. The rack system has for safety and ergonomic reasons a height restriction for storing components of maximum 1.6 meters above floor.

Figure 4.2: *The flow rack system, which is the main storage system used for storing load carriers within the case facility.*

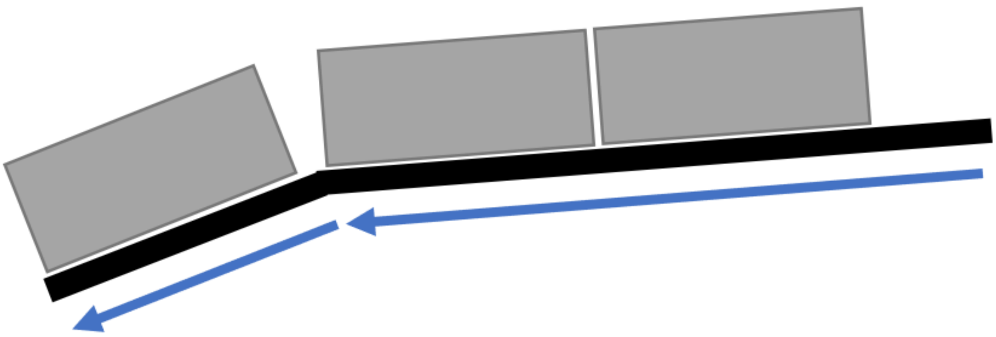

Figure 4.3: *Visualizes the flow principle in the flow rack system used at the case facility.*

4.4.1 The E-serie load carriers

The flow rack system is highly adapted to the case company's main standardized bins (i.e., the E-serie load carriers), which exists in four different versions: the E4312, which is

400x300x120 mm EUR-bin; the E4317, which is 400x300x170 mm EUR-bin; the E4322, which is a 400x300x220 mm EUR-bin; E8623, which is a 800x600x235 mm EUR-bin that always is stored and handled on a plastic half pallet. The E4312, E4317, and the E4322 versions have a maximum weight restriction of 32 kg per bin, though the target weight is about 20-25 kg per bin, while the E8623 has a maximum weight restriction of 500 kg per bin. For effective and ergonomic handling of the E4312, E4317, and the E4322 standardized bins, the case company has internally developed an electric lifting device that can handle weights up to 40 kg per bin. There exists about 25 such lifting devices equipped with gripper arms, which are specifically designed for the three smaller standardized versions of the EUR-bin (i.e., the E-serie load carrier). In addition, there are about 5 lifting devices equipped with a flat lifting platform, which are designated for other types of load carriers and packages. Both the functional and ergonomic performance of these electric lifting devices is perceived as excellent, by both the operators and managers. Considering the overall performance of the standardized EUR-bins (i.e., the E-serie load carriers), the load carrier system is internally considered as non-optimal mainly due to the EUR-bins' low rate of adaptation to the stored components. Though, since basically all the internal material handling processes over time have been adapted for these standardized EUR-bins, it would be both complex and very costly to change the system.

4.4.2 The F-serie load carriers

Another type of standardized load carrier, which contain components and that are stored in the flow racks, are the smaller F-serie load carriers that exists in three versions: the F19075, which is a 1 litre type 9075 storage bin; the F49074, which is 4 litre type 9074 storage bin; and F89067, which is a 8 litre type 9067 storage bin. For these F-serie load carriers there are no maximum weight restrictions nor any target weights, as for the E-serie.

4.4.3 The P-serie load carriers

Additional types of load carriers, which contain components, and that are stored in the rack system, though not in the parts that have flow channels installed, are: the P11, which is a 800x600 mm half-pallet with a single pallet collar; the P12, which is 800x600 half-pallet with two pallet collars; the P21, which is a 1200x800 full-pallet with a single pallet collar; the P22, which is a 1200x800 full-pallet with two pallet collars . There is a maximum weight restriction of 500 kg, being equally distributed, for the half-pallets P11 and P12, while a maximum weight restriction of 1000kg, being equally distributed, for the full-pallets P21 and P22. Neither the P11, P12, P21 nor P22 have any target weights.

For handling these P-series load carriers, pallet jacks with a lifting device are used. An internal perception is that implementing a new type of pallet jacks, which are able to lift goods 1.5 meters above the floor, would significantly reduce the load carrier handling time.

4.5 Storage areas

There are multiple storage locations for components within the case facility. Mostly these exist at the different assembly lines, at the Centralized storage/ Kitting area, at some overstocking areas like the “803” and the “heated storage”, and at the component manufacturing lines (see Figure 4.1). Most components have both a primary storage location and a secondary storage location, within the case facility. The secondary storage location is where the actual component picking/kitting takes place, while the primary storage location exists because the storage space at the secondary storage location is not enough. For some components the primary storage location and the secondary storage location are actually the exact same spot (i.e., when there is no lack of storage space at the secondary storage location). When the primary storage location and the secondary storage location are not the same, M-Cards are used for signaling the need for replenishing components at the secondary storage location. These physical M-cards basically work as transport Kanbans since they are used for triggering transport of unit loads containing a specific component type from that component types’ primary storage location to its secondary storage location.

Current inventory data from Plan For Every Part files (PFEP files) shows that the case company has 2092 line items in total, which comprises 1484 of purchase components and 608 in house manufactured components. Table 4.2 includes data for the total number of unit loads that existed within the case facility at a specific date during the year 2020. The formulas are attached in Appendix R. These unit loads were distributed among the multiple storage locations previously described. There were limitations regarding available data for some components. To normalise the missing data, approximate estimations based on the available data have been done. Further, Table 4.2 only includes data for the quantity of unit loads, which comprises different types of load carriers like the F-serie, E-serie and P-serie. Since a maximum storage height of 1.6 meter is applied for the flow rack system within the facility, this makes the current storage capacity low compared to the facility’s total cubic space. Table 4.3 includes data for the distributed percentage for primary storage locations versus secondary storage locations. The data indicates that the primary storage locations, which are used due to a lack of storage space at each component’s secondary storage location, contain as high as about 47 percent of all purchased components and about 37 percent of all in-house manufactured components. This data supports the perception, which several managers have expressed, that there is a general lack of storage space at the assembly lines.

Table 4.2: *The total number of unit loads, which existed within the case facility at a specific date during the year 2020.*

	Purchased items	**In-house manufactured items**	**Total**
# of unit loads	8613	2480	11093

Table 4.3: *The percentage distribution of primary storage locations and secondary storage locations, at a specific date during the year 2020.*

	Purchased items	**In-house manufactured items**
Primary location	47,35%	37,07%
Secondary location	52,65%	62,93%

4.5.1 Component inventory build up before for summer

A major issue regarding the storage capacity needs occurs during the period before each summer. The reason is that several component suppliers reduce their own production capacity during a couple of weeks in the summer, due to vacations or maintenance needs. The delivery patterns of components are affected for about 20 percent of the suppliers. In addition, the case company's own component manufacturing lines have reduced production capacity during a couple of weeks in the summer, due to manpower reductions caused by summer leaves. These reductions in production capacity of both purchased and in-house manufactured components require the case company to build up inventory of the affected components before each summer period. Since there is a general lack of storage space within the case facility, this temporary overstocking takes place everywhere inside the facility. Both in the rack systems and at other locations.

4.5.2 Storage replenishment methods

Overall, there are six co-existing storage replenishment methods being used for signaling the need for replenishment of components in the rack systems used in the case facility. These are: Kanban cards; Hybrid Kanban cards; Material cards; Lot numbers; and Stock balance replenishment. That several storage replenishment methods are simultaneously used, for replenishing components stored at the assembly lines and in the Centralized storage / Kitting area, influences the storage capacity requirements and the internal transport needs within the facility, as well as increases the overall complexity of the material handling operation.

4.5.2.1 Kanban cards - used for triggering production of in-house manufactured components

Physical Kanban cards are used for signaling the need for replenishment of many in-house manufactured components and each internal value stream has its own Kanban cards, which are easily distinguishable due to a colour scheme. The Kanban system is internally perceived to be easy to use and easy to learn by new operators. In total, there are: about 430 different types of Kanban cards for AAA; about 120 different types of Kanban cards for BBB; and about 75 different types of Kanban cards for CCC:DDD. Though, these numbers are highly approximative since also inactive Kanban cards are included. Therefore, the number of different Kanban cards actually being used are lower than these numbers presented.

The Kanban cards at the Centralized storage / Kitting area are collected by a continuously routing tug train called the V1 (i.e, "Verkstadsrundan 1"), while Kanban cards for the BBB, CCC:DDD, and the AAA:3 assembly line are collected by a tug train called the V2 (i.e., "Verkstadsrundan 2") that routes ones an hour. The V1 and V2 also perform the physical replenishment of load carriers. The V1 and V2 hang the collected Kanban cards at one of the Kanban billboards, which are located at the component manufacturing lines. When the number of Kanban cards of a specific type reaches a predetermined level, the manufacturing process of that specific component is triggered. The Kanban billboards have different color markings that represent different levels of component urgency, which helps prioritizing the manufacturing sequence of different components. Accordingly, it is crucial that no Kanban cards disappear since this will affect the manufacturing sequence and can lead to shortages of the needed component type. The number of physical Kanban cards used for a specific component varies over time depending on the volume demand. There have been internal discussions about changing to an electronic Kanban system, but these discussions have not led to any concrete plans yet. The route of the V1, which only supplies the Centralized storage/Kitting area with components being stored at other locations within the facility, is shown in Figure 4.4. A similar route map for the V2 does not exist since the V2 tug train drives different routes based on the assignments at each work orders.

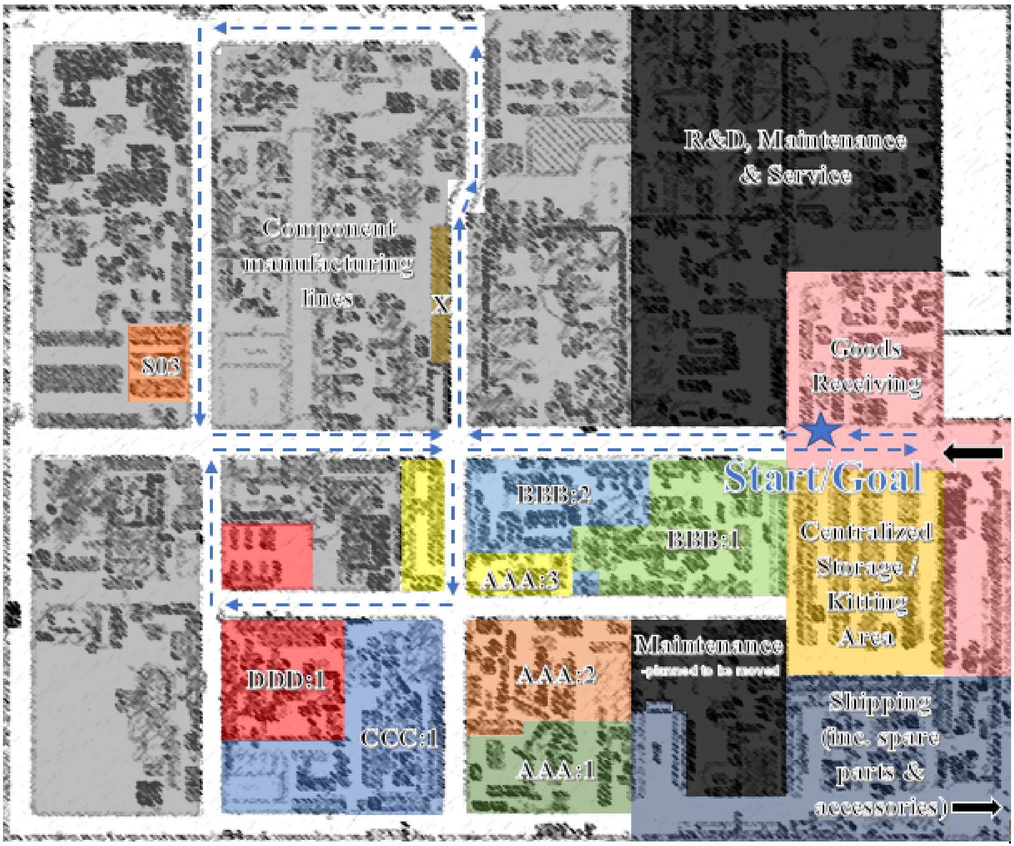

Figure 4.4: *Shows the route of the continuously going tug-train "V1", which supplies the Centralized storage/Kitting area with components being stored at other locations within the facility.*

4.5.2.2 Hybrid Kanban cards - used for triggering call-offs of purchased components

There is also a separate hybrid Kanban system used for a few number of purchased components, which applies a combination of physical cards and electronic signalling. These Kanban cards for purchased components never leave the facility. Instead, when an individual Kanban card is marked as empty by a component picking/kitting operator using a barcode scanner, there is automatically an internal order registered in the ERP system for that specific Kanban card number. When a predetermined number of these hybrid Kanban cards have been registered as empty, the personnel that are responsible for making call-offs from external suppliers send a request, for a new delivery of components, to the specific supplier.

4.5.2.3 Material cards - used for signaling the need for component replenishment

For components that have separate secondary storage location and primary storage location, a Material card (M-card) system is used for signaling the need for replenishment at the secondary storage location. These M-cards are used for both in-house manufactured components and for purchased components, though these M-cards never leave the facility. As opposed to the Kanban cards that are used for many in-house manufactured components, an M-card does not trigger any production directly. Instead, the ERP system manages the triggering of production of in-house manufactured components that M-cards are used for, while personnel that are responsible for making call-offs from external suppliers perform the ordering of the purchased components that M-cards are used for.

In practice, an M-card can be viewed as a tool for signaling the need of transporting a unit load of a specific component type, from a distant storage location within the facility, to the assembly line where needed. The number of M-cards used for a specific component type is always one less than the number of load carriers used for that component, which corresponds to one M-card less than the number of load carriers in the rack system. The M-cards are collected by the V1 and V2 tug train, which also executes the actual replenishment of load carriers. It is important that the order picking/kitting operators directly register when a load carrier with an attached M-card becomes empty, since queuing problems involving the tug train otherwise may occur.

The total numbers of M-cards, which each represents a specific component type, are: 106 M-cards for AAA; 11 M-cards for BBB; and 44 M-cards for CCC:DDD. Though, these numbers also include inactive M-cards. Consequently, the number of different M-cards actually being used are lower than these numbers presented and the numbers should rather be interpreted in relation to one another. The case company believes that in a future material supply operation, there will be no need for M-cards since all components then only should be stored at a single storage location within the facility.

4.5.2.4 Lot numbers - a system used for replenishing individual unit loads of components

There is also a system based on lot numbers for individual load carriers, which is used for all product groups except for the DDD:A and DDD:B models at the DDD:1 assembly line. Though, components for the new product group DDD:C, which also will be assembled at the DDD:1 assembly line, will utilize lot numbers. Each load carrier, which contains components that are included in the lot number system, is assigned an individual lot number when it is added to the internal stock balance by operators at the Goods receiving. Also full lot sizes of in-house manufactured components, which often corresponds to a full pallet, are assigned unique lot numbers before being sent to external suppliers for further treatments. When these full pallets of components are returned to the case facility, operators at the Goods receiving assign each individual load carrier an individual lot number. Each lot number represents the year, month, and day, when the load carrier is added to the stock balance, as well as a four digit serial number for further identification. What component types that are integrated into the lot system are decided by the production technician, at each assembly line, in agreement with the respective product designer. The lot number system is internally perceived to reduce the number of picking errors made by operators, as well as removing the issue of accumulated stock balance errors, but the need for extra barcode scanner handling when a load carrier becomes empty is perceived as a disadvantage. Further, the lot number system is perceived to increase the traceability of individual components, which is regarded as a great advantage when a defect component is discovered. This, since all components belonging to an individual batch easily can be identified and sorted out, which reduces the risk for further production disruptions or quality issues.

4.5.2.5 Stock balance replenishment - based on the stored volume of unique item numbers

All component types stored within the facility have an unique item number. Most components, which neither Kanban cards nor M-cards are used for, the ERP system is used for controlling the replenishing of components in the rack systems. This, based on the stock balance of the unique item numbers. This stock balance system does not imply a need for extra barcode scanner handling every time a load carrier becomes empty, since it is the total number of components in the stock balance that is used for controlling the replenishing, not the total number of load carriers. Though, this stock balance system reduces the traceability of components and the occurrence of stock balance errors is higher than for components included in the lot number system. Personnel responsible for call-offs make the decision of when and what quantity of components to order from external suppliers, while the ERP system mainly controls when production of in-house manufactured components should start.

4.5.2.6 Two-bin system - used for some smaller materials

The replenishing of some smaller materials, like screws and bolts, are controlled by two-bin systems where a single load carrier covers the demand for a component until the second load carrier has been refilled and returned to the two bins' location in the rack system.

4.6 The assembly lines - the internal customers of components stored

All internal processes at the case company should be designed to support end customer satisfaction and the characteristics of the end customer demand directly influence the internal assembly processes, which in turn directly influence the requirements on the internal material feeding operation. Since an optimized On-Time-In-Full (OTIF) delivery of the components being required at the fed assembly lines is a primary objective for an internal material feeding operation, it is crucial to map and understand the characteristics of the demand from the seven assembly lines at the case facility (i.e., the AAA:1, AAA:2, AAA:3, BBB:1, BBB:2, CCC:1, and DDD:1). Thus, the seven assembly lines are the internal customers of stored components, whose needs must be fully ensured by a future material feeding operation based on a higher level of automation

4.6.1 Product group AAA - the AAA:1, AAA:2, and AAA:3 assembly line

The main product group AAA is assembled in three parallel assembly lines (i.e., the AAA:1, AAA:2, and AAA:3) that differ regarding several main characteristics, which are summarized in Table 4.4.

Table 4.4: *Summarizes the main characteristics of the AAA:1, AAA:2, and AAA:3 assembly line, in which AAA products are assembled. See Appendix Q for calculations of production pace.*

Assembly line /Characteristics	***AAA:1***	***AAA:2***	***AAA:3***
Manufacturing strategy	Mainly ATO/MTO	Mainly ATO/MTO	Mainly ATO/MTO
Volume assembled (annual number of products assembled)	~[20 000, 40 000] products assembled annually	~[20 000, 40 000] products assembled annually	~[0, 20 000] products assembled annually
Production pace (products assembled per hour)	~22 products per hour	~19 products per hour	~4 products per hour
Flexibility / Lot sizing (Approximate annual number of batches assembled)	*Multi-model* (~2700 batches)	*Multi-model* (~2800 batches)	*Multi-model* (~500 batches)
Batch sizes (Number of finished products per batch)	*Min: 1* *Average: 11.7* *Median: 8* *Max: 63* *Standard deviation: 11.6*	*Min: 1* *Average: 7.7* *Median: 5* *Max: 36* *Standard deviation: 6.6*	*Min: 1* *Average: 2.7* *Median: 3* *Max: 4* *Standard deviation: 1.3*
Material feeding principle	Mainly *Sequenced kitting supply*	Mainly *Sequenced kitting supply*	Mainly *Sequenced kitting supply*
Storage policy	*Centralized storage*	*Centralized storage*	*Decentralized storage*
Storage assignment policy	*Dedicated storage,* mainly in flow racks	*Dedicated storage,* mainly in flow racks	*Dedicated storage,* mainly in flow racks
Storage replenishment method	ERP-controlled/Kanban /M-card/Two-bin System	ERP-controlled /Kanban /M-card /Two-bin System	ERP-controlled/Kanban /M-card/Two-bin System

Manufacturing strategy and Customer order decoupling point

The assembly in the AAA:1, AAA:2, and AAA:3 is initiated by customer orders received almost exclusively. Only a few AAA products being dedicated for Elite customers may be assembled to stock. Further, extraordinarily large customer orders received may on the case company's request be delivered in batches during a period in time. Both the production of in-house manufactured components and the ordering of finished components are initiated by different pull systems, which are based on the actual consumption of components. Though, many components required at the AAA:1, AAA:2, and AAA:3 are also stored in safety and buffer stocks of various quantities, based on speculation of demand and expected supplier lead times. Consequently, the exact location of the customer order decoupling point is rather diffuse for AAA and in practise it depends on the volume and specification of a customer order. Accordingly, the applied manufacturing strategy for the AAA:1, AAA:2, and AAA:3 corresponds to a mix of ATO (Assemble-To-Order) and MTO (Manufacture-To-Order) strategies. Further, there exist stock points of safety and buffer stock both between the purchase process and the component manufacturing processes, between the component manufacturing and assembly processes, as well as between the purchase process and the assembly processes.

Technical characteristics of the products assembled
Each AAA product consists of about 30-34 components and there exist about 1200 different sellable versions. In the AAA:1 assembly line, AAA products that belong to the sub-product group with the same name (i.e., AAA:1) are assembled. In the AAA:2 assembly line, AAA products that belong to the sub-product group AAA:2 are assembled. These AAA:2 are similar, though larger and heavier, compared to the AAA:1. In the AAA:3 assembly line, are extra large AAA:2 assembled. These AAA:3 are both larger and heavier than the AAA:2 being assembled in the AAA:2 assembly line. These differences in size and weight of the finished products, between AAA:1, AAA:2, and AAA:3 assembly line, are transferred into similar differences in size and weight of the input components required. The actual assembly activities in the AAA:1, AAA:2 and AAA:3 assembly line are of medium complexity, in relation to the other main product groups.

Volume assembled, production pace and lot sizing
There are differences in the volume assembled between the three assembly lines for AAA products (see Table 4.4). Further, the current approximate production pace is 22 units of AAA:1 per hour, 19 units of AAA:2 per hour, and 4 units of AAA:3 per hour. Further, the annual volume assembled of different product variants differ rather significantly for both the AAA:1, AAA:2, and AAA:3 assembly line (see Appendix A, Appendix C, and Appendix E). In addition, each of the sub-product groups includes multiple variants that customers can order.

Even though set up times are negligible short for all three assembly lines for AAA products, the assembly is performed in batches of various sizes (see Appendix A, Appendix C, and Appendix E) that make the AAA:1, AAA:2, and AAA:3 correspond to the definition of multi-model assembly lines (see Section 3.1.7.1), even though some assembly lot sizes equal a single finished product only (see Table 4.4).

Material feeding principles, storage assignment policies, and pace control
As a material feeding principle, both the AAA:1 and AAA:2 assembly line utilises sequenced kitting supply in a centralized storage, which is performed by the operators from the respective assembly line who take turns having that work task. The material feeding processes for the AAA:1 and AAA:2 assembly lines are unpaced asynchronous (see Section 3.1.7.4), in relation to the respective assembly process. This, since the delivery of component kits to the respective assembly line is triggered by the return of empty kitting carts in combination with that the kitting carts are never sent to the respective assembly line before the kitting procedure is fully complete, which make them not correspond to the definition of an unpaced synchronous line process. Neither is there any defined cycle time that each component kitting operator is measured on, which make them not correspond to the definition of a paced line process (see Section 3.1.7.4). For the AAA:3 assembly line, the material feeding process is also unpaced asynchronous since the kitting and assembling are performed by the same operator, who works with no defined cycle time for the kitting procedure and always finishes the kitting before starting to assemble. Though for the AAA:3 assembly line, the picked components are not only located within the designated Centralized storage/ Kitting area. Instead, the kitting operator must walk to different locations in the facility to collect all components required.

Some very small materials like bolts and screws are not kitted for any of the AAA assembly lines. Instead are these small materials stored at each assembly line and two-bin systems are used for controlling the replenishment of these. Small screws and bolts are also stored in a separate rack that works as a bulk storage, which an external supplier is responsible for replenishing. This occurs about once a week.

The Kitting area / Centralized storage
The kitting for the AAA:1 and AAA:2 assembly line take place in a separate kitting area (i.e. the Centralized storage/ Kitting area in Figure 4.1) that contains two separate corridors, with flow racks on both sides, which are designated for the AAA:1 and AAA:2 respectively. Only the case company's standard bins are used as load carriers in the Centralized storage/Kitting area and all components have fixed locations in the flow racks. Operators at the Goods receiving are responsible for replenishing components in the flow racks and do so immediately when new components arrive at the facility. Only a few especially large components are first stored in a separate heated area at arrival, before being moved to the Centralized storage/ Kitting area when free space is available at the designated location in the flow racks.

A continuously routing tug train, internally referred to as the V1, replenishes the Centralized storage/ Kitting area with both in-house manufactured components and a few number of purchased components, which due to a lack of space in the Centralized storage/ Kitting area cannot directly be stored there at arrival to the facility. The V1 does not deliver any components or materials directly to any assembly line, but only to the Centralized storage/Kitting area (see Figure 4.4). Previously the V1 made its replenishment routes in fixed time intervals, but that occasionally created component shortages at the Centralized storage/ Kitting area. This led to the implementation of continuous routing, which reduced the occurrence of component shortages. Though, there is a target for the V1 of making three routes per hour. In addition the V1, there is the tug train called the V2 (i.e., "Verkstadsrundan 2") which supplies the AAA:3 assembly line with in-house manufactured components. This V2 tug train is shared between the AAA:3 assembly line, BBB, and CCC:DDD.

The component kitting procedure at the Centralized storage/ Kitting area is the same for the AAA:1 and AAA:2 assembly line and is performed with support of a pick-by-voice system, which provides the respective kitting operator with information about which and what quantity of components to pick. This allows the kitting operators to verbally confirm individual work steps on the work order, while simultaneously being able to use both hands for the actual picking. The pick-by-voice system is activated when the kitting operator scans the barcode at a work order, which is provided as a printed document. The kitting operator places the picked components in kitting trays, made of hard plastics, which are located on the top of a kitting cart. For the AAA:1 assembly line, there are 6 designated kitting carts, while for the AAA:2 assembly line there are 4 designated kitting carts. Each kitting tray contains components for a single finished AAA. The kitting carts are designed so they can be connected to the respective assembly line for automatic unloading of the kitting trays, which travels along the assembly process. The kitting trays for the AAA:1 and AAA:2 assembly line are universal in the sense that each one can be used for all variants of the finished products that are assembled in the respective assembly line.

Also the AAA:3 assembly line utilises kitting supply as material feeding principle, though for the AAA:3 there is no operator designated for component kitting only, as for the AAA:1 and AAA:2 assembly line. Instead, kitting for the AAA:3 is made by the same operator who assembles the components into a finished product. The reason for why there is no operator designated only for kitting, during each work shift at the AAA:3, is that the volume assembled is much lower at the AAA:3 assembly line than at the AAA:1 and AAA:2 assembly line. Unlike the kitting procedure for the AAA:1 and AAA:2 assembly line, some components kitted for the AAA:3 assembly line are picked from flow racks located at the production floor close to the assembly line (i.e., outside the Centralized storage/ Kitting area).

For transporting the kitting carts, between the Centralized storage/ Kitting area and the respective assembly line, has for the AAA:2 recently an AMR (MiR250) been implemented, which moves a single kitting cart at a time. Transport tasks of moving empty kitting carts from the AAA:2 assembly line back to the Centralized storage/ Kitting area, are initiated by the assembling operators. The kitting operator, which is dedicated for the AAA:2 assembly line, initiates work tasks for the AMR of moving replenished kitting carts from the Centralized storage/ Kitting area to the AAA:2 assembly line. For the AAA:1 assembly line, transport of replenished kitting carts from the Centralized storage/ Kitting area to the assembly line is performed manually by the operator that is designated for kitting components for that assembly line.

The newly implemented AMR

The case company uses an AMR (Autonomous Mobile Robot), MiR250, for internal transportation of kitting carts from the Kitting area / Centralized storage to the AAA:2 assembly line. This MiR250 has a base dimension of 580 X 800 mm, is 300 mm in height, and can transport a maximum payload of 250 kg at the speed of 2 m/s, which makes this an more agile and adaptable AMR on the market. With maximum payload, the MiR250 can operate 13 hours, as claimed by the manufacturer. The MiR250 has recently been operationalized and is currently used for the AAA:2 assembly line alone. Though, there are plans for using it for transporting kitting carts for the AAA:1 assembly line too.

The MiR250 has been fed with different missions based on the transport requirements for the AAA:2 assembly line, for instance a mission could be to transport an empty cart from the assembly area to the kitting area. Designated spots have been assigned in the virtual map of the MiR250, which is used for dropping and picking up empty and loaded kitting carts. Operators in the AAA:2 assembly line and in the Kitting area / Centralized storage, initiate the required predetermined missions through a mobile device stored at each location. The current workload is low (i.e the frequency of trips is low) since it currently is serving the AAA:2 assembly line only. The battery effectiveness, as claimed by their manufacturer, cannot be determined or analysed due to the fact that the MiR250 recharges in the available time between missions. Continuous missions can also be assigned, if that is the case, the MiR250 completes the missions in their respective assigned sequence. In the delivery point at the AAA:2 assembly line there are three slots available for delivering kitting carts. The MiR250 delivers the kitting cart at the first visible empty slot in its virtual map and sometimes that is not inline with the sequence of the assembly process. Currently operators at the AAA:2 assembly line are responsible for arranging the delivered kitting carts in a sequence so that the empty slot is always in line with the sequence of the assembly work order.

4.6.2 Product group BBB - the BBB:1 and BBB:2 assembly line

The main product group BBB, is assembled in two parallel assembly lines (i.e., the BBB:1, and the BBB:2) that differ regarding several main characteristics, which are summarized in Table 4.5.

Table 4.5: *Summarizes the main characteristics of the BBB:1 and BBB:2 assembly line, in which BBB products are assembled. See Appendix Q for calculations of production pace.*

Assembly line /Characteristics	***BBB:1***	***BBB:2***
Manufacturing strategy	Mainly MTO/ATO/MTS	Mainly MTO/ATO
Volume assembled (annual volume of products assembled)	∼[20 000, 40 000] products assembled annually	∼[0, 20 000] products assembled annually
Production pace (products assembled per hour)	∼15 products per hour	∼3 products per hour
Flexibility / Lot sizing (Annual number of assembly batches)	*Multi-model* (∼2800 batches)	*Multi-model* (∼700 batches)
Batch sizes (Number of finished products per batch)	*Min: 1 product* *Average: 10.2 products* *Median: 8 products* *Max: 42 products* *Standard deviation: 8.86 products*	*Min: 1 product* *Average: 4.6 products* *Median: 5 products* *Max: 11 products* *Standard deviation: 2.9 products*
Material feeding principle	*Continuous supply*	*Continuous supply*
Storage policy	*Decentralized storage*	*Decentralized storage*
Storage assignment policy	Mainly *Random storage* in flow racks, but also *Dedicated storage* for smaller materials	Mainly *Random storage* in flow racks, but also *Dedicated storage* for smaller materials
Storage replenishment method	ERP-controlled/Kanban /M-card/Two-bin System	ERP-controlled/Kanban / M-card/Two-bin System

Manufacturing strategy and Customer order decoupling point
BBB is the only main product group that on a larger scale is assembled to stock, based on speculation about future demand. This MTS (Make-To-Stock) manufacturing strategy is only applied for the BBB:1, which are assembled in the BBB:1 assembly line. Further, assembly of the BBB:1 are, like all the assembly in the BBB:2 assembly line, also initiated by customer orders received. Though, for both these assembly lines very large customer orders received may on the case company's request be delivered to the customer in batches during a period in time. Since there are stock points of safety and buffer stocks between both the purchasing process and the component manufacturing processes, between the component manufacturing processes and the assembly processes, between the purchasing process and the assembly processes, and for the BBB:1 also a stock point between the assembly process and the delivery process, a mix of MTO/ATO/MTS is mainly applied for the BBB:1 assembly line, while a mix of MTO/ATO mainly is applied for the BBB:2 assembly line. Since some customer orders of relatively small quantities, with no customized adaptations required, may not directly affect the purchasing and component manufacturing processes, or even the assembly process for the BBB:1, but larger order quantity or customized product orders will, the customer order decoupling point, in practice, varies

depending on the characteristics of customer orders received.

Technical characteristics of products assembled

Each BBB product consists of about 24-39 parts per unit, which makes BBB the main product group that contains the fewest number of input components per finished product (see Table 4.1). BBB products exist in about 300 sellable versions. The input components are to a high degree standardized and each component is often used in several variants of the finished products. Especially the BBB:1 assembly line, uses a lot of standardized components in the assembly process. Since all assembly in the BBB:2 assembly line is initiated on customer orders, the level of standardization of input components is lower for this assembly line. The finished products that are assembled in the BBB:1 assembly line is larger and heavier than the finished products assembled in the BBB:2 assembly line, which entail that also the input components are larger and heavier at the BBB:1 assembly line compared to at the BBB:2 assembly line. The actual assembly activities in the BBB:1 and BBB:2 are of low complexity, in relation to the other main product groups.

Volume assembled, production pace and lot sizing

There is a large difference in the annual volume assembled and the production pace between the two assembly lines for BBB products, where about 15 finished products per hour are assembled in the BBB:1 assembly line, while only about 3 finished products per hour are assembled in the BBB:2 assembly line. The annual volume assembled of different product variants differ significantly between the BBB:1 and BBB:2 assembly line (see Appendix G and Appendix I). In addition, each of the sub-product groups includes multiple variants that customers can order.

Both the BBB:1 and BBB:2 assembly line correspond to the definition of multi-model assembly lines (see Section 3.1.7.1), since assembly of each product variant is made in batches (see Appendix G-I). This, even though some assembly lot sizes equal a single finished product only (see Table 4.5). At the BBB:2 assembly line, the batch sizes are much smaller and lot sizes equaling 1-5 finished products constitutes a larger share of the annual volume assembled than at the BBB:1 assembly line (see Appendix G-I).

Material feeding principles, storage assignment policies, and pace control

At the BBB:1, there is an operator assigned for material supply/component picking activities only, while at the BBB:2 the assembling operators working there pick themselves the components required for assembly. The operators take turns working at the BBB:1 and BBB:2 respectively.

The material feeding principle applied is the same for the BBB:1 and BBB:2 assembly line, which both practices continuous supply where all material and components required for all product variants constantly are stored in the storage racks at the respective assembly line. As load carriers, both the standardized bins, pallets, and other smaller packaging units are used for storing components. Some very small materials like screws and bolts are stored in small packages within the assembly line, while larger units loads of these are stored in racks located just beside. These unit loads of small screws and bolts are replenished from a special rack that works as a bulk storage, which an external supplier is responsible for replenishing. Some components used at the BBB:1 and BBB:2 assembly line are also used at the CCC:1 assembly line, where CCC products are assembled. These components are stored at the assembly area for BBB products too, but are replenished from racks that belong to the CCC:1 assembly line. Components that are purchased from external suppliers, are at arrival to the facility directly transported by operators at the Goods receiving, from the Goods receiving to the BBB:1 and BBB:2 assembly line. Full pallets are by the Goods receiving operators placed just outside the actual assembly area for the BBB:1 and BBB:2, while the Goods receiving operators put the standardized bins directly into the flow racks. There is also the tug train called the V2 (i.e., "Verkstadsrundan 2") that is shared between the BBB, CCC:DDD, and the AAA:3 assembly line, which replenishes components that are in-house manufactured. The V2 does not always drive the same route, like the tug train V1 that is dedicated for the Centralized storage/Kitting area does. Instead, each route for the V2 varies based on the assignments at each work order.

As a storage assignment policy, both the BBB:1 and BBB:2 mainly use a random storage policy where components do not have a constantly fixed location in the rack system. Instead, if an inbound component type is not already located anywhere in the rack system it is by the ERP-system allocated to where an empty flow track is available. Though, to avoid really ineffective allocation of load carriers the production technician has the possibility to influence these decisions. Previously, a dedicated storage policy was used, where all components had a constantly fixed location in the rack system, but this created a low utilization rate of the racks. Since the random storage assignment policy was implemented, there have generally been no major problems caused by a lack of storage space for components, even though the space utilization since the policy change has been very high. Though, an exception is during the period before the summer leave, since components then are piled up at the assembly area in order to prepare for the lack of replenishment of components during the actual leave.

The operator that is designated for component picking at the BBB:1 assembly line, starts the sequenced component picking procedure by taking a printed work order, which includes a picking list that describes where each component type is located in the rack system and how many of each component to pick. The work order presents the components in an order that facilitates the picking procedure, so the component picker does not have to run back and forth between the different racks. The order picker scans each load carrier, which anything is picked from, using a barcode scanner and registers how many components that were retrieved. P-serie load carriers are sometimes placed just beside the assembly line for direct pick and place, but otherwise is a manual cart used for temporary storing during the component picking procedure. The component picking is time consuming and it takes approximately the same time to pick components for four finished products as for a single one.

Even though the BBB:1 assembly line is highly automated with a paced line control, the material feeding process is unpaced asynchronous (see Section 3.1.7.4) in that sense that there is no defined cycle time for the component picking procedure and each printed work-order, for component picking, is always completely finished before the next one is started. Several components can simultaneously be put at the inbound point of the BBB:1 assembly line, which in practice act as a buffer between the assembly process and the material feeding process. At the BBB:2 assembly line, the assembly process is more manual and since each designated assembler first needs to pick all required components himself/herself, with no determined cycle time, the material feeding process for the BBB:2 assembly line is also unpaced asynchronous (see Section 3.1.7.4).

4.6.3 Product group CCC - the CCC:1 assembly line

All versions of the main product group CCC are assembled in a single assembly line, referred to as the CCC:1. Further, there is a small assembly cell just next to the CCC:1 assembly line where regulators/controllers are pre-assembled for use in the CCC:1 assembly process. All materials used in this pre-assembly cell are stored there. The main characteristics of the CCC:1 assembly line are summarized in Table 4.6.

Table 4.6: *Summarizes the main characteristics of the CCC:1 assembly line, in which CCC are assembled. See Appendix Q for calculations of production pace.*

Assembly line/Characteristics	***CCC:1***
Manufacturing strategy	Mainly MTO/ATO
Volume assembled (annual volume of products assembled)	~[0, 20 000] products assembled annually
Production pace (products assembled per hour)	~2 products per hour
Flexibility / Lot sizing (Annual number of assembly batches)	*Multi-model* (~1400 batches)
Batch sizes (number of products per batch)	*Min: 1 product* *Average: 4.8 products* *Median: 6 products* *Max: 12 products* *Standard deviation: 1.8 products*
Material feeding principle	Mainly *Sequenced kitting supply*
Storage policy	*Decentralized storage*
Storage assignment policy	Both *Random storage* and *Dedicated storage*, mainly in flow racks
Storage replenishment method	ERP-controlled/M-card/Two-bin system

Volume assembled, production pace and lot sizing
The annual volume of products assembled in the CCC:1 assembly line is low compared to several other assembly lines. Further, the annual volume assembled of the different sub product groups of CCC differs rather much (see Appendix K). The different variants of CCC products are assembled in batches, which make the CCC:1 correspond to the definition of a multi-model assembly line (see Section 3.1.7.1). The assembly batch sizes are almost exclusively in the range of 1-10 CCC products per assembly batch (see Appendix K).

Manufacturing strategy and Customer order decoupling point
As for the assembly lines for AAA products and DDD products, the assembly at the CCC:1 assembly line is initiated by customer orders received almost exclusively. Though, a few finished products dedicated for Elite customers may be assembled to stock. Further, extraordinarily large customer orders received may on the case company's request be delivered in batches to the customer. Mainly, there exist stock points of safety and buffer stocks between both the purchase process and the component manufacturing processes, between the component manufacturing processes and the assembly process, as well as

between the purchase process and the assembly process. The quantity and the technical specifications of a customer order received determines if it initiates assembly activities only, or if manufacturing of components and purchase activities are initiated as well. Consequently, the exact position of the customer order decoupling point, in practice, varies between customer orders received.

Technical characteristics of products assembled
Each CCC product assembled at the CCC:1 assembly line consists of about 62 components and there are about 50 number of sellable versions of CCC products. The actual assembly activities in the CCC:1 assembly line are of high complexity, in relation to the other main product groups.

Material feeding principles, storage assignment policies, and pace control
One operator att CCC:1 is dedicated for the pre-assembly of regulators/controllers and for driving the V2 tug train. At the CCC:1 is kitting supply applied as the main material feeding principle, where the operator being dedicated for component kitting picks components for several CCC products each work cycle. The components that are kitted are components that need to be traceable, that may cause picking errors, or which are easily missed when assembling. Since it is resource consuming to kit components, some smaller components are stored at the assembly bench. For these smaller components, two-bin systems are used. Regarding the storage assignment policy used, both dedicated storage and random storage is applied at the CCC:1 assembly line. Since the component kitting process does not have to be performed within a specific cycle time and because each kitting work order always is completed before the components are transferred to the assembly process, the material feeding process for the CCC:1 assembly line is unpaced asynchronous (see Section 3.1.7.4).

4.6.4 Product group DDD - the DDD:1 assembly line

The DDD is a product group that is assembled in multiple variants under the DDD:A and DDD:B sub product groups. An additional sub product group called the DDD:C is planned to be introduced in near time, though to consider the DDD:C is out of the scope of this thesis, due to a lack of data required. All the variants of DDD products are assembled in the same assembly line, labeled as the DDD:1 assembly line. The main characteristics of the DDD:1 assembly line are summarized in Table 4.7.

Table 4.7: *Summarizes the main characteristics of the DDD:1 assembly line, in which DDD products are assembled. See Appendix Q for calculations of production pace.*

Assembly line /Characteristics	***DDD:1***
Manufacturing strategy	Mainly ATO/MTO
Volume assembled (annual volume of products assembled)	~[0, 20 000] products assembled annually
Production pace (products assembled per hour)	~1 product per hour
Flexibility / Lot sizing (Annual number of assembly batches)	*Multi-model* (~1200 batches)
Batch sizes (in number of products per batch)	*Min: 1 product* *Average: 3.9 products* *Median: 4 products* *Max: 10 products* *Standard deviation: 2.7 products*
Material feeding principle	Mainly *Sequenced kitting supply*
Storage policy	*Decentralized storage*
Storage assignment policy	Mainly *Dedicated storage* in flow racks, though *Random storage* for a few low runner components
Material replenishment method	ERP controlled /Kanban/ Two-bin system

Manufacturing strategy and Customer order decoupling point
The assembly in the DDD:1 assembly line is almost exclusively initiated by customer orders received, though a few DDD products being dedicated for Elite customers may be kept in stock. Also, extraordinarily large customer orders received may on the case company's request be delivered in batches to the customer. Both purchased finished components and in-house manufactured components are used in the assembly process. The production of in-house manufactured components required is controlled by Kanban cards and the ERP system. However both purchased and in-house manufactured components are stored in safety/buffer stocks to handle the variability in volume demand and supplier lead times. Hence the manufacturing strategy is mainly a mix of both ATO (Assembly-to-Order) and MTO (Manufacture-to-Order) and the customer order decoupling point varies dependent on the quantity and the technical specifications of a customer order received since these customer order characteristics determines if only assembly activities are initiated, or if manufacturing of components and purchase activities are initiated as well.

Technical characteristics of products assembled
Each DDD product assembled at the DDD:1 assembly line consists of approximately 86 components. Further, the number of sellable versions of DDD products is about 500. This makes the level of product customization at the DDD:1 assembly line high and complex and only specialized operators are used, due to this high complexity of the assembly process. The DDD products are heavier than the other main product groups and the weight of some input components are also high in relation to the final product, for instance bearing housing, but there are also smaller and lighter components included.

Volume assembled, production pace and lot sizing
The annual volume assembled at the DDD:1 assembly line is low as compared to several other main product groups (see Table 1.1), and the average production rate is about 1 DDD products per hour. The volume assembled differs rather much between the different sub product groups of DDD products (See Appendix M). Further, each of the sub-product groups includes multiple variants that customers can order. At the DDD:1 assembly line, assembly is made in batches that all are in the range of 1-10 DDD products per assembly batch (See Appendix M). This makes the DDD:1 assembly line correspond to the definition of a multi-model assembly line (see Section 3.1.7.1), even though the assembly lot sizes sometimes only equal a single finished product (see Table 4.7).

Material feeding principles, storage assignment policies, and pace control
At the DDD:1, one operator is designated for kitting components for the assembly process but this operator also has some other supporting work assignments too, like moving full load carriers into the rack system. In each kitting work cycle, components for several finished products are kitted for the assembly process.

The DDD:1 assembly line uses different material feeding principles based on the input components' characteristics. Kitting supply is used for heavier components and components being unique to the respective product variant. Though, continuous supply is used for smaller materials, such as bolts, screws and nuts, and most of these are stored alongside the assembly station. Two-bin systems are used for these smaller materials, which are replenished from a separate storage rack, which in turn is replenished by an external supplier. All the components required are stored primarily in the racks at the DDD:1 assembly line from which the material feeding operator kits and feeds components to the assembly station.

The components required are stored in different unit loads, based on the components' characteristics, in a decentralized storage area near the assembly station. Unit loads, such as the E-serie load carriers, are used for mid sized components and are stored in the flow racks, whereas a few larger sized components are stored in P-serie load carriers (i.e. pallets).

If the secondary location that is near the DDD:1 assembly line is full, the components are stored in an overstocking storage location being labeled “803” (see Figure 4.1). Mostly, larger components are stored in this overstocking storage location “803”, which includes both purchased components and in-house manufactured components. The “803” overstocking storage location is also shared with the other product group AAA. For ease of identification the storage locations within the “803” storage are marked with different colours.

Sometimes globally sourced components, for instance from Japan, are procured in higher quantities than required for purchasing cost reasons, which make the primary storage locations full. Low runner components are mostly stored at the Goods receiving, however some of the low runner components that do not have designated rack location are stored at the DDD:1 assembly line in special purple colored racks, which also are used for overstocking. The components stored at the Goods receiving are transported by the V2 tug train, which is initiated by the ERP system. Apart from the low runner components stored at the Goods receiving, other components are directly stored in their respective storage rack locations near the DDD:1 assembly line. The replenishment of purchased components are performed by operators at the Goods receiving, while the V2 tug train is used for replenishing in-house manufactured components. The V2 tug train is shared between CCC:DDD, BBB and the AAA:3 assembly line. For larger in-house manufactured components, such as housings, the Kanban system is used, while mostly two-bin systems are used for the smaller components.

A designated kitting operator is assigned for the DDD:1 assembly line, who walks around the storage racks and kits components based on the work order sequence. Some of the large sized parts are moved directly near the assembly station in pallets, so the operator who assembles the final products can pick directly from these pallets. Mainly a dedicated storage assignment policy is applied, for the storage racks at the DDD:1 assembly line, in which each component has a designated storage rack location in which the components are stored and retrieved from. Though, a random storage assignment policy is applied for some components, for example low runners that temporarily are stored in the purple marked overstocking racks.

Since the component picking/kitting procedure has no defined cycle time and since there is no fully synchronized flow between the component picking/kitting procedure and the assembly process, the materiel feeding process for the DDD:1 assembly line is also unpaced asynchronous (see Section 3.1.7.4).

4.7 Equipments/Automation used

The case company uses Oracle JD Edwards world 7.3 version as ERP system. JD Edwards has different applications or tools to support the different functions of the organisation such as distribution and manufacturing management, finance management, human resource management and so on. Within the distribution module, tools or sub modules such as advanced warehouse management, inventory management, procurement guide etc are available; and within the manufacturing module, forecasting, product data management tools etc., are available. Moreover these tools could integrate in a necessary manner to provide information for effective operation within the facility (ERP 1, 2021). Further within the advanced warehouse management solution, JDE offers tools to support warehouse setup, picking and putaway, processing and replenishment (ERP 2, 2021). These tools make JDE a complex WMS which optimize their operations to be effective. Further JD Edwards world 7.3 tools has the ability to integrate web application servers, reporting tools, other third party solutions and database systems (ERP 3, 2021). This allows the JDE to transfer and receive information from other systems and ICT tools such as barcode scanners, pick-by-light, RFID and so on.

Barcode scanners are used for registering data during picking, putaway activities. Mostly the barcode scanners are used for the components within the lot number system and/or with unique item identification number. Further it is used predominantly at the goods receiving area for consignment-note recording and data entry. Along with barcode scanners, a pick-by-voice tool is used in the kitting process. This is to assist the component picker/kitter to be effective in picking and to reduce the number of picking errors.

4.8 Logistics performance measurements applied

It is crucial that the performance of any recommended warehouse automation system is aligned with the performance aspects that are important for the case company. This means that the recommended warehouse automation system must support the performance measures that are used by the case company. These are presented in this section.

The case company uses a performance measurement system that includes both revenue-, cost-, and asset influencing logistics variables. In addition, aspects of the work environment are continuously measured and evaluated. What unique logistics performance measures that are used, are determined on the corporate level. These and the ergonomic influencing variables used, are summarized in Table 4.8.

Table 4.8: *Summarizes the logistics performance measures and the ergonomic influencing variables used by the case company.*

Revenue influencing variables	-Line Items Shipped Correctly (LISC) -Returned Parts Per Million (RPPM),of shipped products -Warranty costs in percent of total sales
Cost influencing variables	-Volume produced -Number of defect products -Total value of defect products and components, in SEK -Returned Part Per million (RPPM), of inbound components
Asset influencing variables	-Days Sales of Inventory (DSI) -Return On Net Assets (RONA) -Return on Sales (ROS), (may replace RONA)
Ergonomic influencing variables	-Near misses -Work incidents -Personnel attendance

4.8.1 Revenue influencing logistics variables

The highest prioritized logistics performance measure, overall, is the Line Item Shipped Correctly (LISC), which refers to the percent of order lines that have been shipped according to customer orders received. This measure of delivery performance is rather rough, since it considers a shipment of a single unit of a low price unit being equally important as a shipment of 30 high price unit. LISC is measured on the overall level, as well as per value stream (i.e. for AAA, BBB, and CCC:DDD respectively). If LISC is measured on a weekly or monthly basis differs between the finished products. The LISC targets for premium customers are prioritized, though these are also more challenging to meet since premium customers have low restrictions for what order lead times they can demand. The

LISC measure for the 16 highest prioritized customers, internally referred to as elite customers, are especially evaluated on a weekly basis. This higher prioritisation of premium and elite customers have consequences for the internal assembly scheduling, which in turn affects the material supply processes. For other customers, internally referred to as select customers, the order lead times are predetermined and known by these customers. The overall target for the LISC measure has been raised to 98 percent, after the previous target of 95 percent was reached. There is also a second revenue influencing logistics variable being measured and evaluated for the elite customers. That is the Returned Parts Per Million (RPPM), which measures the quality of delivered products only and does not consider any time related performance aspects of deliveries. Quality issues concerning finished products are rare. A third related revenue influencing logistics variable used, is the Warranty costs in percent of total sales, which is measured per product group.

4.8.2 Cost influencing logistics variables

Every morning at 8 o'clock, the volume produced during the last 24 hours, alternatively during the weekend in the case of mondays, is reported. Further, the number of defect products during this time period is reported, though this mainly concerns the component manufacturing lines since quality issues are rare at the assembly lines. Basically, if required components are available, the assembly most often goes as planned. Though, the total value of defect products and components, calculated in SEK, are measured. Further, the quality of inbound components to the facility is measured considering the number of RPPM per month, which represents the number of components returned to external suppliers due to quality issues.

4.8.3 Asset influencing variables

The two main asset influencing variables used are Days Sales of Inventory (DSI) and Return On Net Assets (RONA). Further, the status of individual investments are followed up and compared to the projected outcome.

The DSI is followed-up on a monthly basis and considers the facility's aggregated inventory levels, which include both components, work-in-process, and finished products. The calculated DSI corresponds to the number of days that the local inventory could cover demand, if the sales rate equals the last three months average, without considering what individual components that are required for assembling. If the determined target levels are exceeded, actions must be taken by the management. To measure the inventory levels in DSI, instead of in absolute monetary values, is by the management perceived to be more concrete and facilitates taking proper actions when target levels are not reached.

RONA is calculated on company division level, as the ratio between the net profit and the capital invested. The calculated RONA forms the basis for the internal bonus system, which each employee within the division participates in. The size of the individual bonus payment is affected by an employee's position within the company hierarchy. The use of RONA as a performance measure is internally perceived to occasionally have reduced the will of investing, therefore, discussions about using Return on Sales (ROS) instead are ongoing.

4.8.4 Ergonomic influencing variables

A safe work environment for all employees is internally considered as crucial. All Near misses, which are events that could have happened but did not, are evaluated and potential changes to prevent the event from recurring are evaluated. Further, if an employee must be home from work due to a work incident, a written report must be made. This is resource consuming, although this type of incident very rarely occurs. In addition, the Personnel attendance is measured on a monthly basis and if deviations from set targets are large, further evaluations are made. The Personnel attendance varies between seasons, where it is at its highest level in the spring and lowest during the autumn.

5

Market Research

This chapter presents some examples of market available Warehouse automation systems that are possible to use for component storage purposes. This chapter describes some basic principles and certain technical specifications or characteristics of those systems which are plausible for implementation. Table 5.1 shows the systems and suppliers which are studied. All information collected was through secondary sources only i.e google searches and supplier brochures.

Table 5.1: *Warehouse automation systems (i.e., AS/RS) and supplier studied.*

Supplier/System	***Dematic***	***Swisslog***	***SSI Schaefer***	***Kardex***
Mini load	Dematic Rapidstore	Tornado		
Shuttle based		Cyclone	SSI Flexi	
Horizontal Carousel				Megamax Horizontal
Vertical Carousel				Megamat RS
VLM				Shuttle XP
AGV		Autostore		

According to Novara (2020), based on the requirement of the facility, different automated storage solutions are possible for light loaded component storage. one such comparison is based on the number of SKUs and picking rate, but not limited to that only. Other factors should also be considered for detailed analysis. Figure 5.1 indicates the applicability of different systems based on SKUs and picking rate.

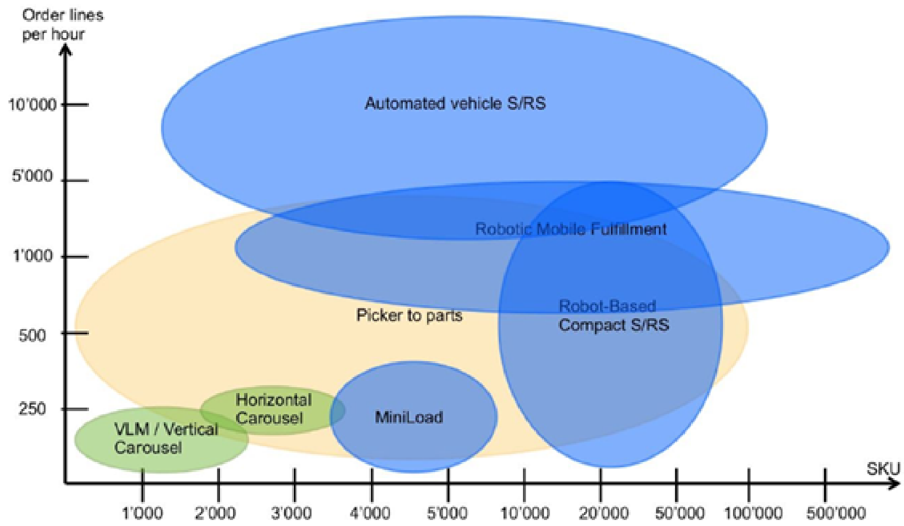

Figure 5.1: *Application of AS/RS based on number of SKUs vs Picking rate (Source: Manzini, 2012; Novara, 2020)*

5.1 Mini-Load AS/RS

Miniloads are rack based AS/RS systems, where cranes in between the aisle are used to retrieve the components. Having smaller structure and lower allowable maximum weight than other systems, makes this lighter and faster system. However Miniloads are usually lower in throughput due to their setup. It uses only one crane for each aisle, this restricts the number of load carriers retrieved in an hour. This system could be scalable, provided the space availability (Azadeh, de Koster & Roy, 2019).

Dematic Rapidstore comes in different variants based on their load handling device (LHD) capacities. Variants ML10, ML14 with single mast structure were used for handling lesser weight LHD. Whereas ML20, ML+300, ML+350, ML+400 with double mast structure were mostly used where maximum LHD weight is higher. ML10 and ML14 have the highest travel speed of 6 m/s which assist this system for high end performance with quick transverse acceleration and precise positioning than other variants. Whereas ML20, ML+300 and ML+350/ML+400 have travel speeds of 5 m/s, 4 m/s and 2 m/s respectively. These miniload have different height restrictions from 10m to 20m based on their variant. The minimum aisle width required is 950 mm for ML10/ML14/ML20 whereas other bigger systems (ML+350/ML+400) require 1060 mm. Load handling devices (LHD) come with both fixed and flexible types so that system could be adapted to use different types of packaging unit sizes (i.e totes, trays, cartons etc). ML10/ML14/ML20 has 2 LHDs carriers with each having a maximum load capacity of 50 kg. Whereas ML+300/ML+350 and ML+450 can carry a maximum load of 340 kg and 455 kg respectively. ML+300 is the only variant which is capable of being used in both single deep and double deep storage systems. Based on the customer throughput requirement LHDs can be designed to carry single, double or triple load units in side-by-side configuration (see Figure 5.2), however limited by the dimensions of the load carrier (Dematic, n.d).

5.1.1 Dematic Rapidstore

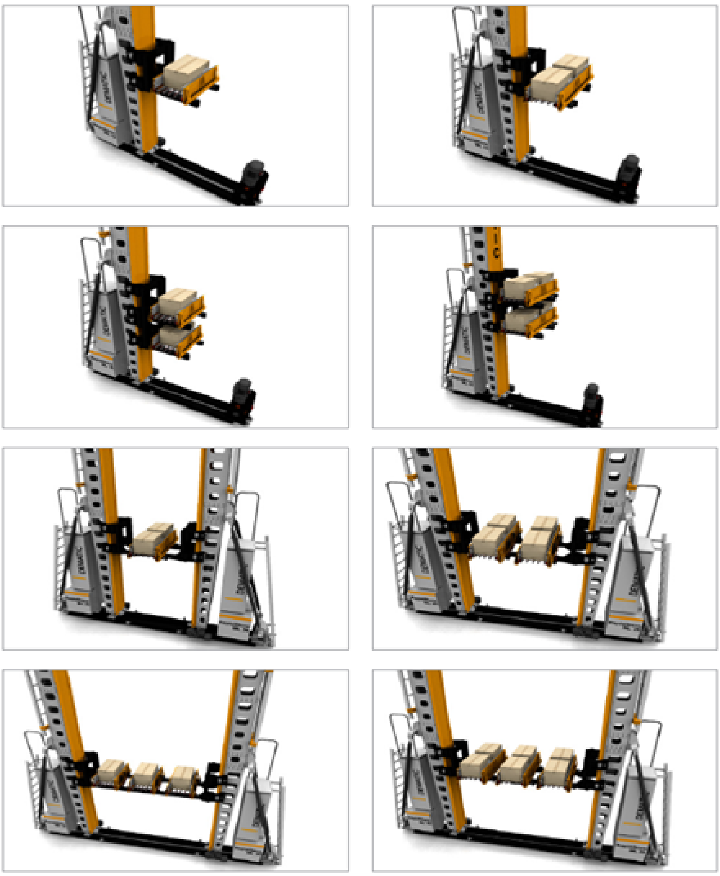

Figure 5.2: *Different configuration of LHDs within Dematic miniload AS/RS (source: demtatic, n.d)*

5.1.2 Swisslog Tornado

Swisslog Tornado is another miniload crane AS/RS (see Figure 5.3) which is widely used in the current market. Swisslog has a patented single mast structure design that effectively uses the available spaces. It has an optional low noise model which could be used nearer to any workstation. Tornado can be adapted to different load handling devices and different heights. The aisle height ranges up to 24 meter. The load carrying capacity of LHD ranges from 70 kg to 250 kg which is the standard model, however could be resigned for customer specific requirements (Swisslog 1, n.d).

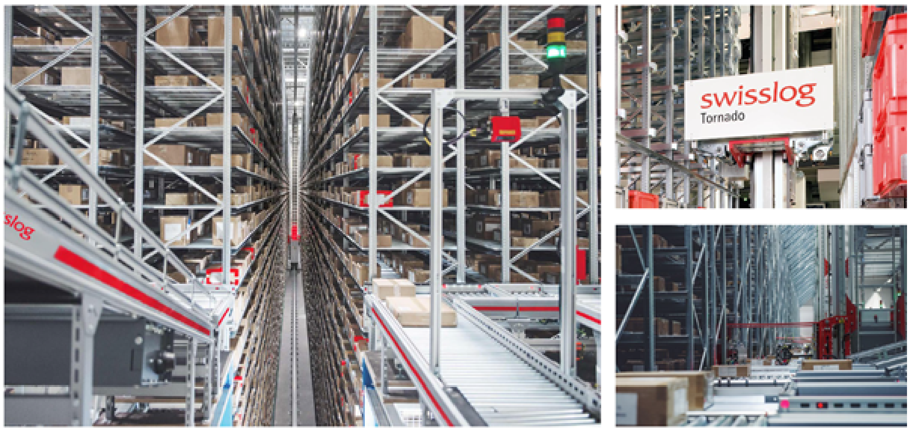

Figure 5.3: *Swisslog Tornado - miniload (source: Swisslog 1, n.d)*

Load handling devices come in two types: telescope loader with maximum payload of 250 kg which is suitable for containers and trays in standard sizes of 400x300 mm, 600x400 mm and 800x600 mm in either single, double or quadruple depth storage type; Carton loader with maximum payload of 70 kg which is ideal for cartons, containers and trays in sizes of 200x200 mm and 800x600 mm. The operating speed of the machine ranges up to 6 m/s. Tornado comes with syncQ warehouse management system, developed by Swisslog itself for effective operations such as bin location management, which could be integrated with complementing other subsystems in the warehouse (Swisslog 1, n.d).

5.2 Shuttle- and Robot- based AS/RS

Shuttle based systems are emerging AS/RS where the robots called shuttle are used for retrieval and storing of goods in the racks. This system is easily scalable, either scale up or scale down, with minimal effort.This is mostly suitable for light loads and high frequent picking such as in E-commerce warehouses.

5.2.1 Swisslog Cyclone

Swisslog cyclone has maximum hourly throughput of 2000 feeds of loading and unloading of components per aisle. It offers double to multi deep storage racks. Each storage level within the system is equipped with one shuttle vehicle (see Figure 5.4) which makes it a higher throughout system. The shuttle vehicle carries the unit load from and to the I/O point which acts as a load handling device. This shuttle vehicle has two versions as fixed width load handling device and adjustable width load handling device which makes it suitable to use in the environment with different types of unit loads. The maximum load that can be carried by each vehicle is 35 kg for standard application and the load can be increased to 50 kg at the expense of reduced dynamics or performance. The size of unit load which could be accommodated in this system ranges from 200x200x500 mm to 470x670x500 mm (Swisslog 2, n.d).

Figure 5.4: *Swisslog Cyclone- shuttle based (source: Swisslog 2, n.d)*

Each aisle has one lift which assists in storage and retrieval of the unit loads. The maximum height of the lift is 25 meter which restricts the maximum height of the system too. Transfer conveyors are present between the lift and the vehicle which can act as buffer storage also. The maximum speed of both vehicle and lift is 4m/s. CycloneBox software controls the lift, vehicle and conveyors in order to get optimized performance from all subsystems (Swisslog 2, n.d).

5.2.2 SSI Flexi

This system is designed based on the scalable single level shuttle with maximum payload of 50 kg per unit load. Its load handling device has adjustable width which makes it suitable for different sizes of unit loads. It offers storage with single, double and multi deep storage. Further SSI Flexi can accommodate different sizes and types of unit loads. The maximum size of the unit loads is 860x680 mm. The maximum length of the storage system is 150 meter and height is restricted upto 30 meter. However the speed of the shuttle is similar to the Swisslog Cyclone which is 4 m/s. SSI Flexi claims the system as an intelligent functional variety because of its adjustable height division between the racks and its adaptable storage location sizes. This helps SSI flexi to be efficient in terms of storage density combined with flexible positioning of unit loads (SSI Schaefer, n.d).

5.3 Carousel-based AS/RS

Carousels based AS/RS have shelves which are linked together and rotated either horizontally or vertically and it is suitable for small and mid sized products to store (Azadeh et al., 2019). This system has a fixed location at front where the parts are presented for the picker. These systems are suitable for smaller and medium sized goods. Vertical systems are ergonomically better than the horizontal system in terms of ease of picking and thus compromising the picking throughput (Azadeh et al., 2019).

5.3.1 Horizontal Carousel -Kardex Remstar

Kardex Remstar (see Figure 5.5) comes with a different configuration based on the stations layouts: dual, triple or quadruple stations. These stations are arranged in L, I, U shaped configuration at multi level too. Dual, triple, quad are suitable for rooms up to 3 meter height and could be operated by a single person with L shaped configuration. Kardex remstar maximum payload ranges from 450 kg to 900 kg. The total carousel length varies from 5.9 meter to 46.7 meter. Carrier depth has three different sizes 460 mm, 560 mm and 610 mm. The maximum number of carriers in the system varies from 12 to 120 and depends on the different width sizes of 622 mm, 825 mm and 960 mm. Total height of the carousel can be ranging from 2.2 meter to 4.1 meter, however the usable height is between 1.8 meter to 3.65 meter. The rotational speed is 24 meter per minute which is equivalent to 0.4 m/s. These carriers could be closed from side and rear walls for safety purposes (Kardex 1, n.d).

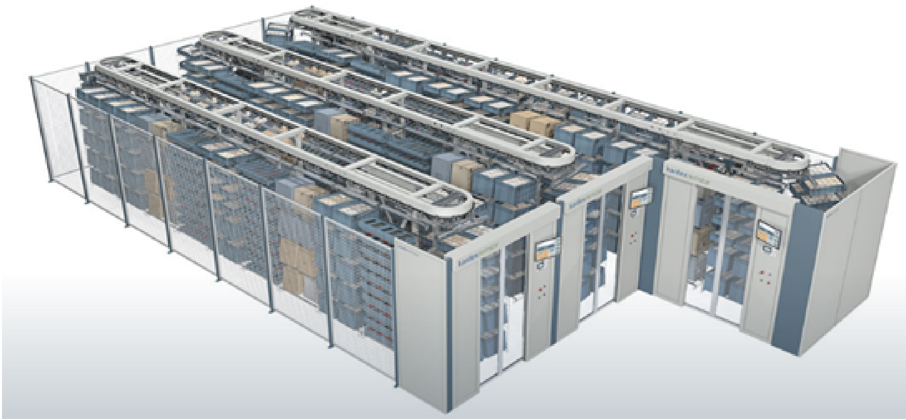

Figure 5.5: *Kardex Remstar horizontal carousel - L shaped station (source: Kardex 1, n.d)*

5.3.2 Vertical Carousel -Megamat RS

The Megamat RS (see Figure 5.6) can be installed as a stand alone solution, or be set up as multiple coordinated vertical storage shafts into a larger storage system (Kardex 5, n.d.). Therefore, in this thesis report *a single vertical carousel* do not refer to the number of vertical storage shafts installed, but instead refers to how the warehouse automation system is operated. This means that *a single vertical carousel* can consist of multiple lined up in parallel, coordinated, and integrated vertical storage shafts that are operated as a single unit from a single display.

Megamat RS comes in three variants based on the maximum payload of the unit loads: Megamat RS 180 which is suitable for loads which are smaller in size for instance in medical industry, vehicle manufacturing, electronics industry; Megamat RS 350 and Megamat RS 650 which can handle loads up to 350 kg and 650 kg per unit load respectively. And the maximum weight of the system including the carrier is 6000 Kg, 12500 Kg and 19000 Kg for Megamat RS 180/350/650 respectively. The width ranges from 1875 mm to 4275 mm, height ranges from 2.1 meter to 9.7 meter based on the variants. These vertical carousels are preferable for ceiling height under 7 meter. Further the carriers in the system are spaced evenly and height between the shelves could be adjusted, however manually. This makes the vertical carousel ideal for similar sized products in storage. However the carriers come with dividers which makes it possible to adjust the size both horizontally and vertically- but a tedious process due to manual work involved in the adjustment. The maximum throughput of a vertical carousel is 400 line items per hour. The system could be complemented with pick-to-light to attain the maximum throughput by reducing the search time for the picker (Kardex 2, n.d).

Figure 5.6: *Kardex Remstar Megamat RS- Vertical carousel (source: Kardex 2, n.d)*

5.4 Vertical Lift Module (VLM) AS/RS

This VLM consists of two columns of trays attached to a mechanical inserter/extractor at the centre which assist in loading and retrieving of unit loads. The operation is similar to conventional elevators and this system has doors at both the front and rear side. This VLM can be twice as deep as a vertical carousel which maximises the storage density with a smaller footprint. The width ranges from 1.5 meter to 4.5 meter and depth ranges from 2 meter to 3 meter. The height of the system ranges from 1.2 meter to 3.9 meter. This is ideal to to maximum height of trays with 530 mm, however ergonomics consideration to be given for the operator to have minimal efforts while picking. The maximum load of the carrier is 997 kg. VLM could be configured with integrated lift and crane for operating heavier loads. This makes VLM more suitable for heavier loads. Depending on configuration the maximum throughput could be 350 items/hour. However, similar to vertical carousel, VLM also could be assisted by picking technologies such as pick-to-light to achieve the maximum throughput (Kardex 3, n.d).

Shuttle XP (see Figure 5.7) is market-available VLM which comes in three variants XP250/500, XP 700 and XP1000 and categorised based on the maximum load of trays 560 kg, 725 kg and 1000 kg respectively. The storage and retrieval speed is 0.7 m/s for lower capacity variants and 0.39 m/s for higher capacity variants. The width varies from 1.5 meter to 4.3 meter. Height varies from 2.5 meter to 30.5 meter. depth varies from 2.3 meter to 4.3 meter. XP250/500 is optimal for smalls and light weight goods; XP 700 is optimal for medium loads with highly compact storage. Position indicator and lighting indicator are used along with the system for faster and efficient picking. VLM has a double tray function where order picking is processed in one tray, the next tray is prepared simultaneously behind the access door which assists for higher throughput (Kardex 4, n.d).

Figure 5.7: *Shuttle XP - Vertical Lift Module (source: Kardex 4, n.d)*

5.5 Autostore AGV

Swisslog autostore is a robot based AS/RS for both fast- and slow- moving items and small case pick SKU with high storage density. High storage density and maximum floor space utilization are major advantages since robots do not need the space between the aisle as in other storage systems. It is optimal for small sized loads and the assisted software system is designed in such a way that it learns which item is picked frequently and stores those items in the upper layer for quicker retrieval. However this system has standard bins sizes (L: 649 mm x B: 449 mm x H (220 mm, 330 mm or 425 mm)). The maximum payload of each bin is 30 kg. This system is expandable based on the inventory requirement, it can store from 5000 to 300,000 bins. Each robot can deliver 25 bins per hour. Overall throughput is based on the number of robots used for retrieval (Swisslog 3, n.d).

6

Analysis

6.1 Part 1 - Identification and analysis of requirements for the selection of warehouse automation system(s) for component storage

In this first part of the Analysis, the requirements that are imposed by the case company's Operations / Factory environment, Material Supply System and Performance Objectives, for what warehouse automation system(s) to select, are identified and analysed. This is done by applying each part of the Theoretical Framework (see Figure 6.1) on the Empirical data (see Chapter 4). Accordingly, the answer for RQ1 (i.e, *What are important requirements for the case company to consider when selecting warehouse automation system(s) for component storage?*), is provided in this first part of the Analysis.

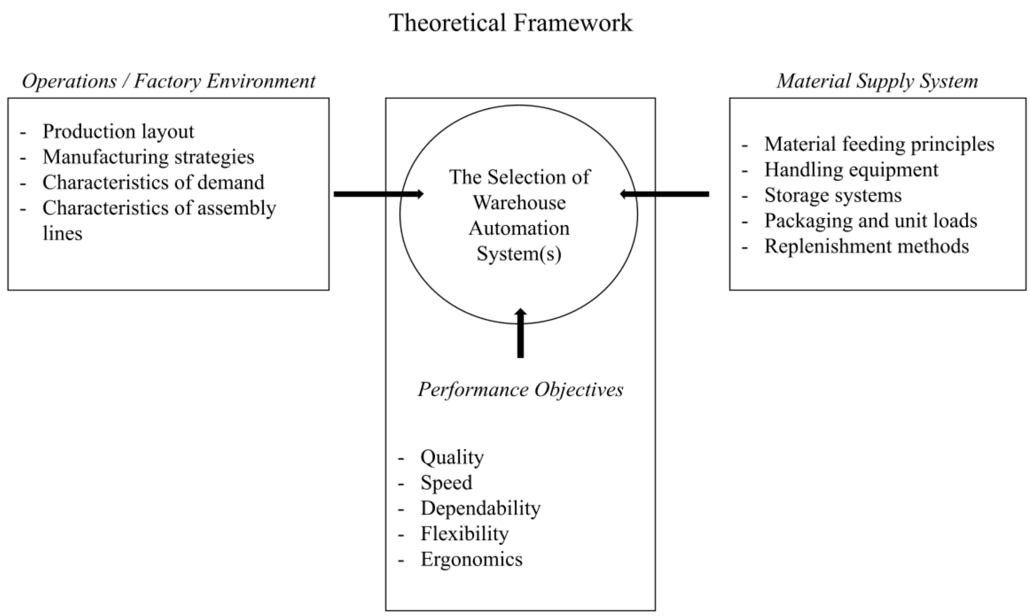

Figure 6.1: *The theoretical framework, developed in section 3.4, that is applied on the empirical data in the analysis section 6.1 and 6.2*

First, the requirements implied by the case company's Operations / Factory Environment for the selection of warehouse automation system(s) are identified, which includes analysis of requirements caused by the case company's: Production Layout; Manufacturing strategies; Characteristics of demand; and Characteristics of assembly lines. Thereafter, the requirements implied by the case company's Material Supply System for the selection of warehouse automation system(s) are identified, which includes analysis of requirements caused by the case company's: Material feeding principles; Handling equipment; Storage; Packaging and unit loads; and Replenishment methods. Lastly, the requirements implied by the case company's Performance objectives for the selection of warehouse automation system(s) are identified, which includes analysis of requirements caused by the need for high performance in Quality, Speed, Dependability, Flexibility, and Ergonomics, within the case company's material feeding processes.

6.1.1 Operations / Factory Environment

In this subsection, are the implications of the Operations/Factory Environment, for the selection of warehouse automation system(s), analysed. This includes analysis of the existing Production layout; the Manufacturing strategies applied by the case company; the Characteristics of demand (i.e., the Four Vs); and the Characteristics of assembly lines.

6.1.1.1 Implications of the existing Production layout - for the selection of warehouse automation system(s)

In this subsection, are the implications of the existing production layout, for the selection of warehouse automation system(s), analysed. This includes analysis of implications of: the case facility's physical space; different localisation alternatives; possible combinations of storage policies and materials feeding principles; and effects of the warehouse automation system(s) localization on the internal transports.

To begin with, the facility's high roof ceiling of approximately 7 meter constitutes a major advantage considering potential warehouse automation system(s) based on vertical storage technique. In most areas, there is no bearing construction between the factory floor and the roof ceiling, which facilitates installation of warehouse automation system(s) since no reconstruction of the building's roof bearing structures will be necessary. Since there is a general lack of horizontal factory floor space, it is strongly recommended that the warehouse automation system(s) takes advantage of the large available free vertical space within the facility. Though, a drawback with using vertical storage techniques is that it creates a large weight per square meter that may require reinforcement of the facility's floor construction.

Since enlarging the facility is not an option considered in this thesis, the selected warehouse automation system(s) must fit inside the current factory space. Further, since the existing production layout regarding assembly lines and component manufacturing lines localisation is considered as being non-changeable, there is basically no free floor space to install any additional component storage in the form of warehouse automation system(s). Though, the floor space at the assembly lines and in the Centralized storage/Kitting area where flow racks currently are installed can be used for new warehouse automation system(s). In addition, the floor space located between the AAA:2 assembly line and the Shipping area, which is currently being used as a Maintenance area, is also available for installing warehouse automation system(s) (see Figure 6.2). This, since the maintenance activities currently taking place there are planned to be relocated to another area within the facility. This Maintenance area, as well as the Centralized storage/Kitting area are the only locations within the facility that potentially could fit one, or a few, larger warehouse automation system(s). Accordingly, one or both of these two areas must be occupied by warehouse automation system(s) if a centralized storage policy is applied, where all components are stored in large central warehouse automation system(s), at distance from the fed assembly lines, just until being needed in the assembly processes.

Figure 6.2: *Facility floor areas, which are available for installing warehouse automation system(s).*

If a decentralized storage policy is applied, where all components are stored in smaller warehouse automation system(s) located just next to each fed assembly line, the factory floor that is currently occupied by flow racks at the assembly lines, must be occupied by smaller warehouse automation system(s).

If a hybrid storage policy is applied, where a centralized storage policy is used for some assembly lines while a decentralized storage policy is used for the other assembly lines, larger warehouse automation system(s) need to occupy the current Centralized storage/Kitting area or the existing Maintenance area, while smaller warehouse automation system(s) needs to occupy floor space where flow racks currently are installed next to the fed assembly line(s).

When deciding if to apply a centralized storage policy, decentralized storage policy, or hybrid storage policy, it is necessary to consider the consequences for what material feeding principles that are suitable. For example, to combine a centralized storage policy with continuous supply or batch supply would create a large number of handling tasks per load carrier/stored component since these first would need to be transported from the Goods receiving or the component manufacturing lines to the centralized storage, be unloaded into a warehouse automation system at the centralized storage, later be retrieved from that warehouse automation system, then be transported to the assembly line where needed, then be unloaded into picking racks at the assembly line, later be picked by the component picker and moved to the work bench or entry point at the assembly line. This would increase the number of handling tasks per load carrier/stored component with 75 percent compared to if combining a centralized storage policy with kitting supply, or a decentralized storage policy, where warehouse automation system(s) are located next to the assembly line(s), with continuous supply, batch supply, or kitting supply (see Table 6.1).

The least number of handling tasks per load carrier/stored component occurs if a centralized storage policy is combined with kitting supply, as well as, for any type of material feeding principle being combined with a decentralized storage policy. Accordingly, if a centralized storage policy is applied, it should be combined with kitting supply for the fed assembly line(s). Though, the choice between a centralized storage policy and a decentralized storage policy is not absolute since, for example, centralized kitting supply can be complemented with decentralized continuous supply for high-runner smaller materials that are used in several models and that are not easily wrongly picked.

Basically, there are four possible general storage policy alternatives if the existing production layout of assembly lines and component manufacturing lines is considered as non-changeable and if the number of handling tasks per load carrier/stored component, is desired to be minimized:

1. A centralized storage policy with kitting supply as material feeding principle, where one or a few larger warehouse automation system(s) are located at the current Centralized storage/Kitting area

2. A centralized storage policy with kitting supply as material feeding principle, where one or a few larger warehouse automation system(s) are located at the existing Maintenance area between the AAA:2 assembly line and the Shipping area

3. A decentralized storage policy with continues supply, batch supply, or kitting supply as material feeding principle, where several smaller warehouse automation system(s) are located just next to each assembly line where flow racks currently are installed

4. A hybrid storage policy based on a combination of (1) and (2), or a combination of (1) and (3).

Further, the proximity between, on one hand, Storage 803 and Storage X and, on the other hand, the component manufacturing lines (see Figure 4.1 and Figure 6.2) make these two storage locations suitable for temporary overstocking of in-house manufactured components that is needed, for example during the component build-up before summer.

Warehouse automation system(s) based on vertical storage techniques could dramatically increase the storage capacity at these two locations, compared to the current state, since the ceiling height is about 7 meters.

Table 6.1: *How the number of handling tasks, per load carrier/stored component, differs between possible combinations of storage policies and material feeding principles applied.*

Material feeding principle / Storage policy	Continuous supply (number of handling tasks per load carrier/stored component)	Batch supply (number of handling tasks per load carrier/stored component)	Kitting supply (number of handling tasks per load carrier/stored component)
Centralized storage policy	1. Transport of load carrier from Goods receiving/component manufacturing line to the centralized storage. 2. Unloading of load carrier into warehouse automation system located at the centralized storage. 3. Retrieval of load carrier from warehouse automation system located at the centralized storage. 4. Transport of load carrier from the centralized storage to assembly line where needed. 5. Unloading of load carrier into picking racks at the assembly line where needed. 6. Individual components picked from load carrier at the assembly line. 7. Movement of individual components/component kits to the work bench/entry point at the assembly line.	1. Transport of load carrier from Goods receiving/component manufacturing line to the centralized storage. 2. Unloading of load carrier into warehouse automation system located at the centralized storage. 3. Retrieval of load carrier from warehouse automation system located at the centralized storage. 4. Transport of load carrier from the centralized storage to assembly line where needed. 5. Unloading of load carrier into picking racks at the assembly line where needed. 6. Individual components picked by from load carrier at the assembly line. 7. Movement of individual components/component kits to the work bench/entry point at the assembly line.	1. Transport of load carrier from Goods receiving/component manufacturing line to the centralized storage. 2. Unloading of load carrier into warehouse automation system located at the centralized storage. 3. Individual components picked directly from the warehouse automation system at the centralized storage. 4. Transport of component kit from centralized storage to the work bench/ entry point at the assembly line.
Decentralized storage policy	1. Transport of load carrier from Goods receiving/component manufacturing line to the assembly line where needed. 2. Unloading of load carrier into warehouse automation system located at the assembly line where needed. 3. Individual components picked from load carrier presented by the warehouse automation system at the assembly line. 4. Movement of individual components/ component kits to the work bench/entry point at the assembly line.	1. Transport of load carrier from Goods receiving/component manufacturing line to the assembly line where needed. 2. Unloading of load carrier into warehouse automation system located at the assembly line where needed. 3. Individual components picked from load carrier presented by the warehouse automation system at the assembly line. 4. Movement of individual components/component kits to the work bench/entry point at the assembly line.	1. Transport of load carrier from Goods receiving/component manufacturing line to the assembly line where needed. 2. Unloading of load carrier into warehouse automation system located at the assembly line where needed. 3. Individual components picked from load carrier presented by the warehouse automation system at the assembly line. 4. Movement of individual components/component kits to the work bench/entry point at the assembly line.

Effects of the warehouse automation system(s) localization on the internal transports

When deciding where to locate warehouse automation system(s), it is crucial to consider that no internal material flows are disturbed or hindered by the new production layout. This means that both incoming and outgoing material flows to/from the focal warehouse automation system(s) should be considered, as well as, all the material flows to/from other storage systems, fed assembly lines, and component manufacturing lines. Changes to the existing material flow routes can be done, but such changes should be considered when selecting warehouse automation system(s) in order to avoid unexpected and unwanted surprises, such as too narrow spaces between installed assembly equipment and storage systems. The width between warehouse automation system(s) and other equipment must in most cases be wide enough to allow fully loaded milk-runs, AMRs, picking-carts, as well as personnel to pass through unhindered. This especially considers the corridors between each manufacturing/assembly "island", where all the material transports between the Goods receiving, component manufacturing lines, and the assembly lines take place (see Figure 6.3). Therefore, when deciding where to locate warehouse automation system(s) within the facility, it is important to consider the effects on the internal transports. In principle, the further a way a warehouse automation system is located from the Goods receiving and the component manufacturing lines the more internal transports of unit loads of load carriers are required, while the further away from the fed assembly line(s) a warehouse automation system is located the more internal transports of individual load carriers or component kits are required.

Figure 6.3: *The blue dashed arrows show the transport corridors, where all material flows pass and which cannot be blocked by warehouse automation system(s)*

An option to reduce the risk of congestion in the transport corridors, is to implement one-way directions where this is possible. Though, this would most certainly increase the total transport distances for AMRs, component replenishing operators, and kitting carts, which accordingly would increase the total amount of traffic within the facility.

The decision for where to locate warehouse automation system(s) within the facility should consider the effects on non-value-adding activities, which within lean management is defined as waste (see Section 3.1.6.1). This includes minimizing internal transports, which only creates costs and risks but adds no end customer value. To minimize internal transports by optimizing the location of warehouse automation system(s) would require considering that inbound transports from the Goods receiving and from the component manufacturing lines will be made in varying lot sizes of load carriers, while the outbound components will be transported in varying batches of prepared kits (i.e, if kitting supply is applied), or be co-transported in varying sizes of consolidated replenishment batches of load carriers (i.e., if continuous supply or batch supply is applied).

The task to optimally locate warehouse automation system(s) within the facility would be resource consuming since there are: several types of load carriers used; the bin quantity for line items varies; the size and number of consolidated inbound transports of load carriers is unknown; the size and number of consolidated outbound transports of load carriers (i.e., if continuous supply or batch supply is applied) is unknown; and there exists a huge variety of component kits that will be transported to the fed assembly line(s) in varying batch sizes (i.e., if kitting supply is applied). Though, in this case, the number of possible locations within the facility is strictly limited, due to the lack of available facility floor space, and only three available localisation alternatives for the warehouse automation system(s) currently exists (see Table 6.2-6.5).

Regarding the decision about where to locate warehouse automation system(s), the Alternative (PFSL) allows the most flow oriented production layout of the different alternatives (see Table 6.2-6.6) and imply low internal transport distances for kitting carts between, one one hand, the new common kitting area for the AAA:1, AAA:2, AAA:3 and DDD:1, and, on the other hand, each of these fed assembly lines. The Alternative (PFSL) also implies low internal transport distances for in-house manufactured components, between the component manufacturing lines and the new kitting area for the AAA:1, AAA:2, AAA:3, and DDD:1. The extra internal transport distance required for purchased components (i.e., compared to the current Centralized storage/Kitting area location) from the Goods receiving to the new common kitting area is negligible, since these two areas are located just next to one another. Consequently, Alternative (PFSL) is superior to Alternative (1)-(4) with regard to minimizing the waste of internal transports. Obviously, implementing Alternative (PFSL) would imply major temporary disruptions in the assembly processes, but such implementation issues are out of the scope of this thesis and are therefore not analysed.

Comparison of the general storage policy alternatives

The benefits and drawbacks of the general storage policy alternatives, which are possible to implement at the case facility, are summarized in Table 6.2-6.6.

Table 6.2: *Summary of benefits and drawbacks with the storage policy Alternative 1.*

Localisation alternatives for warehouse automation system(s)	**Applied storage policy** (material feeding principle)	**Benefits**	**Drawbacks**
Alt. (1): *The warehouse automation system(s) (W.A.S.) is located at the existing Centralized storage/ Kitting area*	***Centralized storage*** *(kitting supply at centralized storage)*	-The W.A.S. will be located right next to Goods receiving, which results in minimal internal transport distances for the inbound unit loads that contain purchased and externally treated components (see Figure 6.2). -Enables the Goods receiving personnel to move unit loads from the load carriers shipped by suppliers (e.g, full pallets) directly to the W.A.S, which imply that no internal transshipment of load carriers to internal transport vehicles are needed. -The W.A.S. will be located right next to the Component room and Spare parts department, which will minimize the internal transport distances for the order pickers from these two departments (see Figure 6.2). -Large floor space is available(i.e., since the rack system currently used for kitting for the AAA:1 and AAA:2 won't be needed), which allows large W.A.S. that provides economies of scale and economies of scope.	-The W.A.S. will be located at distance from all assembly lines, except the BBB:1, which will entail long internal transport distances for outbound internal transports of components from the W.A.S to each fed assembly line (see Figure 6.2). -The W.A.S. will be located at distance from the components manufacturing lines, which will result in long internal transport distances for in-house manufactured components that are moved to the W.A.S (see Figure 6.2). -Long walking distances required for assemblers when replacing broken or wrongly picked components, especially for the operators at the CCC:1 and DDD:1 (see Figure 6.2).

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Continuation of Table 6.2			
Alt. (1): *The warehouse automation system(s) (W.A.S.) is located at the existing Centralized storage/ Kitting area*	***Centralized storage*** *(kitting supply at centralized storage)*	-The high roof ceiling in the existing Centralized storage/Kitting area enables W.A.S. based on vertical storage techniques, which will limit the floor space needed and increase the utilization of the volume space. -Will free up floor space, which currently is occupied by flow racks, at the assembly lines. -Will result in few handling tasks per load carrier/ stored component on its way to the assembly line where needed (see Table 6.1).	- A large warehouse automation system(s) must be able to handle a large variety of different load carriers since multiple assembly lines potentially will be fed by the same W.A.S. Though, this drawback is largely negligible since standardized load carriers, with fixed sizes and general weight restrictions, are used within the facility (see Table 6.1).
End of Table 6.2			

Table 6.3: *Summary of benefits and drawbacks with the storage policy Alternative 2.*

Localisation alternatives for warehouse automation system(s)	**Applied storage policy** (material feeding principle)	**Benefits**	**Drawbacks**
Alt. (2): *The warehouse automation system(s) (W.A.S.) is located at the current Maintenance area, between the AAA:2 assembly line and the Shipping area*	***Centralized storage*** *(kitting supply at centralized storage)*	-The W.A.S. will be located rather close to the Goods receiving, which will entail rather short internal transport distances for the inbound unit loads that contain purchased and externally treated components (see Figure 6.2).	-The Maintenance area are smaller compared to the existing Centralized storage/Kitting area (i.e., Alternative (1))

Continued on next page

Continuation of Table 6.3			
Alt. (2): *The warehouse automation system(s) (W.A.S.) is located at the current Maintenance area, between the AAA:2 assembly line and the Shipping area*	***Centralized storage*** *(kitting supply at centralized storage)*	-The W.A.S. will be located rather close to the Component room and Spare parts department, which will result in rather short internal transport distances for the order pickers from these two departments (see Figure 6.2). -The W.A.S will be located closer to all assembly lines compared with Alternative (1), where the W.A.S. is located at the existing Central storage/ Kitting area. -Large floor space is available (i.e., since the maintenance activities currently being performed at the Maintenance area will be relocated elsewhere), which allows solutions with economies of scale and economies of scope. -Locating the W.A.S. in the Maintenance area may enable routes for kitting carts in the lower corridor, which starts at the Shipping area, that may reduce the risk for congestion in the corridor between the AAA:3 and AAA:2 assembly line.	-The Maintenance area is rather distant from the CCC:1 and DDD:1, which entail rather long internal transports of kitted components from the W.A.S. to these two assembly lines. -Rather long walking distance is required for assemblers, especially from the CCC:1 and DDD:1, when replacing broken or wrongly picked components from the W.A.S. -The Maintenance area is distant from the components manufacturing lines, which will entail long inbound internal transport distances for in-house manufactured components to the W.A.S. -There is risk of congestion and disturbed inbound transports from the component manufacturing lines to the W.A.S., since the shortest routes to the W.A.S. will cross likely routes for outbound kitting carts.

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Continuation of Table 6.3			
Alt. (2): *The warehouse automation system(s) (W.A.S.) is located at the current Maintenance area, between the AAA:2 assembly line and the Shipping area*	***Centralized storage*** *(kitting supply at centralized storage)*	-The high roof ceiling in the existing Maintenance area enables W.A.S. based on vertical storage techniques, which will limit the floor space needed and increase the utilization of the volume space. -Locating the W.A.S. in the Maintenance area will free up space at the assembly lines that are currently occupied by flow racks. -Locating the W.A.S. in the Maintenance area will imply few handling moments per load carriers/stored components (see Table 6.1)	- A large warehouse automation system(s) must be able to handle a large variety of different load carriers since multiple assembly lines potentially will be fed by the same W.A.S. Though, this drawback is largely negligible since standardized load carriers, with fixed sizes and general weight restrictions, are used within the facility (see Table 6.1).
End of Table 6.3			

Table 6.4: *Summary of benefits and drawbacks with the storage policy Alternative 3*

Localisation alternatives for warehouse automation system(s)	**Applied storage policy** (material feeding principle)	**Benefits**	**Drawbacks**
Alt. (3): *The warehouse automation system(s) (W.A.S.) are located at the fed assembly lines, where flow racks currently are installed*	***Decentralized*** *(continuous/ batch/ kitting supply at assembly lines)*	-Each W.A.S. will be located right next to each fed assembly line, which entails minimal outbound internal transport distances of components. -Minimal walking distance is required for assemblers, when replacing broken or wrongly picked components from the W.A.S.	-Each W.A.S. will be located at distance to some, or most, of the components manufacturing lines, which will entail long inbound internal transports of in-house manufactured components.

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Continuation of Table 6.4			
Alt (3): *The warehouse automation system(s) (W.A.S.) are located at the fed assembly lines, where flow racks currently are installed*	***Decentralized*** *(continuous/ batch/ kitting supply at assembly lines)*	-Locating each W.A.S. just next to each assembly line could completely remove the need for internal transports of kitting carts. -The high roof ceiling at each assembly line enables solutions based on vertical storage technique, which will limit the floor space needed and increase the utilization of the volume space. -The in-house manufactured components can be transported directly to the point of use (i.e., to each assembly line), instead of being intermediately stored at a centralized storage (i.e., Alternative (1) and Alternative (2)). -Allows co-loading and co-transports of inbound load carriers with different W.A.S. as destination (i.e., similar to the existing V1 tug train). -Locating each W.A.S. just next to each assembly line will free up space at the existing Centralized storage/Kitting area. -Locating each W.A.S. just next to each assembly line enables each W.A.S. to be specialized for a lower variety of components/ load carriers handled. Though, this benefit is largely negligible since standardized load carriers with general weight restrictions are used for all assembly lines.	-There will be a long transport distance from the Goods receiving to each W.A.S., in all cases but the BBB:1 and BBB:2 assembly line, which will entail long inbound internal transport distances for purchased and externally treated components. -There is a risk of creating congestion of inbound internal transports, which supply components for each W.A.S. located at each assembly line.

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Continuation of Table 6.4			
Alt. (3): *The warehouse automation system(s) (W.A.S.) are located at the fed assembly lines, where flow racks currently are installed*	***Decentralized*** *(continuous/ batch/ kitting supply at assembly lines)*	-Locating each W.A.S. just next to each assembly line will create few handling moments per load carriers/ stored component (see Table 6.1)	
End of Table 6.4			

Table 6.5: *Summary of benefits and drawbacks with the storage policy-alternative 4.*

Localisation alternatives for warehouse automation system(s)	**Applied storage policy** (material feeding principle)	**Benefits**	**Drawbacks**
Alt. (4): *A combination of (1) and (2), or a combination of (1) and (3).*	***Hybrid*** *(a centralized storage policy with kitting supply as material feeding principle for a single or several assembly line(s), while a decentralized storage policy with continuous supply, batch supply, or kitting supply as material feeding principle for the other assembly line(s))*	-A combination of a decentralized and a centralized storage policy allows the material supply processes to be more adapted for each assembly line's needs. -Some in-house manufactured components will be transported directly to the assembly line(s) where needed, instead of first being transported to a centralized storage (see Alternative (1) and Alternative (2)), which will reduce the amount of internal transports. -Some existing flow racks can be kept at the assembly line(s) for storage of certain components, such as bulk material or in-house manufactured components. -The partly applied centralized storage policy for components will free up space, which is currently occupied by flow racks, at some of the assembly lines compared to if a completely decentralized storage policy is applied (see Alternative (3)).	-A combination of a decentralized and a centralized storage policy risks creating complex material flow systems that are difficult to overview and difficult to manage in an integrated way, which in turn may aggravate positive coordination effects.

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Continuation of Table 6.5			
Alt. (4): *A combination of (1) and (2), or a combination of (1) and (3).*	**Hybrid** (a centralized storage policy with kitting supply as material feeding principle for a single or several assembly line(s), while a decentralized storage policy with continuous supply, batch supply, or kitting supply as material feeding principle for the other assembly line(s))	-A combination of a decentralized and a centralized storage policy will free up more space at the current Centralized storage/Kitting area and at the existing Maintenance area, between the AAA:2 assembly line and the Shipping area, compared to if a completely centralized storage policy is applied (see Alternative (1) and Alternative (2)). -The roof ceiling height within all location alternatives enables W.A.S. based on vertical storage techniques, which will limit the floor space needed and increase the utilization of the volume space.	-A combination of a decentralized and a centralized storage policy risks creating complex material flow systems that are difficult to overview and difficult to manage in an integrated way, which in turn may aggravate positive coordination effects. -A combination of a decentralized and a centralized storage policy risks creating congestion of inbound and outbound internal transports to/from the different W.A.S.
End of Table 6.5			

Table 6.6: *Summary of benefits and drawbacks with the storage policy Alternative PFSL*

Localisation alternatives for warehouse automation system(s)	Applied storage policy (material feeding principle)	Benefits	Drawbacks
Alt. PFSL: *BBB:1 & BBB:2 are relocated to the maintenance area and the area these currently occupy will be used for kitting supply for the AAA:1, AAA:2, AAA:3 and DDD:1. The warehouse automation system(s) (W.A.S.) is located in this new kitting area.*	***Hybrid*** *(a centralized storage policy with kitting supply as material feeding principle for the AAA:1, AAA:2, AAA:3 and DDD:1, while a decentralized storage policy with continuous supply, batch supply, or kitting supply as material feeding principle for the BBB:1, BBB:2 and CCC:1)*	-The central location of the new common kitting area enables effective inbound internal transports of in-house manufactured components between the component manufacturing lines and the W.A.S. at the new common kitting area for the AAA:1, AAA:2, AAA:3 and DDD:1. -The central location of the new common kitting area enables effective inbound internal transports of purchased and externally treated components from the Goods receiving to the new common kitting area for the AAA:1, AAA:2, AAA:3 and DDD:1. -The central location of the new common kitting area allows effective outbound internal transports of kitted components from the W.A.S, at the new common kitting area for the AAA:1, AAA:2, AAA:3 and DDD:1, to each fed assembly line.	-There is a risk of creating complex internal material flows that are difficult to overview and difficult to manage in an integrated way, which in turn may aggravate positive coordination effects. -There is a high risk of production disturbances during the implementation phase (out of the scope of this thesis)

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Continuation of Table 6.6			
Alt. PFSL: *BBB:1 & BBB:2 are relocated to the maintenance area and the area these currently occupy will be used for kitting supply for the AAA:1, AAA:2, AAA:3 and DDD:1. The warehouse automation system(s) (W.A.S.) is located in this new kitting area.*	***Hybrid*** *(a centralized storage policy with kitting supply as material feeding principle for the AAA:1, AAA:2, AAA:3 and DDD:1, while a decentralized storage policy with continuous supply, batch supply, or kitting supply as material feeding principle for the BBB:1, BBB:2 and CCC:1)*	-The high roof ceiling at the new common kitting area enables solutions based on vertical storage technique, which will limit the floor space needed and increase the utilization of the volume space -Implementing kitting supply at the new centralized storage for the AAA:3 and the DDD:1 will free up floor space, where flow racks currently are installed, at these two assembly lines. -The central location of the new common kitting area requires rather short walking distances for assemblers, when replacing broken or wrongly picked components.	
End of Table 6.6			

6.1.1.2 Implications of the existing Manufacturing strategies applied - for the selection of warehouse automation system(s)

In this subsection, the implications of the case company's existing manufacturing strategies applied, for the selection of warehouse automation system(s) for component storage, are analysed. That mainly a combined ATO/MTO manufacturing strategy is applied for the seven assembly lines, makes the customer order decoupling point (CODP) occur within the internal material supply operation that implies that the selected warehouse automation system(s) must be flexible enough to handle quick changes in the number of load carriers handled per day and in the technical characteristics of the components needed in the assembly processes. Though, since components mainly are handled in a few variants of standardized load carriers with general weight restrictions, the impact of these requirements for warehouse automation system(s) to be able to handle components for different product models within a short time period is limited. This, even though the size and weight of components varies rather much between different models within the same product group. That also an MTS manufacturing strategy is applied for the BBB:1 assembly line, facilities optimizing the product mix for that assembly line, which improves the order response time, as described in Section 3.1.7.3. This implies that the capacity requirements on the feeding warehouse automation system(s) can be more balanced over time for the BBB:1 assembly line, compared to the other assembly lines in which mainly ATO/MTO manufacturing strategies are applied.

6.1.1.3 Implications of the existing Characteristics of demand (i.e., the four Vs) - for the selection of warehouse automation system(s)

In this subsection, are the implications of the existing Characteristics of demand (i.e., the four Vs), for the selection of warehouse automation system(s), analysed. To begin with, the selected warehouse automation system(s) will be a core part of the internal material supply operation and will constitute a potential bottleneck for the whole internal material flow between, on one hand, the Goods receiving and the component manufacturing lines and, on the other hand, the fed assembly line(s). Therefore, it must be ensured that the selected warehouse automation system(s) do not constrain neither the physical internal material flow nor the production scheduling, which otherwise could negatively influence end customer lead times and consequently the end customer satisfaction and the volume demand. The characteristics of the end customer demand, defined in Section 3.1.2. as the Four Vs, directly influence the performance requirements on the assembly processes, which in turn directly influence the performance requirements on the internal material supply processes. Therefore, annual production data for the seven assembly lines can be used for analysing the four influential characteristics of demand (i.e. the Four Vs) for the internal material supply processes. The selected warehouse automation system(s) must be able to meet all these influential characteristics of demand, which originate in the end customer demand characteristics and then are transferred through the performance requirements on the assembly processes to indirectly impact the internal material supply processes (see Figure 6.4).

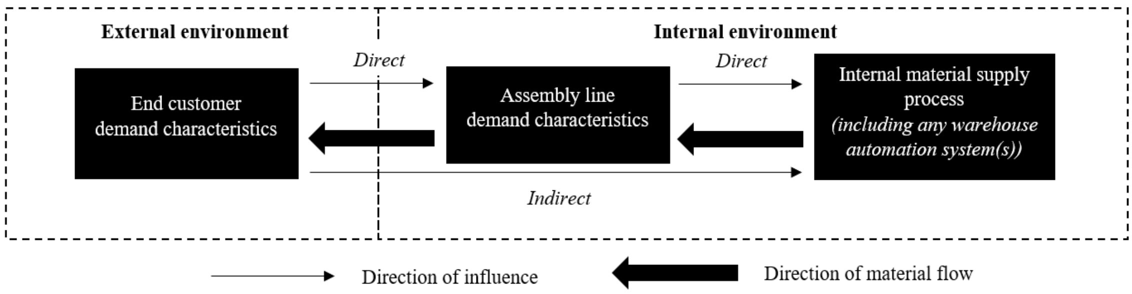

Figure 6.4: *The relationship between end customer demand characteristics, the assembly lines' demand characteristics and the requirements on the internal material supply processes (including any warehouse automation system(s)).*

Volume - a characteristic of demand with implications for the selection of warehouse automation system(s)

In this subsection, the implications of the characteristics of Volume demand, for the selection of warehouse automation system(s) for component storage at the case facility, are analysed. This includes analysis of the implications of: the volume of finished products assembled for the throughput capacity requirements; shift times for the throughput capacity requirements; the number of assembly batches per day and the requirements for short set-up times; and the relationship between a high volume of finished products assembled and internal transports.

The implications of the volume of finished products assembled for the through-

put capacity requirements on the selected warehouse automation system(s): There is a dependency between the volume of finished products assembled, at each assembly line, and the volume of components handled, in the respective internal material supply process, and accordingly also for requirements regarding the volume of load carriers handled. The volume of finished products assembled, at an assembly line, directly influences the flow capacity requirements for the serving warehouse automation system(s). Consequently, the flow capacity requirements on each installed warehouse automation system are affected by which assembly lines that are to be served, as well as the number of parallel warehouse automation systems that are installed. That is, the more assembly lines to be served by a single warehouse automation system, the higher is the flow capacity requirements for that system. Accordingly, in principle the more warehouse automation systems that are installed, the lower is the flow capacity requirements for each installed system. For example, if components for all seven assembly lines are to be handled by a single warehouse automation system, that system must be able to handle components for in average 405 assembled finished products per day (i.e., 128+87+8+116+16+28+22, see Table 6.7), which corresponds to presenting about 15 323 line items per day (i.e., 5120+2871+296+2784+624+1736+1892, see Table 6.7) or about 2917 load carriers per day (i.e, 528+600+177+495+171+426+520, see Table 6.7) for the picking/kitting operators. Further, if all seven assembly lines happens to assemble on each ones maximum pace during the same production day, though the likelihood of this happening is extremely low, it would require a single warehouse automation system to be able to handle components for about 1206 assembled finished products per day (i.e., 374+315+32+278+54+92+61, see Table 6.7), which corresponds to presenting about 46 267 line items per day (i.e., 14960+10395+1184+6672+2106+5704+5246, see Table 6.7) or about 8275 load carriers per day (i.e, 1152+1650+708+1125+627+1349+1664) for the picking/kitting operators. If for example, a single warehouse automation system instead is designated for only handling components for the AAA:1, AAA:2, and AAA:3, the flow capacity requirements for that system will correspond to components for in average 223 assembled finished products per day (i.e., 128+87+8, see Table 6.7), which corresponds to presenting about 8287 line items per day (i.e., 5120+2871+296, see Table 6.7) or about 1305 load carriers per day (i.e., 528+600+177, see Table 6.7) for the picking/kitting operators from these three assembly lines. Another example is if the AAA:1 assembly line alone is to be served by two parallel smaller warehouse automation systems, each of these two systems must be able to handle components for in average 64 assembled finished products per day (i.e., 128/2, see Table 6.7), which corresponds to presenting about 2560 line items per day (i.e., 5120/2, see Table 6.7) or 264 load carriers per day (i.e., 528/2, see Table 6.7) for the picking/kitting operator.

Considering both the average and maximum volume of load carriers being picked from by picking kitting operators per hour, the throughput capacity requirements are highest for warehouse automation system(s) that would serve the BBB:1 assembly line (see Table 6.7). This implies that the possible degree of process repetition, systematization, and specialization is comparably the highest for a warehouse automation system(s) that support the BBB:1 assembly line. A high degree of specialization could be to use several warehouse automation systems that are dedicated and specially adapted to a selection of components. The high volume of load carriers handled also implies that the warehouse automation system(s) supporting the BBB:1 assembly line requires high capital investments, but at the same time enables low handling costs per load carrier. The comparably lowest average volume, regarding the number of load carriers being picked from by picking/kitting operators per hour, are the AAA:3, BBB:2 and the DDD:1 assembly line (see Table 6.7). This comparably low average volume demand implies that the warehouse automation system(s) that will support any of the AAA:3, BBB:2, and DDD:1 assembly line, will have the lowest possible degree of repetition, specialization, and systematization and consequently have high handling costs per load carrier.

A benefit reached by installing several smaller warehouse automation systems in parallel, compared to a single large one, is that internal set up times that hinders the picking/kitting operator may be converted into external set up time, which will allow a higher utilization rate of the picking/kitting operator. Further, to install separate warehouse automation system(s) that are dedicated for each assembly line reduces the risk of massive costs caused by component shortages at the assembly lines. This, since a stop in a warehouse automation system then only will affect the material supply for a single assembly line.

Table 6.7: *Requirements for the Volume of finished products assembled, Volume of line items picked, and Volume of load carriers handled, for each of the seven assembly lines. The underlying calculations are available in Appendix O - Appendix Q. Some of the data presented in this table, are visualized in Appendix A - Appendix N.*

Assembly line/Volume measurement (unit)	**AAA:1**	***AAA:2***	***AAA:3***	***BBB:1***	***BBB:2***	***CCC:1***	***DDD:1***
Annual volume of finished products assembled (finished products per year)	[20 000, 40 000]	[20 000, 40 000]	[0, 20 000]	[20 000, 40 000]	[0, 20 000]	[0, 20 000]	[0, 20 000]
Annual volume of assembly batches (batches of finished products assembled per year)	2731	2834	515	2765	724	1352	1215
Weighted average number of line items per product (component types per finished product, i.e. the quantity per item line is NOT considered)	40	33	37	24	39	62	86
Average volume of finished products assembled per day (finished products per production day)	128	87	8	116	16	28	22
Maximum volume of finished products assembled per day (finished products per production day)	374	315	32	278	54	92	61
Average number of line items assembled per day (component types per production day)	5120	2871	296	2 784	624	1 736	1892
Maximum number of line items assembled per day (component types per production day)	14 960	10 395	1 184	6 672	2 106	5 704	5 246
Average number of assembly batches per day (assembly batches per production day)	11	11	3	11	3	6	5
Maximum number of assembly batches per day (assembly batches per production day)	24	33	12	25	11	19	16
Estimated likely number of load carriers & packages being picked from per average assembly batch (load carriers & packages per assembly batch)	48	50	59	45	57	71	104
Estimated likely number of load carriers/packages being picked from PER DAY (load carriers & packages per production day)	528	600	177	495	171	426	520
Estimated likely number of load carriers & packages being picked from PER HOUR (load carriers & packages per production hour)	36	41	25	65	23	29	24
Estimated maximum likely number of load carriers & packages picked from PER DAY (load carriers & packages per production day)	1152	1650	708	1125	627	1349	1664
Estimated maximum likely number of load carriers & packages picked from PER HOUR (load carriers & packages per production hour)	79	113	100	148	83	92	77

The implications of shift times for the throughput capacity requirements on the selected warehouse automation system(s):
Since shift times at the different assembly lines mostly overlap one another, the possibility to levelling the flow capacity requirements during the day is low for a selected warehouse automation system(s) that is shared between several assembly lines. Though, it would be possible to implement component picking/kitting during hours when the assembly line(s) are not running, which would level the flow capacity requirements over a day's 24 hours. But, this would imply additional costs for inconvenient work hours, increase the operators' solo work and reduce variation in work tasks, as well as, increasing the risk of systematic picking errors being discovered first after a buffer of prepared kits has been built up (i.e., first when the next morning shift starts assembling in the fed assembly line(s)). It would also entail other disadvantages of increased WIP inventory, described in Section 3.1.4.3.

The implications of the number of assembly batches per day and the requirements for short set-up times on the selected warehouse automation system(s):
The volume demand, measured as the average number of assembly batches per day, also has implications for the selection of warehouse automation system(s) since such a system must be able to change the presented load carriers, which contain components for the product model assembled in the finished assembly batch, to other load carriers that contain components for the product model in the new assembly batch. Since different product models being assembled at the same assembly line partly contain the same components, the number of load carriers that need to be changed at each batch change is sequence dependent. Since the model variety within each product group is large, the possible number of batch sequences is extremely high and rather impossible to optimize. Further, sequencing the assembly batches based on the warehouse automation system(s) capability would most certainly constrain the production scheduling of the assembly processes.

Because the selected warehouse automation system(s) must be able to handle the maximum number of load carriers that need to be changed when a new assembly batch is started, it is reasonable to approximate that the system must be able to change all load carriers being presented for the picking/kitting operator within a reasonable time. Further, this overestimating approximation of required set-up time capabilities ensures that the selected warehouse automation system(s) does not become a bottleneck in the internal material supply process.

To reduce the negative impact of long internal set up times, may two or more smaller warehouse automation systems be lined up beside one another so the system(s) that currently are not being picked from can be changing the load carriers being presented for the picking/kitting operator. This would transform constraining internal set-up time to non-constraining external set-up time, which allows full utilization of the picking/kitting operators time. Though, a drawback with installing two or more parallel warehouse automation systems is the lower utilization rate of each system, compared to if a single system is used.

Relationship between a high volume of finished products assembled and internal transports:
An important effect the volume of finished products assembled has on the selection of warehouse automation system(s), is that the higher the volume assembled is, the more non-value-adding transports between the warehouse automation system(s) and the fed as-

sembly line(s) are required. Figure 6.5 visualizes the differences in characteristics between inbound and outbound deliveries of components from a future warehouse automation system at the case company. As described in Section 3.1.6.1 internal transports are waste, which only imply costs and risks but no value for the end customer, and should therefore be reduced as much as possible. This issue is partly reduced by the increased possibility to make internal transports of component kits in larger batches, which reduces the total number of transports, if the volume of finished products assembled is high. A complicating factor, is that the components obviously also must be internally transported between, on one hand, the Goods receiving (i.e., in the case of purchased and externally treated components) and the component manufacturing lines (i.e., in the case of in-house manufactured components) and, on the other hand, the warehouse automation system(s). Though, the impact of this complicating factor is reduced due to the limited number of available locations to install any warehouse automation system(s) (see Table 6.2, Table 6.3, Table 6.4, Table 6.5, Table 6.6).

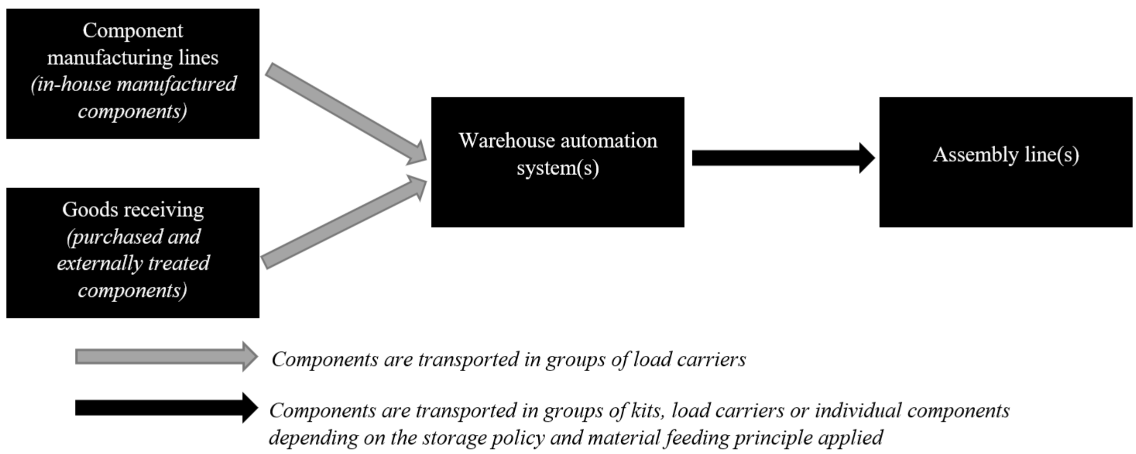

Figure 6.5: *The incoming components to the warehouse automation system(s) are transported in groups of load carriers, while outgoing components are transported in groups of kits, load carriers or individual components depending on the storage policy and material feeding principle applied.*

All else being equal, the relationship between the volume of finished products assembled at an assembly line and its need for component kits, implies that the lower the volume assembled is, the less beneficial it is to locate warehouse automation system(s) close to the fed assembly line. This, due to the low total number of transported kits/load carriers/-components per day. At the same time, the lower the volume assembled is, the fewer are the opportunities to kit components for several finished products at the same time, without creating relatively long lasting WIP inventory at the assembly line and consequently creating all disadvantages related with such waste (see Section 3.1.6.1). Though, also the average bin quantity in the load carriers used for transporting unit loads of components, as well as, the number of kits per kitting cart influence the need for non-value-adding internal transports. All else being equal, the higher the average bin quantity per load carrier is, in relation to the volume of finished products demanded, the less beneficial it is to locate the warehouse automation system(s) closer to the Goods receiving and the component manufacturing lines (i.e., in the case of kitting supply being applied). On the other hand, all else being equal, the larger the number of kits per kitting cart is, the less beneficial it is with a shorter transport distance between the warehouse automation system and the fed assembly line(s) (i.e., in the case of kitting supply being applied).

Variation - a characteristic of demand with implications for the selection of warehouse automation system(s)
In this subsection, are the implications of the characteristics of Variation in volume demand, for the selection of warehouse automation system(s), analysed. Just like the absolute Volume demand has implications for the selection of warehouse automation system(s), so does the Variation in volume demand. This, since the variation in volume demand of finished products assembled per day directly influences the variation in volume of line items handled per day and consequently also the variation in volume of load carriers handled per day (i.e., in the selected warehouse automation system(s)).

There is some seasonal variation (calculated as 22-day moving average) in the requirements for the number of load carriers handled per day (see Appendix A-N). Especially the AAA:1, AAA:2, BBB:1, and DDD:1 show dips in the volume of finished products assembled per day during the turn of the month between July and August, which can be explained by a lower assembly capacity caused by summer leaves. The elevated volume of finished products assembled per day and consequently the elevated requirements for load carriers handled per day in the period after the summer leave, can partly be explained by summer backlogs at the customers.

In Table 6.8, is the variation in throughput capacity requirements for the selected warehouse automation system(s) summarized, represented by the minimum, maximum, range, and standard deviation of finished products assembled per day and assembly batches per day, as well as the minimum, maximum, and range of number of load carriers picked from per day. Since each assembly batch start requires the warehouse automation system(s) to change the load carriers being presented for the picking/kitting operator to pick from, the variation in number of batches per day also has implications for what warehouse automation system(s) to select. This, because a large variation in the number of assembly batches per day requires shorter set-up times to avoid idle picking/kitting operators and in turn idle assembly lines. At the same time, a large variation in volume demand implies a risk for overcapacity, from time-to-time, regarding the warehouse automation system(s) capability to timely present the required number of load carriers.

The assembly lines with the highest variation in volume demand (measured as standard deviation in number of assembly batches per day) are the AAA:1, AAA:2, and BBB:1, (see Table 6.8). Consequently, the requirements for flexibility in set-up times (i.e. the speed of changing the load carriers being presented for the picking/kitting operator at assembly batch changes) are therefore the highest for warehouse automation system(s) that will feed any of these three assembly lines. The AAA:3 and BBB:2 assembly line have comparatively the lowest variation in volume demand (measured as standard deviation in number of assembly batches per day) and therefore also have the lowest requirements regarding flexibility in set-up times. The CCC:1 and DDD:1 assembly line, have similar variation in volume demand (measured as standard deviation in number of assembly batches per day) and consequently imply similar requirements for flexibility in set-up times on the selected warehouse automation system(s). The requirements for flexibility in set-up times (measured as standard deviation in number of assembly batches per day) for the CCC:1 and DDD:1 assembly line, are higher than for the AAA:3 and BBB:2 assembly line, but lower compared to the AAA:1, AAA:2, and BBB:1 assembly line (see Table 6.8).

Table 6.8: *Variation in demand per production day, for each assembly line. The underlying calculations are available in Appendix O - Appendix Q. Some of the data presented in this table, are visualized in Appendix A - Appendix N.*

Variation measurement (number per day)	**AAA:1**	**AAA:2**	**AAA:3**	**BBB:1**	**BBB:2**	**CCC:1**	**DDD:1**
Minimum (number of finished products assembled per day)	2	1	1	2	1	1	1
Maximum (number of finished products assembled per day)	374	315	32	278	54	92	61
Range (number of finished products assembled per day)	372	314	31	276	53	91	60
Standard deviation (number of finished products assembled per day)	65.6	46.2	5.6	55.2	10.9	15.5	12.8
Minimum (number of assembly batches per day)	1	1	1	1	1	1	1
Maximum (number of assembly batches per day)	24	33	12	25	11	19	16
Range (number of assembly batches per day)	23	32	11	24	10	18	15
Standard deviation (number of assembly batches per day)	5.3	5.7	1.8	5.3	2.0	3.2	3.1
Minimum (number of load carriers picked from per day)	48	50	59	45	57	71	104
Maximum (number of load carriers picked from per day)	1152	1650	708	1125	627	1349	1664
Range (number of load carriers picked from per day)	1104	1600	649	1080	570	1278	1560

Variety - a characteristic of demand with implications for the selection of warehouse automation system(s)

In this subsection, are the implications of the characteristics of Variety in demand, for the selection of warehouse automation system(s), analysed. To begin with, there is a large variety in demand, regarding the technical characteristics (i.e., mainly regarding size and weight) of the components handled in the internal material supply processes. This considers variety, in the technical characteristics of components handled, between the different assembly lines, as well as of components used in different product models being assembled at the same assembly line. Though, the implications of these differences in technical characteristics of components for the selection of warehouse automation system(s) are limited, since most components are stored and handled in a limited number of load carriers (see Section 4.4)

Any selected warehouse automation system(s) should be optimized to the size and weight of the handled load carriers, which implies that a large variety in size or weight of handled load carriers can create low system effectiveness. For example, if a warehouse automation system must be able to handle both the P-serie pallets and the E-serie boxes, the system will have either built-in over-capacity or built-in under-capacity, regarding the allowed size and/or weight of load carriers handled. Though, effectiveness issues caused by a large variety in the size and weight of load carriers can partly be reduced if the sizes are combinable with one another. This is the case for the E-Serie boxes and P-serie pallets where the length of two E-serie boxes (2*400mm) equals the size of a single P-serie half-pallet

(1*800mm). The same relationship exists regarding the width of the same load carriers, where the width of two E-serie boxes (2*300mm) equals the width of a single P-serie half-pallet (1*600mm). Though, that the sizes of the E-serie and P-serie load carrier types are combinable do not remove the issue of the different allowed maximum weight per load carrier (i.e., 32 kg for the E-serie boxes vs 500 kg for the P-serie half pallets, see Table 6.13) or the difference in maximum weight per unit area (i.e, 267 kg/m2 for the E-serie vs 1042 kg/m2 for the P-serie, see Table 6.9), which imply different requirements for the selection of warehouse automation system.

Table 6.9: *Maximum storage footprint for load carrier*

Load Carrier type		Max. Storage Footprint (kg/m2)
E-Serie boxes	E4312	267
	E4317	267
	E4322	267
E-serie box that always is handled/stored on a plastic half-pallet (OBS: is treated as P-serie half pallet in this thesis)	(E8623)	1042
P-Series pallets	P11	1042
	P12	1042
	P21	1042
	P22	1042

A warehouse automation system that would supply the AAA:1 and/or AAA:2 assembly line would have the lowest load capacity requirements, since the components required at these two assembly lines are only stored in F-serie or E-serie load carriers, where the heaviest load carriers used (i.e., the E-serie boxes) have a weight restriction of only 32 kg per box that corresponds to 267 kg/m2. The relatively small weight range of 32 kg for load carriers used for the AAA:1 and AAA:2 assembly line (see Table 6.13), in combination with the relatively similar sizes of the F-series and the E-serie load carriers, make both the AAA:1 and AAA:2 assembly line suitable for larger warehouse automation system(s) in which all the components required are stored.

For the AAA:3 assembly line, components are not only picked from the F-serie and E-serie boxes but also from the P11 half-pallets, with a weight restriction of 500 kg per load carrier corresponding to a maximum weight per unit area of 1042 kg/m2, that also requires a lot more space than an F-serie or E-serie boxes. The large differences in size and weight restrictions between, on one hand, the P11 half-pallet and, on the other hand, the F-serie and E-serie boxes make these types of load carriers unsuitable to handle within the same warehouse automation system. This, since the P-serie load carriers imply completely different size and weight capacity requirements on a warehouse automation system compared to the E-serie and F-serie load carriers (see Table 6.9). For example, storing the P-serie load carriers increases the storage footprint by 775 kg/m2, compared to if only E-serie boxes are stored, and may cause imbalances in a warehouse automation system that is used for storing smaller load carrier types as well. The much higher maximum weight per square meter caused by the P-serie pallets, compared to for the E-serie boxes, emphasizes the likelihood of causing imbalances in a warehouse automation system if these load carrier types are stored simultaneously. In addition, the large size of the P-serie load carriers requires much larger I/O points at the warehouse automation system compared to the F-serie and E-serie load carriers. Accordingly, there are multiple reasons for why the P-serie load carriers are recommended to be handled in a separate warehouse automation system that is optimized for its technical characteristics, or alternatively continue to be handled in manual rack systems. Since only a relatively small share of the total number of load carriers handled within the facility are P-serie pallets (see Table 6.10), will continuous manual handling of the P-serie load carriers not require any major work efforts by the operators at Goods receiving, which most certainly will be responsible for handling them.

The data in Table 6.10, show that the E-serie and F-serie boxes make up about 65 percent of the total number of load carriers stored, while only constituting about 31 percent of the total weight of the components stored. In contrast, the P-serie pallets make up only 2 percent of the total number of load carriers stored, while constituting about 20 percent of the total weight of the components stored.

Table 6.10: *Distribution of overall weight and number of bins between different types of load carrier, during a specific date in year 2020*

	Number of bins		**Total weight**	
	Quantity	**%**	**Quantity in Kg**	**%**
E-serie & F-serie	4410,0	65%	95067,8	31%
P-series	101,0	2%	38441,2	20%
LEVEMB AND NA	1995,0	33%	95421,0	49%

The data in Table 6.11-6.12 indicates that the E-serie load carriers are the predominantly used load carrier at all assembly lines, for both purchased and in-house manufactured components, compared to the F-serie and P-serie load carriers. The selected warehouse automation system(s) should accommodate or be optimized to the E-serie load carriers for better performance in terms of storage density. Moreover, the dimensions of the F-serie load carriers is lesser than the E-serie load carriers, which inherently helps the selected warehouse automation system(s) to accommodate the second most used load carrier type (i.e, F-serie load carriers) optimally. The variety in demand, in the form of the handled load carriers' technical characteristics, are summarized for each assembly line in Table 6.13.

Table 6.11: *Distribution of number of load carrier for purchase components*

	AAA	**BBB**	**CCC:DDD**
E series	1678	213	1288
F series	391	41	212
P Series	24	2	75
LEVEMB	360	94	83

Table 6.12: *Distribution of number of load carrier for in-house manufactured components*

	AAA	BBB	CCC:DDD
E series	974	404	249
F series	9	0	0
P Series	0	0	0
LEVEMB	199	1	8

Table 6.13: *Summary of variety in demand, in the form of the handled load carriers' technical characteristics, for each assembly line.*

Assembly lines/ Measures of variety	*AAA:1*	*AAA:2*	*AAA:3*	*BBB:1*	*BBB:2*	*CCC:1*	*DDD:1*
Max weight (per load carrier)	E-serie: 32kg F-serie: No weight restriction P-serie: Not used	E-serie: 32kg F-serie: No weight restriction P-serie: Not used	E-serie: 32kg F-serie: No weight restriction P-serie: 500/1000 kg	E-serie: 32kg F-serie: No weight restriction P-serie: 500/1000 kg	E-serie: 32kg F-serie: No weight restriction P-serie: 500/1000 kg	E-serie: 32kg F-serie: No weight restriction P-serie: Not used	E-serie: 32kg F-serie: No weight restriction P-serie: 500/1000 kg
Range of max weight (for load carriers)	~[0,32] kg	~[0,32] kg	~[0,1000] kg	~[0,1000] kg	~[0,1000] kg	~[0,32] kg	~[0,1000] kg
Range of max storage footprint (due to load carriers)	~[0,267] kg/m2	~[0,267] kg/m2	~[0,1042] kg/m2	~[0,1042] kg/m2	~[0,1042] kg/m2	~[0,267] kg/m2	~[0,1042] kg/m2

Visibility - a characteristic of demand with implications for the selection of warehouse automation system(s)

In this subsection, are the implications of the characteristics of Visibility in demand, for the selection of warehouse automation system(s), analysed. To begin with, the visibility of demand is from an end customer perspective non-existing since any installed warehouse automation system(s) will not perform any activities that are value-adding for the end customers. Consequently, there is no need for customization for end customer needs and accordingly there is no need for consulting end customers when selecting warehouse automation system(s). The low level of visibility from external demand increases the possible level of process standardization, as well as, the possible utilization rate since no warehouse automation system(s) need to be adapted to certain end customer needs. This in turn, implies lower handling cost per load carrier, compared to if the visibility of external demand was high.

If the visibility of demand instead is considered from an internal customer perspective (i.e., from the assembly processes perspective), the visibility can be regarded as extensive since any installed warehouse automation system(s) can provide both time utility, in the form of high OTIF-deliveries of the components required, as well as, place utility by making the required components easily available in a way that facilitates ergonomic component picking/kitting processes. This high visibility, considering an internal customer perspective, implies that there will be a short waiting tolerance for the warehouse automation system(s) services, which in practice means that there will be high requirements for OTIF-deliveries in the form of components being presented for the picking/kitting operators to pick. Further, the high visibility implies that the internal customers' (i.e., the assembly processes) perception of the warehouse automation system(s) performance is important and that there must be well-functioning communication channels between the personnel responsible for the warehouse automation system(s) and the personnel responsible for the assembly processes. An ideal situation could be if the same manager that is responsible for a specific assembly process also takes the managerial responsibility for the serving warehouse automation system(s). This could facilitate a combined and flow oriented management of the closely interlinked assembly processes and internal material supply processes and would increase the responsiveness in action-taking when friction between these processes arises. A drawback with the high visibility, from an internal customer perspective, is that it implies higher handling costs per load carrier compared to if the level of visibility was low.

6.1.1.4 Implications of the Characteristics of assembly lines - for the selection of warehouse automation system(s)

In this subsection, are the implications of the characteristics of assembly lines, for the selection of warehouse automation system(s), analysed. This includes analysis of the implications of: the assembly batch sizes; the assembly lines' takt time and the corresponding production pace; and the assembly lines' pace control.

Implications of the assembly batch sizes for the selection of warehouse automation system(s)
In each of the seven assembly lines, are different finished product models assembled that contain components being model unique, as well as components that are used in several different models. All the seven assembly lines are multi-model assembly lines (see Section 3.1.7.1), in which assembly is performed in batches, but from time-to-time single unit customer orders are creating a need for batch sizes of a single finished product only (see Table 6.14). The distribution of batch sizes for each of the assembly lines, are available in Appendix A-N.

It is crucial to avoid that the selected warehouse automation system(s) becomes a bottleneck that constrains either the production scheduling, by limiting the possible batch sizes, or hinders the physical material flow to the assembly line, by not being able to present all needed components for the picking/kitting operator during each batch's process time. Especially the maximum batch size at an assembly line has implications for the selection of warehouse automation system(s), since a large maximum batch size implies that the system(s) must be able to present a relatively large number of load carriers containing the same line item for the focal assembly line's picking/kitting operator. This, because the bin quantity in a single load carrier in many cases will not contain enough components for the relatively larger batches. An option to address this issue is to install flow racks inside the warehouse automation system(s), which allows immediate replenishment of the presented line items that are needed by the component picker. Another option is to store high runner line items at several spots that are easily accessible by the picking/kitting operator. These two options may also be used in combination, for example by locating load carriers containing the same line item in multiple parallel flow tracks in the same flow rack system being installed in the warehouse automation system(s).

The AAA:1, AAA:2, and BBB:1 assembly line have both the largest average bath sizes and the largest maximum batch sizes of the seven assembly lines (see Table 6.14). Though, the differences in maximum batch sizes are much larger than the differences in average batch sizes, in relation to the other assembly lines. Also, the standard deviation in assembly batch sizes are largest for the AAA:1, AAA:2, and BBB:1 assembly lines. Though, when comparing the estimated likely number of load carriers and packages being picked from per average assembly batch (see Table 6.14), which not only consider the actual assembly batch sizes but also the number of line items per product, the number of components required of each line item, the maximum bin quantity for each line item needed, the probability of more than the minimum numbers of load carriers for each line item are needed, it is the CCC:1 and DDD:1 assembly line that stand out with large values compared to the other assembly lines. This, shows that the implications of the assembly batch sizes on the requirements for the selected warehouse automation system, regarding the capability to present multiple load carriers containing the same line item for the picking/kitting operator, is limited due to the balancing factors: the number of line items per product; the number of components required of each line item; the maximum bin quantity for each line item needed; and the probability of more than the minimum numbers of load carriers for each line item are needed.

Table 6.14: *Data of batch sizes, for each assembly line, which have implications for warehouse automation system(s) capacity requirements regarding the capability to present multiple load carriers containing the same line item. The underlying calculations are available in Appendix O-Q*

Assembly line/ Batch size	*AAA:1*	*AAA:2*	*AAA:3*	*BBB:1*	*BBB:2*	*CCC:1*	*DDD:1*
Minimum (assembly batch size)	1	1	1	1	1	1	1
Average (assembly batch size)	12	8	3	10	5	5	4
Median (assembly batch size)	8	5	3	8	5	6	4
Maximum (assembly batch size)	63	36	4	42	11	12	10
Range (assembly batch size)	62	35	3	41	10	11	9
Standard deviation (assembly batch size)	11.6	6.6	1.3	8.9	2.9	1.8	2.7
Estimated likely number of load carriers & packages being picked from per average assembly batch (load carriers & packages per assembly batch)	48	50	59	45	57	71	104

Implications of the assembly lines' takt time and the corresponding production pace for the selection of warehouse automation system(s)

A warehouse automation system(s) supporting the AAA:1, AAA:2, BBB:1, CCC:1, or the DDD:1 assembly line must allow the dedicated component picking/kitting operator to perform the assigned work tasks in a cycle time that corresponds to the takt time in the fed assembly line (see Figure 6.6). For example, if the warehouse automation system(s) cannot present the needed components within a time-window that is short enough for the picking/kitting operator to also being able to pick and deliver the required components, within the defined takt time, there will arise component shortages at the fed assembly line, which will stop the assembly process and in turn create major costs for loss production time and potentially delayed deliveries for the end customers. If the warehouse automation system(s) instead systematically serves the component picking/kitting operator with the components required within an unnecessary short time window, compared to the takt time in the fed assembly line, the system probably suffers from overcapacity that implies unnecessarily high investment costs and consequently high handling costs per load carrier. Hypothetically, a very high work pace of warehouse automation system(s) could increase the WIP inventory at the fed assembly line, but this problem could easily be removed by directing the component picking/kitting operator to not create queues of component kits. This potential idle time for the picking/kitting operator, could be used for performing other supporting activities such as replenishing load carriers that have been delivered to the warehouse automation system(s) by Goods receiving. A benefit of the picking/kitting operator making the actual replenishment of load carriers, instead of personnel from the

Goods receiving, is that the picking/kitting operator never will be hindered in the component picking/kitting process due to the warehouse automation system(s) being blocked by a dedicated replenishing operator putting full load carriers into the system

In conclusion, for the AAA:1, AAA:2, BBB:1, CCC:1, and DDD:1 assembly line, which each has a dedicated component picking/kitting operator, the warehouse automation system(s) should have a work pace that is fast enough to not hinder the dedicated picking/kitting operator from fulfilling assigned work tasks, within the defined takt time, but neither be able to systematically work at a pace that is much faster than required. In Table 6.15, is the takt time and the corresponding average production pace presented for these five assembly lines. The BBB:1 assembly line stands out with a low takt time and accordingly a high average production pace, which indicates that the requirements for a warehouse automation system to enable short component picking/kitting cycle times is toughest for the one used for storing components for the BBB:1 assembly line.

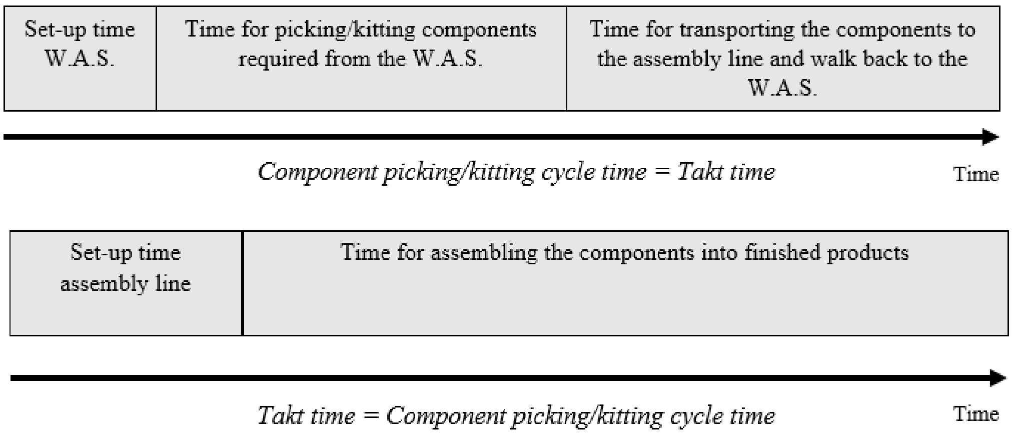

Figure 6.6: *The relationship between the order picking/kitting cycle time, for the AAA:1, AAA:2, BBB:1, CCC:1,and DDD:1 assembly line and the takt time at the respective assembly line.*

For the AAA:3 and BBB:2 assembly line, the situation is different since these have no designated picking/kitting operator that must pick and deliver components in a cycle time that corresponds to the takt time at the fed assembly line. Instead, at the AAA:3 and BBB:2 assembly line the component picking/kitting is performed by the actual assemblers themselves, which makes the component picking/kitting a work task that is part of the takt time at the fed assembly line (see Figure 6.7). Though, the principle of avoiding both a too slow work pace and a too fast work pace of the warehouse automation system(s) is valid for the AAA:3 and BBB:2 assembly line as well. The takt time and the corresponding average production pace at these two assembly lines are presented in Table 6.15 as well.

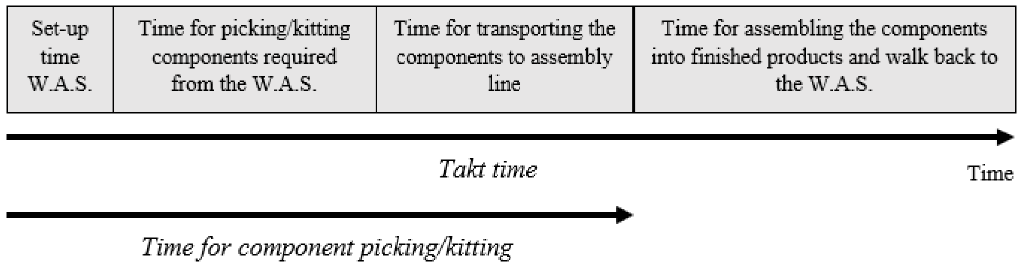

Figure 6.7: *For the AAA:3 and BBB:2 assembly line, which has no dedicated component picking/kitting operator, the component picking/kitting is a work task that is part of the takt time at the respective assembly line.*

Table 6.15: *Data of takt time, production pace, minimum cycle time, and maximum production pace that have been calculated for each assembly line by using annual production data, for year 2020, extracted from the case company's ERP system. (See Appendix O-Q for the underlying calculations.)*

Assembly line/ production pace data	*AAA:1 (a designated component kitter)*	*AAA:2 (a designated component kitter)*	*AAA:3 (component kitting performed by the assembler)*	*BBB:1 (a designated component picker)*	*BBB:2 (component picking performed by the assemblers)*	*CCC:1 (a designated component kitter)*	*DDD:1 (a designated component kitter)*
Takt time (minutes per finished product)	6.9 minutes/ finished product	10.1 minutes/ finished product	52.4 minutes/ finished product	3.9 minutes/ finished products	19 minutes/ finished products	31.6 minutes/ finished products	60 minutes/ finished products
Average production pace (finished products per minute, correspond to takt time)	0.15 finished products/ minute	0.1 finished products/ minute	0.02 finished products/ minute	0.25 finished products/ minute	0.05 finished products/ minute	0.03 finished products/ minute	0.02 finished products/ minute
Minimum cycle time (minutes per finished product, based on historic maximum production per day)	2.3 minutes/ finished product	2.8 minutes/ finished product	13.3 minutes/ finished product	1.6 minutes/ finished product	8.4 minutes/ finished products	9.5 minutes/ finished products	21.2 minutes/ finished products
Maximum production pace (finished products per minute, corresponding to minimum cycle time)	0.43 finished products/ minute	0.36 finished products/ minute	0.08 finished products/ minute	0.6 finished product/ minute	0.12 finished products/ minute	0.10 finished products/ minute	0.05 finished products/ minute

Implications of the assembly lines' pace control for the selection of warehouse automation system(s):

The warehouse automation system(s) must be able to present the components required by the picking/kitting operator with such a low process time variability that no further component buffer is required between the warehouse automation system and the fed assembly line(s) (see Section 3.1.5.2, for a description of the relationship between process time variability and WIP inventory). The component picking/kitting process for the AAA:1, AAA:2, BBB:1, CCC:1, and DDD:1 assembly line are unpaced asynchronous in that sense that the component picking/kitting activity is not strictly restricted to a specific time interval, instead, each picking/kitting operator transports the picked/kitted components to the fed assembly line whenever the assigned picking/kitting tasks are completely finished. Though, since general differences in the cycle time between the component picking/kitting process and the assembly process will remove the effect of the buffer in-between, the component picking/kitting cycle time must equal the takt time at the fed assembly line. Another good argument for always matching the component picking/kitting cycle time with the takt time at the fed assembly line, is to reduce the process time variability and all its related negative effects on the plant performance, such as reduced delivery reliability, reduced speed of delivery and lower productivity (see Section 3.1.5.2). Accordingly, if a dedicated component picking/kitting operator is to be implemented at another assembly line, the component kitting/picking cycle time should equal the fed assembly line's takt time. Though, as described in Section 3.1.5.1, differences in cycle time between work stages can be compensated by adding other supporting or administrative work tasks for operators to perform when otherwise being idle.

For the BBB:2 and AAA:3 assembly line, in which there is no dedicated component picking/kitting operator, the component picking/kitting activity is not a separate work stage, but instead a part of the assembly process, and can therefore not be defined as either paced, unpaced asynchronous, or unpaced synchronous (see Section 3.1.7.4). A benefit implied by the component picking/kitting activities being a part of the fed assembly line's takt time, is that each operator's longer cumulative task time, which includes both component picking/kitting work tasks and assembly work tasks, allows for compensating time losses gained in the component picking/kitting activities by performing the assembly work tasks faster than average. Thereby, the assembler can still finish all the assigned work tasks without deviating from the assembly line's takt time. This implies that the requirements for low process time variability are less for any warehouse automation system(s) serving the BBB:2 and AAA:3, since there is no dedicated component picking/kitting operator at these two assembly lines.

6.1.2 Material Supply System

In this subsection, are the implications of the material supply system, for the selection of warehouse automation system(s), analysed. This includes analysis of: material feeding principles; Handling equipment; Storage; Packaging and unit loads; and Replenishment methods applied within the case facility.

6.1.2.1 Material feeding principles

Currently, sequenced kitting supply is applied for all three assembly lines within AAA, which is the main product group with the highest number of sellable product variants (see Table 4.1). Further, kitting supply is also the main material feeding principle for DDD, which is the main product group with the highest number of input line items per finished product (see Table 4.1). Also, kitting supply is applied for CCC that is the main product group with the next most complex assembly process (see Table 4.1). However, for DDD and CCC is continuous supply applied for the smaller sized components. For the main product group BBB, which has the comparatively fewest number of line items per product (see Table 4.1), is only continuous supply applied.

Kitting supply is applied for the main product groups with a high number of sellable variants or a high number of input line items per finished product, which in turn support the assembly processes. The kitting supply for the AAA' assembly lines are the only structured kitting processes with a separate kitting area, whereas kitting supply for the DDD and CCC is operated from the same storage racks, closer to the respective assembly line, which feeds for continuous supply methods of smaller components. By combining both material feeding principle methods within the same storage racks, this can entail increased operators' walking distance and picking time for components served by the kitting principle. However, combining the different feeding principle for a specific assembly line could be beneficial for overall performance, if the application of feeding principle is based on the economic differentiation such as ABC analysis (see Section 3.2.3.5.

The kitting principle currently applied for the AAA, CCC, and DDD, is based on a picker-to-parts system low level picking assisted by a pick-by-voice ICT tool. The material feeding principles applied will have implications for the selection of warehouse automation system(s). This, since consideration should be given to the component picking/kitting rate/throughput (i.e number of components to be retrieved and kitted in a certain time) and the future warehouse automation system(s) should be able to deliver the required throughput. This should, of course, be inline with the production replenishment pace.

In conclusion, it is recommended that the warehouse automation system(s) selected for supporting the internal material supply processes for the AAA, DDD, and CCC main product groups, are compatible with kitting supply as material feeding principle. This, since these main product groups are characterized by either a high number of sellable product variants or a high number of input line items per finished product (see Table 4.1). Any warehouse automation system selected for supporting the internal material supply processes for the BBB main product group, should instead be compatible with continuous supply as material feeding principle due to the low number of line items per finished product, the highly standardized components, and due to the low complexity of the assembly processes.

6.1.2.2 Handling equipment

The internally designed load carrier lift, which assists the loading and unloading of unit loads from Goods receiving, internal primary storage to secondary storage (i.e., where component picking/kitting take place) is both effective and ergonomic in its design. Though, if these load carrier lifts are to be used in combination with warehouse automation system(s) some limitations are implied on the selection of such system(s). This since the load carrier lifts cannot handle load carriers at a height that exceeds about 1.6 meters above floor, which limits the height of the inbound point of the selected warehouse automation system(s). The load carrier lifts also has a very limited reach that approximately corresponds to the length of an E-serie load carrier (i.e. 400mm), which constrains the design of the inbound point of the selected warehouse automation system(s) since it must be possible to safely unload each load carrier at a platform within that short range. In addition, the load carrier lift's forward sticking design, where the forward wheels are fixed on the load carrier lift, requires the floor space under the platform for unloading at the warehouse automation system(s) to be free from obstacles to allow full mobility of the load carrier lift. Heavier load carriers such as the P11, P12, P21 and P22 are handled by pallet jacks. If consideration is given to accommodate those heavier load carriers in warehouse automation system(s), then the required I/O points will have implications for the selection of such system(s) based on the dimensions of the pallet jacks such as operational length, width, and height.

6.1.2.3 Storage systems

Based on current inventory data presented in Table 6.10, there is a total storage volume needed for about 4410 number of E-serie and F-serie load carriers and about 1995 number of other smaller packages, with a combined weight of about 190 489 kg. These unit loads are currently stored in both primary and secondary storage locations, while as previously mentioned, the case company wants to remove all primary storage locations and only store each line item at a single location within the facility. The maximum number of load carriers stored (i.e volume capacity) will have prime implications for the selection of warehouse automation system(s). Further, the applied storage assignment policies have implications for the selection of the warehouse automation system(s). For example, if a dedicated storage policy is deployed, this will entail low space utilization in the warehouse automation system(s) and consequently require larger volume capacity. Random storage policy could be used for high space utilization within the warehouse automation system(s), but at the expense of lower operator orientation, as well as, increased travel distance and picking/kitting time. Accordingly, a random storage policy is most suitable to apply for the low runner line items. Further, a random storage policy could be beneficial if the total travel time or retrieval time of the unit loads is lesser then the throughput requirement. For effective storage assignment and retrieval, the warehouse automation system(s) must be compatible with the ERP system (i.e., JD Edwards World 7.3) and ICT tools for data management and optimization. Further, the selected warehouse automation system(s) should be compatible with class based storage assignment. A-Class components, which are high volume and fast moving, should be stored optimally closer to the output point for quick retrieval followed by B-class and so on. However, a combination of different storage assignment policies might impact the overall performance of warehouse automation system(s). Further, the inputs based on tacit knowledge of internal material planners and production engineers are critical when allocating the components (i.e slotting), in any warehouse automation system(s) when determining the storage assignment policies for effective operation.

In addition, the maximum weight and storage footprint of the unit loads, which are assigned to the storage location, have implications for the selection of warehouse automation(s) (see table 6.9, 6.13 (variety in demand)). Due to the variety in the weight of different unit loads, there is a risk of system imbalances during storage allocation. Mostly in systems such as VLM and vertical carousels, weight imbalance could happen if storage allocations do not consider the weight of unit loads. This risk may be leveled if a random storage assignment policy is applied since the locations of line items within the warehouse automation system(s) then constantly will change. Further, systems with vertical automation configuration will have maximum allowable weight restriction due to the risk of imbalances within the system.

6.1.2.4 Packaging and unit loads

The size variation between the unit loads stored (see Table 6.9) could affect the storage density of the selected warehouse automation system(s), since the unit loads with smaller dimensions will not utilize the whole designated storage area. Since the components characteristics such as weight, volume and size vary, it is practically not suitable to use a common load carrier either. Further, the sizes of packaging unit loads are designed in order to ease the retrieval of components at the assembly lines. Thus, the different unit load sizes have implications on the selection of warehouse automation system(s) in terms of its rack design such as single deep, double deep etc., which in turn impact the storage density. Also, the maximum dimension of the packaging unit load will influence the design of I/O (Input/Output) points at the warehouse automation system(s). Since there are many warehouse automation system(s) on the market that are capable of handling different types of unit loads like bins, totes, cartons and pallets, the different types of unit loads used at the case facility is not a problem, in that sense that there exist multiple types of warehouse automation system(s) that can handle all these types of unit loads. However, different types and sizes of unit loads used should be compatible with different ICT systems such as pick-by-light, pick-by-voice, and perhaps RFID which enhances the performance of warehouse automation systems.

6.1.2.5 Replenishment methods

Both Kanban cards, M-cards, Two-bin systems, and ERP controlled signals are used as replenishment methods within the case facility. Many of the in-house manufactured components use a physical Kanban card as a signal for replenishment or initiation of production. The Material card (M-card) system is based on a physical card and is used for replenishment of components from primary storage location to their secondary storage location, where the stored components are picked/kitted by operators. If M-cards are to be used after implementation of warehouse automation system(s), which the case company wants to avoid, the M-card replenishment system may have implications for the warehouse automation system(s) performance in retrieval time or component preparation time. This is because in the current process of M-card handling, the signals (i.e., physical cards) are physically collected by the milk run operator on every trip. When the assembly demand peaks, which in turn also increases the replenishment pace, the number of M-cards could be in high numbers. This may entail longer retrieval time in the picking process at the warehouse automation system(s), in terms of component preparation for the next milk run trip, since the signal for which components to be retrieved is received only at the return of the milk run operator to the primary storage location. This is another argument for removing the M-cards as a replenishment system. Though, if there still will be a need for both primary and secondary storage locations after the implementation of warehouse automation system(s) and accordingly a need for moving components from primary to secondary storage locations, it is recommended that the physical M-cards are replenished by electronic transport-Kanbans. This would also remove the risk of physical M-cards disappearing, which eventually can lead to component shortages at the assembly line.

Other ERP controlled replenishment signals for lot number systems and unique article numbers have lesser impact on the selection of warehouse automation(s), since the data captured through barcode scanners is transferred in real time. Potentially the preparation of milk run deliveries can be decoupled from the actual transport, so that the future warehouse automation system(s) may not be influenced as heavily by the variation in the replenishment pace. Another possibility is that, if the existing physical Kanban signals are digitized to be electronic signals in the ERP system, it might not influence the performance of the warehouse automation system(s) in terms of higher retrieval times in the order picking/kitting processes due to the demand being communicated in real time.

6.1.3 Performance Objectives

This subsection describes the requirements implied by the need for high process performance in the case company's internal material supply operation, for the selection of warehouse automation system for component storage.

6.1.3.1 Quality

As described in Section 3.1.3.1, internal benefits of high process quality include fewer errors in processes, less complexity and disruptions, higher internal reliability and less processing costs, which the selected warehouse automation system(s) can contribute to by providing a maximum degree of OTIF deliveries (i.e., On Time In Full deliveries) by presenting all components required by the picking/kitting operator at the right time. This will support a high line fill rate (see Section 3.1.4.3) and high line efficiency (see Section 3.1.4.3) at the served assembly line(s). Further, as described in Section 3.1.3.1, there are also external benefits of high process quality, such as fewer errors in products, allows highly specified products, and increased reliability of products, which can be supported by warehouse automation system(s) that supports quality at the source through minimizing the risk of picking errors. In practice, this could be that the warehouse automation system(s) should be compatible with the currently used pick-by-voice system that has proved to both reduce the component picking/kitting time and the number of picking errors. Further, the degree of quality at the source in the selected warehouse automation system(s) can be elevated by complementing the pick-by-voice system with a replenish-by-voice or replenish-by-light system, which would reduce the risk of full load carriers being allocated to the wrong storage location.

It is reasonable to assume, the lower the variety in the technical characteristics of load carriers stored, the greater are the opportunities to specialize the warehouse automation system(s). This implies, the more assembly lines that a single warehouse automation system is dedicated for, the lower is the possibility to specialize its design and consequently the higher is the risk for process quality related issues in its performance.

6.1.3.2 Speed

As described in Section 3.1.3.1, internal benefits of high process speed are faster throughput times, less inventory, less overhead costs, and less processing costs, which can be supported by warehouse automation system(s) that are able to present all components required by the picking/kitting operators as fast as needed, as well as, allowing replenishment of load carriers to be performed without unnecessary delaying either the replenishing operator nor the component picking/kitting operator. By being able to handle all load carriers, which are needed for presenting all the components required by the picking/kitting operator fast enough to allow delivery of the components to the fed assembly line(s) in a timely fashion, will also create external benefits of high process speed, described in Section 3.1.3.1, such as shorter delivery times, and faster response to customer requests.

For the AAA:1, AAA:2, BBB:1, CCC:1, and DDD:1 assembly line, which each has a dedicated component picking/kitting operator, the warehouse automation system(s) must be able to retrieve and present all needed components within a time window that is short enough for the whole component picking/kitting work cycle to be performed in a time length that corresponds to the fed assembly line´s takt time, as described in Section 6.1.1.4

For the AAA:3 and BBB:2 assembly line that do not have any dedicated component picker, but where the actual assembler pick/kit the required components instead, the warehouse automation system(s) must be able to retrieve and present all needed components within a time window that is short enough for the whole assembly cycle (i.e., both component picking/kitting work tasks and assembly works tasks) to correspond to the takt time at the respective assembly line, as described in Section 6.1.1.4

High process speed in the internal material supply process, at all seven assembly lines, can be supported by having the component picking/kitting operator to make the actual replenishment of load carriers. This, since it would remove the occasions where a dedicated replenishing operator from Goods receiving blocks the access to a warehouse automation system that a component picking/kitting operator needs to pick components from. Though, this requires that the picking/kitting operator have enough idle time from the picking/kitting activities to allow the replenishment of load carriers to take place without slowing down the picking/kitting activities, which are of highest priority. To reduce the time needed by the component picking/kitting operators for replenishing load carriers, the Goods receiving personnel can be directed to place all full load carriers beside each warehouse automation system so they are easily reached by the component picking/kitting operator. In addition, high process speed can also be supported by selecting smaller more specialized warehouse automation systems, like one dedicated for each assembly line, since each system's load carrier retrieval times can be expected to be shorter the smaller the system is. This, due to the shorter system internal retrieval distances in a smaller warehouse automation system, compared to in a larger one.

6.1.3.3 Dependability

As described in Section 3.1.3.1, a high degree of process dependability implies internal benefits such as increased trust in the operation, fewer contingency plans required, increased internal stability, and less processing costs, which can be supported by warehouse automation system(s) that enable a high degree of OTIF deliveries, as well as low process time variability like having a set up time of presented load carriers that is the same each component picking/kitting work cycle and that is independent of what components being retrieved. This will in turn reduce the cycle time deviation (see Section 3.1.4.3) in the component picking/kitting work cycle, for the assembly lines with a dedicated component picking/kitting operator, and reduce the takt time deviation (see Section 3.1.4.3), for the assembly lines that has no dedicated component picking/kitting operator where instead the actual assembler picks/kits all the components required. Further, just like high process speed can be supported by having the component picking/kitting operator to make the actual replenishment of load carriers, may high process dependability also be supported by that. This since the component picking/kitting operator then never will be blocked by a dedicated replenishing operator and consequently will the time needed for each picking/kitting work cycle be more predictable. Further, high process dependability can also be supported by selecting smaller more specialized warehouse automation systems, since each system's load carrier retrieval times can be expected to be shorter the smaller the system is, due to the shorter system internal retrieval distances. All else equal, shorter average load carrier retrieval times can be expected to create lower process time variability in absolute time figures. Further, external benefits, like increased on-time delivery to customers, can be reached by a high level of process dependability, (see Section 3.1.3.1).

6.1.3.4 Flexibility

Warehouse automation system(s) that enables a high level of process flexibility in the form of range flexibility and response flexibility, can be expected to create internal benefits like increased responsiveness to unforeseen events, increased responsiveness to required changes in activities and less process costs, as well as, external benefits like allowing frequent new product introductions, a wide range of products, adjustable volumes, and adjustable deliveries (as indicated in Section 3.1.3.1). A high level of process range flexibility is supported by a warehouse automation system that can handle a large variety of load carriers, for example all kinds of load carriers in both the F-serie and E-serie, while process response flexibility, is supported by a warehouse automation system that easily can change the unit loads of stored components, by allowing easy change of the load carriers being stored. An especially valuable feature of a warehouse automation system is to have a high level of delivery flexibility, in that sense that the sequence in which load carriers are presented for component picking/kitting operators can be changed in a short notice, which enables near time rescheduling of the fed assembly line(s). This is especially valuable since the case company's Elite customers have demands for very short order lead times, which often require the company to make changes to the sequence in which customer orders are assembled. Further, since the volume assembled per day varies, another important feature of a warehouse automation system is to have a high volume flexibility, in that sense that it should be able to easily adapt to changes in the volume assembled per day. An example could be for a warehouse automation system to have several I/O points, which are used depending on the volume handled. Another possibility to increase the process flexibility, is to assign the component picking/kitting operators with other supporting work tasks, which can work as a time buffer when the demand for picking/kitting activities are low.

6.1.3.5 Ergonomics

A high level of ergonomic performance is reached by the selection of warehouse automation system(s) that supports reaching the ISO-standards regarding manual material handling, described in Section 3.1.3.2. This means that work tasks involving manual lifting and carrying, manual pushing and pulling, and manual handling of low loads at high frequency should be minimized, or at least be designed in an optimal way from an ergonomic point of view. To minimize the occurrence of work tasks involving manual lifting and carrying, it is valuable if the selected warehouse automation system(s) are compatible with the internally designed load carrier lifts.

In order to avoid manual pushing and pulling, it is important that the I/O points of the warehouse automation system(s) are designed in a way that such manual pushing and pulling is not required to reach high productivity by the replenishing or component picking/kitting operators. In order to avoid manual pushing and pulling of carts used for transporting load carriers to the warehouse automation system(s) or for kitting carts used for transporting components from it, the warehouse automation system(s) should be able to be located where it easily can be accessed by both inbound and outbound internal transports. In addition, the warehouse automation system(s) should be compatible with the currently used AMR, which obviously reduces the need for manual pushing and pulling greatly.

The warehouse automation system(s) ability to minimize manual handling of low loads at high frequency, is limited since all inbound deliveries are made in unit loads of components, being stored in load carriers, and the outbound deliveries are made in individual components being picked/kitted. Though, as described in Section 3.1.3.2, the human body is designed in a way that manual handling of low loads at high frequency preferably should be performed in a comfortable upright work posture, within a limited vertical space, with a short horizontal distance to the objects handled. Since all humans have unique physical characteristics, it is important that the I/O points of the warehouse automation system(s) can be adapted to individual operators, for example by making the height of the interaction points easily adjustable. This, especially concerns the outbound point for component picking/kitting where a lot of manual material handling of individual components will take place. As indicated in section Section 3.1.3.2, to consider ergonomic factors in the process of selecting warehouse automation system(s) will broaden the case company's possible worker pool, as well as improving productivity and quality by reducing worker fatigue.

6.2 Part 2 - Selection of warehouse automation system(s) for component storage

In this Part 2 of the Analysis, main recommendations are provided for what warehouse automation system(s) for component storage that the case company should select. In addition, the consequences for the internal material supply operation related to following these main recommendations are described. Accordingly, this Part 2 of the Analysis contain the answers for RQ2 (i.e., *What type of warehouse automation system(s) for component storage, are recommended for the case company to select?*) and for RQ3 (i.e., *What are the consequences for the case company's internal material supply operation of selecting the recommended warehouse automation system(s) for component storage?*).

6.2.1 Performance measurements with mediating effects on the case company's main logistics KPIs

As described in Section 3.1.4.1, a performance measurement system should be comprehensive, causally oriented, vertically integrated, horizontally integrated, internally comparable, and useful, which should be considered when evaluating warehouse automation system(s). The case company uses logistics KPIs, which includes both revenue influencing, cost influence, asset influencing, and ergonomic influencing variables (see Section 4.8). Though, except for the ergonomic influencing variables, the case company's logistics KPIs are rather imprecise measurements. This makes them difficult to use directly when evaluating different warehouse automation systems, which only have indirect effects on the end customer satisfaction through the influence on the assembly processes that are supported. Therefore, instead different warehouse automation systems should be evaluated using performance measurements that are directly influenced by the selected warehouse automation system(s), but that in turn support the company's main KPIs. This means that the performance of warehouse automation system(s), considering the support for the company's main KPIs, can be evaluated by studying the effects on several mediating performance measurements, which are directly influenced by the selected warehouse automation system(s). The mediating effects of the selected performance measurements on the company's main KPIs, are summarized in Table 6.16. These mediating performance measurements are results from the analysis of performance objectives, which are imposed on the selected warehouse automation system(s) (see section 6.1.3). In short, Table 6.16 summarize how high performance in the internal material supply processes positively influence the company's overall performance.

Table 6.16: *A summary of how high performance in the selected warehouse automation system(s) influence the performance of the main logistics KPIs used at the case company. That is, high process performance considering a performance measurement being presented in the far right column, have positive effects on the performance of one, or several, of the main logistics KPIs being presented in the middle column.*

Type of logistics performance measurement	**Main logistics KPIs used at the case company**	**Performance measurements with mediating effects on the case company´s main KPIs**
Revenue influencing variables	-*Volume produced* -*Line Items Shipped Correctly (LISC)* -*Returned Parts Per Million (RPPM) of shipped products* -*Warranty costs in percent of total sales*	-High rate of *OTIF-deliveries* ,of components to component picking/kitting operators -High *Response flexibility* - Low *Process time variability* -High ability to create *Quality at the source*, by minimizing *picking errors*
Cost influencing variable	-*Number of defect products* -*Total value of defect products and components, in SEK.* -*Returned Part Per million (RPPM), of inbound components*	-High ability to create *Quality at the source*, by minimizing *picking errors* -High rate of *OTIF-delivery*, of components to component picking/kitting operators -High *Range flexibility* -Low *Process time variability* -Low *Set up time*, of load carriers being presented for component picking/kitting operators
Asset influencing variables	-*Days Sales of Inventory (DSI)* -*Return On Net Assets (RONA)*	-High *Range flexibility* -Low *Process time variability*
Ergonomic influencing variables	-*Near misses* -*Work incidents* -*Personnel attendance*	-Low amount of *Manual lifting and carrying* -Low amount of *Manual pushing and pulling* -Low amount of *Manual handling of low loads at high frequency*

6.2.2 Inter-dependencies between different internal material supply decisions - at the case facility

Developing recommendations for the case company regarding what warehouse automation system(s) to use and what material feeding principles to apply for the different assembly lines cannot be done in isolation from one another. Further, there exists inter-dependencies between these two decisions and the decisions about what storage policies to apply and where to locate the warehouse automation system(s) within the facility (see Figure 6.8).

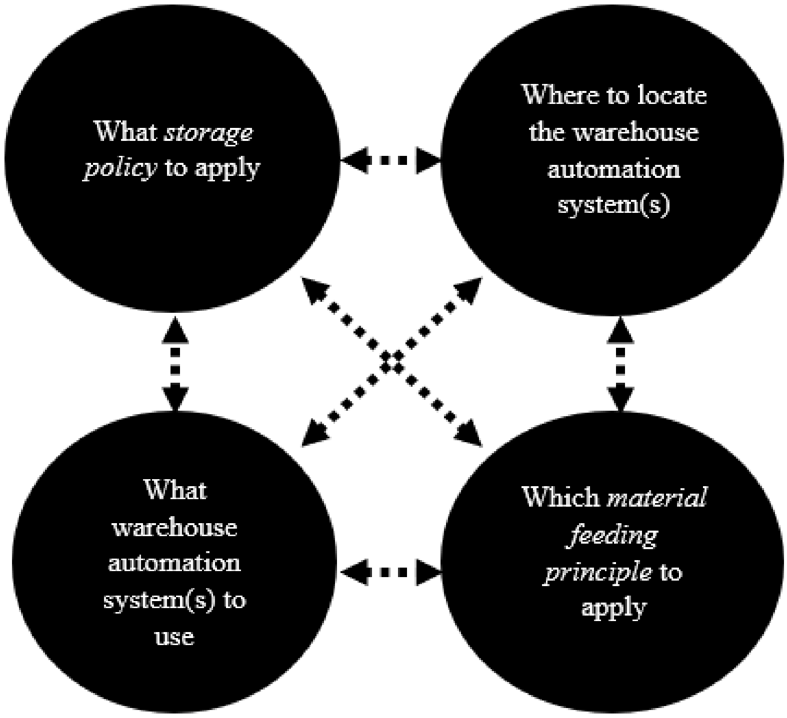

Figure 6.8: *A visualisation of the inter-dependencies between the recommendations about what warehouse automation system(s) to use, which material feeding principle to apply for each assembly line, what storage policies to apply , and where to locate the warehouse automation system(s).*

For example, if a warehouse automation system(s) is recommended to be located to the existing Centralized storage/Kitting area, in order to minimize inbound transports of purchased and externally treated components, this leads to kitting supply being the only viable materiel feeding principle to apply for the assembly lines being fed by these warehouse automation system(s). This since continuous supply or batch supply would create excessive load carrier handling considering the case company's production layout (see Section 6.1.1.1). Further, since kitting supply requires an operator to pick individual components from the warehouse automation system(s) (i.e., because automated kitting is not a realistic option considering the variety and characteristics of the components) the warehouse automation system(s) set up time, of retrieving load carriers being requested by the picking/kitting operator, must be short enough to allow all the components required to be picked, kitted, and transported to the assembly line within a time window corresponding to the fed assembly line's takt time (see Section 6.1.1.4).

6.3 The main recommendations - for a new internal material supply operation

In this subsection, the main recommendations for a new internal material supply operation, based on a higher level of automation, are developed and analysed. If these main recommendations are implemented, it will increase the case company's competitiveness, through supporting the defined mediating performance measurements (see Section 6.2.1) that supports the defined process Performance Objectives (see section 6.1.3), which in turn supports the case company's main KPIs employed (see Section 6.2.1). Further, these main recommendations consider the requirements imposed by the case company's Operations / Factory Environment and the Material Supply System, which are analysed in Section 6.1.1 and Section 6.1.2 respectively.

The main recommendations also consider the interdependence between the recommendations for what warehouse automation system(s) to use, which material feeding principles to apply for each assembly line, what storage policies to apply, and where to locate the warehouse automation system(s) within the facility. The primary characteristics of these main recommendations are summarized in Table 6.17. Further, an approximate production layout associated with the main recommendations is shown in Figure 6.9.

Table 6.17: *The primary characteristics of the main recommendations - for a new internal material supply operation.*

Assembly line	**Storage policy**	**Location of warehouse automation system(s)**	**Material feeding principle**	**Warehouse automation system(s)**
AAA:1	Centralized storage	The existing Centralized storage/Kitting area	Sequenced Kitting supply	**E-serie & F-serie: A single dedicated vertical carousels P-serie: Not used**
AAA:2	Centralized storage	The existing Centralized storage/Kitting area	Sequenced Kitting supply	**E-serie & F-serie: A single dedicated vertical carousels P-serie: Not used**
AAA:3	Centralized storage	The existing Centralized storage/Kitting area	Sequenced Kitting supply	**E-serie & F-serie: A single dedicated vertical carousel P-serie: Manual pallet racks**
BBB:1	Decentralized storage	At the BBB:1 assembly line	Continuous supply	**E-serie & F-serie: A single dedicated vertical carousel P-serie: Manual pallet racks**
BBB:2	Decentralized storage	At the BBB:2 assembly line	Continuous supply	**E-serie & F-serie: A single dedicated vertical carousel P-serie: Manual pallet racks**
CCC:1	Centralized storage	The existing Centralized storage/Kitting area	Sequenced Kitting supply	**E-serie & F-serie: A single dedicated vertical carousel P-serie: Not used**
DDD:1	Centralized storage	The existing Centralized storage/Kitting area	Sequenced Kitting supply	**E-serie & F-serie: A single dedicated vertical carousel P-serie: Manual pallet racks**

Figure 6.9: *Approximate production layout associated with the main recommendations. The recommended new common kitting area for the AAA:1, AAA:2, AAA:3, CCC:1 and DDD:1 will be located at the existing Centralized storage/Kitting area and will house five vertical carousels in total. The two vertical carousels that are dedicated for the BBB:1 respectively the BBB:2 will be located next to these two assembly lines (e.g., in the purple marked area labeled V.C.s BBB).*

6.3.1 Centralized storage policy and kitting supply for the AAA:1, AAA:2, AAA:3, CCC:1, and DDD:1 assembly line

The main recommendations, include that a centralized storage policy is applied for the AAA:1, AAA:2, AAA:3, CCC:1, and DDD:1 assembly line, where all warehouse automation systems storing components for these assembly lines will be located at the current Centralized storage/Kitting area. Locating the warehouse automation systems in the current Centralized storage/Kitting area, will minimize the inbound internal transport of load carriers that contain purchased and externally treated components. This, since such load carriers can directly be transported to the warehouse automation systems by personnel from the Goods receiving, without first having to be transshipped and/or moved to another location within the facility. Another benefit with locating the new common kitting area for the AAA:1, AAA:2, AAA:3, CCC:1, and DDD:1 assembly line at the current Centralized storage/Kitting area, is the direct access to the large central transport corridor (see Figure 6.3) that provides effective transport ways to the component manufacturing lines. For other benefits and drawbacks related to use the current Centralized storage/Kitting area as a centralized storage, see Alternative (1) in Table 6.2 .

In order to minimize the number of handling tasks per load carrier, a centralized storage policy is at the case facility best used in combination with kitting supply as material feeding principle, as described in Section 6.1.1.1. Further, to use kitting supply for the AAA:1, AAA:2, AAA:3, CCC:1, and the DDD:1 assembly line, is preferable also due to the characteristics of these assembly processes where there are many line items per finished product, as well as multiple sellable variants assembled that in many cases include components that are unique for the different variants, which increases the risk of picking errors. These characteristics makes continuous supply highly not recommended, both for space reasons at the assembly lines and due to the high risk of picking errors. Further, to use batch supply as material feeding principle for any of these assembly lines is not recommended, since it would require both primary and secondary storage locations in order to level the differences between inbound volumes of components to the facility and the consumption of components at the respective assembly line. Though, to apply kitting supply from a distant centralized storage for these assembly lines, does not mean that no components at all can be stored at the respective assembly line. Instead, it is recommended that small sized, high runner materials that are difficult to pick by mistake should be stored at the respective assembly line. In order to reduce the number of replenishment of such small high runner components, it is recommended that larger quantities of these are replenished at the same time. This will increase the average stored volume of these components, but since their unit costs are assumed to in most cases be low it will only have small effects on the average WIP inventory value.

Another type of materials that also are recommended to be stored at the respective assembly line, are materials that are used for compensating for tolerance levels in the component manufacturing, such as adjustment plates (i.e., “justerbleck” in Swedish) and spacers (i.e., “distansbrickor” in Swedish), which exists in multiple dimensions and which the demand for is unknown until a certain step in the assembly process. Accordingly, if these types of adjustment materials were to be kitted too, all sizes of each of these adjustment materials would have to be put into each kit while only a single or a few of them would actually be needed in the assembly process. This would create a lot of unnecessary material handling both in the kitting process and when the leftover materials, which were not needed in the assembly process, need to be returned to the distant kitting area.

Further, some large sized high-runner components, which are stored in few numbers in each load carrier, can be stored in manual racks next to the respective vertical carousel. This, since if such components are stored inside the vertical carousels the frequent replenishment needed for such components/load carriers may slow down the component picking/kitting operator too much. Further, the manual racks used for storing load carriers carrying these large sized high-runner component can be replenished by the Goods receiving personnel, in order to reduce the workload for the component picking/kitting operator. Also, storing these large sized high-runner components in manual racks next to the respective vertical carousel will also reduce the storage volume capacity requirements for each vertical carousel.

Regarding what warehouse automation systems to use, it is recommended that the AAA:1, AAA:2, AAA:3, CCC:1, and DDD:1 have a single dedicated vertical carousel each, at the new common kitting area. Though, a single vertical carousel does not refer to the number of vertical storage shafts, but instead to how the vertical carousel is operated. That is, two or more vertical storage shafts may be needed in order to store all components required, but in such cases all vertical shafts should be lined up in parallel, be coordinated and be operated simultaneously through a single display. This enables an increased component picking/kitting speed since multiple vertical storage shafts can present all, or most, of the components needed for a specific finished product or assembly batch, without having to change the horizontal storage shelf being displayed for the component picking/kitting operator.

The estimated likely number of load carriers being picked from per hour for these assembly lines (see Table 6.7), is far below the max capacity of about 400 line items picked per hour (equalling 400 required load carriers presented per hour) for the vertical carousel Megamat RS (see Section 5.3.2). In fact, the actual picking/kitting capacity at each vertical carousel can be expected to be even higher if the line items stored are effectively grouped by product. For example, by storing line items that often are picked at the same time, in the picking sequence at the same shelf within the vertical carousel will reduce the number of shelf changes required. Further, if it is not possible to store such line items on the same shelf within the vertical carousel, they should be stored in adjacent shelves to minimize the system internal retrieval times and consequently the kitting process time. In order to allow the best storage assignment solutions for the line items, this type of grouping by product should be performed with the use of optimization software. The much higher capacity of number of line items picked per hour in the vertical carousel Megamat RS than required, indicate an overcapacity with respect to throughput rate but will at the same time allow the component kitting operator to have more time for supporting activities like replenishing load carriers.

To use vertical carousels will create much higher space utilization, compared to the current situation, and allows large storage volumes while only occupying small floor areas. Further, to use separate vertical carousels allows the order picking process, as well as, the component replenishing process in each of these five assembly lines to be independent from one another. For example, no operator will have to wait for the operator from another assembly line to finish their component picking activities before being able to start their own component picking from the same vertical carousel. For the AAA:1 and AAA:2, which have comparatively high production paces, it is also recommended that each assembly line has a single dedicated vertical carousel, at the common kitting area, but the requirements for short kitting set up times, in order to reduce the total kitting process cycle time, is tougher for these vertical carousels. Though, by running multiple vertical storage shafts as a single vertical carousel allows reduction of the total set up time per assembly batch since all vertical storage shafts should be able to set up simultaneously. Further, it is recommended that personnel from the Goods receiving only places the full load carriers beside the vertical carousel where needed, while the kitting operator performs the actual replenishment into the vertical carousel. This will increase the workload on the kitting operator but can at the same time increase the effectiveness in the kitting process since the kitting operator never will be idle due to a vertical carousel being blocked by a replenishing operator from the Goods receiving. At the same time, having the kitting operator to perform the replenishment of load carriers is a way to utilize the idle time created by process time variability in the component picking/kitting process. Though, having the kitting operator to perform the replenishment of load carriers, will still require personnel from the Goods receiving to place the needed load carriers next to each vertical carousel in order to reduce the actual replenishment time required by the kitting operator. The very short distance (i.e., less than 20 meters) between the Goods receiving and the vertical carousels, in combination with having the kitting operator performing the actual replenishment of load carriers, will greatly reduce the need for personnel at the Goods receiving compared to the current state of the internal material supply operation.

The process of transporting load carriers, which contain in-house manufactured components, from the component manufacturing lines to the vertical carousel where needed ,will be of low complexity since transports are recommended to take place in the large central transport corridor (see Figure 6.9) and because every load carrier only needs to be unloaded next to the vertical carousel, not unloaded into it. The low complexity of this process of transporting load carriers, which contain in-house manufactured components, allows it to be performed by an AMR similar to the existing one being used for transporting kitting carts for the AAA:2 assembly line. Though, this would require adapted movable transport racks to be developed, which are compatible with both the load carriers and the selected AMR. The short distance between the Goods receiving and the new common kitting area for the AAA:1, AAA:2, AAA:3, CCC:1, and the DDD:1 assembly line makes the use of AMR(s) for internal transports of load carriers, containing purchased and externally treated components, unnecessary.

Since the P-serie load carriers imply completely different technical requirements on a vertical carousel compared to the much smaller E-serie and F-serie load carriers (see Section 6.1.1.3), it is recommended that the P-serie pallets that contain components for the AAA:3 and DDD:1 assembly line are stored in manual racks at the new common kitting area. This will allow all the vertical carousels used for the AAA:1, AAA:2, AAA:3, CCC:1, and the DDD:1 respectively, to be optimized for the E-serie and F-serie load carriers. Further, it is not recommended to increase the repackaging of components from P-serie load carriers into E-serie load carriers, in order to store them in the vertical carousels. This, since it would increase the material handling, but add little or no value for the component picking/kitting process. Instead the manual racks for the P-serie load carriers should preferably have adjustable picking heights in order to improve the ergonomic standards of the component picking/kitting processes.

6.3.2 Decentralized storage policy and continuous supply for the BBB:1 and BBB:2 assembly line

The main recommendations, include that a decentralized storage policy is applied for the BBB:1 and BBB:2 assembly line, in combination with continuous supply as material feeding principle. To use kitting supply for the BBB:1 and BBB:2 assembly line would be inefficient since the components required in the two assembly processes are highly standardized and are not easily wrongly picked. Further, to feed the highly automated assembly process at BBB:1 with component kits could even reduce the effectiveness in the assembly process. So, to use kitting supply, which is recommended for all other assembly lines in the facility, would imply time consuming kitting activities while only providing little or even negative value for the two assembly processes at the BBB:1 and BBB:2 assembly line. Neither it is recommended to use batch supply as material feeding principle, since it would require both primary and secondary storage locations in order to balance inbound volumes of components to the facility with the consumption of components at the respective assembly line (see Section 6.1.1.1). Hypothetically, it would be possible to perfectly match the inbound flow of components with the batch sequence at the assembly line, but this is not possible in this case, for example due to the inbound components being shipped in standardized unit loads that do not equal the batch sizes in the assembly processes. Accordingly if batch supply was applied, primary storage locations would be required for storing components during the time between arrival to the facility and until needed at the assembly lines.

The close distance for the BBB:1 and BBB:2 assembly line to the Goods receiving, as well as their locations next to the large central transport corridor (see Figure 6.2 and Figure 6.3), which have effective transport ways to the component manufacturing lines, make their locations favorable regarding minimizing internal transports and material handling. This, since purchased and externally treated components can be moved in unit loads, on the pallets shipped by the suppliers, directly from the Goods receiving to the two assembly lines without first having to be transshipped to another internal transport vehicle. The short distance from the Goods receiving to the two assembly lines also makes the inbound transports' contribution to internal traffic congestion small. Further, the BBB:1 and BBB:2 locations next to the large central transport corridor, which provide effective transport ways to the component manufacturing lines, allows effective coordination of transports of in-house manufactured components being designated for these two assembly lines with transports of in-house manufactured components being designated for the new common kitting area for the AAA:1, AAA:2, AAA:3, CCC:1, and the DDD:1 assembly line, which is recommended to be located in the start of the central transport corridor (see Figure 6.3). These coordination possibilities will increase the utilization rate of internal transport vehicles that transport in-house manufactured components and accordingly reduce the number of internal transports.

Regarding the warehouse automation systems, a single vertical carousel dedicated for the BBB:1 and BBB:2 each is recommended. Though as previously mentioned for the AAA and CCC:DDD, a single vertical carousel does not refer to the number of vertical storage shafts, but instead to how the vertical carousel is operated. That is, two or more vertical storage shafts may be needed in order to store all components required, but in such cases all vertical shafts should be lined up in parallel, be coordinated and be operated simultaneously through a single display.

Further, to use a separate vertical carousel for the BBB:1 and BBB:2 respectively, allows the order picking process, as well as, the component replenishing process in each of these two assembly lines to be independent from one another.

Even though the assembly pace is comparatively high a at the BBB:1, the estimated likely number of load carriers being picked from per hour for both the BBB:1 and BBB:2 assembly line (see Table 6.7) is far below the max capacity of about 400 line items picked per hour (equalling 400 required load carriers presented per hour) for the vertical carousel Megamat RS (see Section 5.3.2). As recommended for all the vertical carousels within the facility, the line items stored should be group by product. For example by storing line items, which often are picked together, in the picking sequence at the same shelf or at least adjacent shelves within the vertical carousel. As previously stated, such storage assignments of line items should be performed with the use of optimization software. Also for the BBB:1 and BBB:2 assembly line, the much higher capacity of number of line items picked per hour in the vertical carousel Megamat RS than required, indicate an overcapacity with respect to throughput rate but will at the same time enable the component picking operator to have more time for supporting activities like replenishing load carriers.

The technical requirements for the two vertical carousels, dedicated for the BBB:1 and BBB:2 respectively, should be adapted for the E-serie and F-serie load carriers and the higher assembly pace in the BBB:1 assembly line will require a larger storage space in its vertical carousel compared to the vertical carousel dedicated for the BBB:2. This since inbound components are not only delivered in small batches that perfectly corresponds to the near time needs.

Since both the BBB:1 and the BBB:2 uses components that are stored in P-serie load carriers, which imply completely different technical requirements on a vertical carousel compared to the F-serie and E-serie load carriers, it is recommended that the P-serie load carriers continue to be stored in manual racks next to the assembly lines. Further, it is not recommended to increase the repackaging of components from P-serie load carriers into E-serie load carriers in order to store them in the vertical carousels. Instead, especially at the BBB:1 it is recommended to continue to pick components directly from P-serie load carriers, being placed next to the assembly process' input point, and place these components directly into the assembly process. This, in order to minimize the material handling. Further, it is recommended that the manual racks used for storing P-serie load carriers should have adjustable picking heights in order to improve the ergonomic standards of the component picking processes.

6.3.3 The use of vertical carousels for all component picking/kitting processes

Since it is possible to install multiple vertical storage shafts in parallel and run them as a single unit (i.e., as a single vertical carousel), which increases the possible storage volume capacity, the vertical carousel can be used as warehouse automation system for all the seven assembly lines within the case facility. This, even though the storage volume capacity requirements differ a lot between the different assembly lines (see Table 6.11-6.12 for a very rough estimate). To some extent, this makes the vertical carousel scalable and allows adaption to changes in future storage volume capacity requirements since more vertical storage shafts can be added to each vertical carousel. Though, this will of course imply problems such as for the effectiveness of the storage assignment policies (i.e., all component storage locations within each vertical shafts may need to be reorganized in order to optimize each components location if an additional vertical storage shaft is added in parallel). Further, how the need for storage volume capacity is affected by a potential increase in end customer demand is difficult to predict since the case company can handle such an increased demand for input components by shortening the time between suppliers' replenishment (i.e., instead of increasing inbound batch sizes of components to the facility), which basically can make the storage volume capacity requirement unaffected by the increased end customer demand. Though, an increased end customer demand would still increase the throughput capacity requirements for the vertical carousels but since each vertical carousel can present about 400 needed load carriers an hour, which is much higher than the current needs, an increased end customer demand will not be a problem for the vertical carousels with respect to increased throughput capacity requirements.

To use vertical carousels as warehouse automation systems will enable short component picking/kitting times, as well as dramatically improve the ergonomic performance since most of the component picking/kitting will take place in an upright ergonomically advantageous work position, which can be expected to improve both the productivity and quality of the order picking/kitting processes due to reduced worker fatigue. Further, to use vertical carousels which have I/O points that are adjustable to each operator's preferred work height will further improve the ergonomic performances. Since more people will be physically capable of performing the order picking/kitting work tasks, the possible worker pool can also be expected to increase when improving the ergonomic performance of the internal material supply processes.

To only use a single type of warehouse automation system (i.e., vertical carousels), even though the storage volume will differ, will create economies of scale both in the purchasing process and in the operation phase (e.g., regarding operational knowledge/experience and in maintenance activities). In addition, to select vertical carousel models that have inbound and outbound points on the opposite sides will facilitate replenishment of load carriers, especially if flow racks are installed inside the carousels.

Regarding the technical expertise needed for operating a vertical carousel, it is comparatively low in relation to other types of warehouse automation systems. This means that it will be easier for the case company to get the expertise needed to operate them effectively, than if any of the more advanced warehouse automation systems are selected. If to bring that expertise required in-house, by recruiting own employees, or if to use external sources is up to the case company. Though, when optimizing the components' storage locations inside each vertical carousel, which requires considering both Bill-of-Materials as input in order to group by product and components/load carriers size and weight characteristics, will most certainly require external expertise within the area of storage optimization.

6.3.4 Strengths and weaknesses of the main recommendations

The strengths and weaknesses of the main recommendations are summarized in Table 6.18, with respect to how well the requirements imposed by the case company's Operations / Factory Environment, Material Supply system, and Performance Objectives, which all are defined in Section 6.1, are met by the main recommendations. Accordingly, also the consequences for the case company's internal material supply operation, of selecting the recommended warehouse automation system(s) for component storage, are summarized in Table 6.18.

Table 6.18: *Summarizes the strengths and weaknesses related to how well the requirements, which are defined in the first part of the Analysis (see Section 6.1), are met by the main recommendations. Accordingly, this table also summarizes the consequences for the internal material supply operation related to selecting the recommended Warehouse Automation Systems for component storage*

The main recommendations	
Performance Objectives	Strengths (+) and Weaknesses (-)
Quality: -Ability to create an exceptional high degree of OTIF-deliveries of the	(+) V.C.s are compatible with pick-by-voice and pick-by-light systems (+) V.C.s allow stored components to be group by

Continued on next page

Continuation of Table 6.18	
Performance Objectives	Strengths (+) and Weaknesses (-)
components required by the picking/ kitting operator -Ability to ensure Quality at the source by minimizing the risk for picking errors of components	product, which reduces the risk for picking errors (+) V.C.s are compatible with flow racks, which allows immediate replenishment of load carrier (+) To have a V.C. dedicated for each assembly line decouples the component picking/kitting processes, as well as the replenishing processes between the different assembly lines (+) Component picking/kitting operators will be responsible for the replenishment of load carriers (i.e., they will bear the consequences for their own replenishing mistakes) (+) V.C.s allow good ergonomic work postures, which improves quality in component picking/ kitting due to reduced worker fatigue (-) The use of several V.C.s in total, may increase the risk of mistakes in the replenishing processes (e.g., placing load carriers in the wrong V.C.)
Speed: -Fast load carrier handling -Fast replenishment of load carriers	(+) The use of several V.C.s in total allows rather small sized V.C.s, which reduce each V.C.'s retrieval times of load carriers (+) V.C.s will be optimized for the E-serie and F-serie load carriers that are small and lightweight, which allows fast handling speeds of load carriers by each V.C. (+) A V.C. can present multiple load carriers simultaneously, which reduces the component picking/kitting process time (+) Applying a dedicated storage assignment policy for most components, especially for high runner components that are often picked/kitted, will facilitate the picking/kitting operators' memorization and consequently increase the picking/kitting speed.

Continued on next page

Continuation of Table 6.18	
Performance Objectives	Strengths (+) and Weaknesses (-)
	(+) Using V.C.s allow stored components to be grouped by product, which reduces the component picking/kitting process times (+) That the Goods receiving will place load carriers just next to the V.C. where needed, will imply short replenishment times of load carriers by the component picking/kitting operators (+) V.C.s allows good ergonomic work postures, which improves the speed in component picking/ kitting due to reduced worker fatigue (-) The P-serie load carriers will be stored in seperate manual racks, which will require the component picking/kitting operators to relocate to these when needed, which will increase the component picking/kitting process time. (-) Each V.C (or at least most V.C.s on the market) only has a single I/O point, which makes it difficult to effectively use several component picking/kitting operators simultaneously to improve the picking speed at demand peaks.
Dependability: -Ability to ensure low process time variability in the picking/kitting processes -Ability to ensure low process time variability in the replenishing processes	(+) To use a V.C. for each assembly line reduces the consequences at breakdown/stop of a V.C., since only a single assembly line then will be affected by component shortage. (+) To have V.C.(s) dedicated for each assembly line decouples the component picking processes, as well as, replenishing processes of the different assembly lines, which will reduce the component picking/kitting process time variability for all assembly lines compared to if a common warehouse automation system is used. This since a component picking/kitting operator never will block a component picking/ kitting operator being dedicated for another assembly line.

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Continuation of Table 6.18	
Performance Objectives	Strengths (+) and Weaknesses (-)
	(+) The use of several V.C.s in total allows rather small sized V.C.s, which reduces each V.C.'s retrieval times of load carriers since the system internal retrieval distances become shorter that in turn will create lower process time variability calculated in absolute numbers. (+) Having the component picking/kitting operator performing the actual replenishment of load carriers in the V.C, which can be performed when the operator otherwise would be idle, reduces the risk of process time variability in the component picking/kitting processes caused by the component picking/kitting operator being blocked by Goods receiving personnel replenishing load carriers. (+) Having the component picking/kitting operator performing the actual replenishment of load carriers in the V.C, will reduce the process time variability for the load carrier handling processes at Goods receiving, since the Goods receiving personnel do not need to wait for a component picking/kitting operators to finish assigned work task before getting access to the V.C. Instead, in the main recommendations the Goods receiving personnel places the full load carriers next to the V.C. where needed. (+) V.C.s allows good ergonomic work postures, which reduces worker fatigue and therefore lowers variability in quality and speed in the component picking/kitting processes
Flexibility: -Ability to ensure a high degree of delivery, range and volume flexibility	(-) The internal material supply processes range flexibility will be restricted since each V.C. is limited to only being able to handle E-serie and F-serie load carriers, as well as other smaller packages. This forces the component picking/kitting operator to relocate to manual racks, which contain the P-serie load carriers, when components stored in these are needed. (-) The internal material supply process response flexibility will be restricted since a dedicated storage assignment policy is recommended for most components, especially high runners that are often picked/kitted.

Continued on next page

Continuation of Table 6.18	
Performance Objectives	Strengths (+) and Weaknesses (-)
	This since the static locations for each component, caused by dedicated storage policies, facilitates the component picking/kitting operators' memorization and accordingly increases the picking/kitting speed, as well as reduces the risk of picking errors. Though, a random storage assignment policy can be applied for low runner components, which are rarely picked, in order to increase the utilization rate of the storage space in each V.C. (+) The internal material supply process delivery flexibility will be increased by the V.C.s short retrieval times for load carriers, which allows the load carriers being presented for the component picking/kitting operator to be changed in only a few seconds. (-) The internal material supply process volume flexibility will be restricted since the storage capacity in each V.C. is completely restricted and is impossible to stretch.
Ergonomics: -Ability to minimize manual lifting and carrying, manual pushing and pulling, as well as manual handling of low loads at high frequency	(+) There exists V.C.s on the market with I/O points that are adjustable to the operator's preferable work height, which can reduce the long term negative effects of manual work (+) V.C.s I/O points are compatible with the existing load carrier lifts, which removes the need for manual lifting and carrying of load carriers (+) Having the component picking/kitting operator to perform the actual replenishment of load carriers facilities for transports of in-house manufactured components from the component manufacturing lines to each V.C. to be performed by an AMR, which reduces the need for manual pushing and pulling. (-) The P-serie load carriers cannot be stored in the V.C.s, which will require the component picking/kitting operator to pick from manual pallet racks that may not provide an ergonomically beneficial work posture. (-) All components must be picked/kitted from each V.C. manually by operators, which requires work tasks involving low loads at high frequency, especially at the V.C.s for the BBB:1, AAA:1, and AAA:2 where the picking/kitting work pace

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Continuation of Table 6.18	
Performance Objectives	Strengths (+) and Weaknesses (-)
	will be comparatively high.
Storage volume: -Ability to provide the storage volume required	(-) The utilization rate of the V.C.s' storage volume is reduced since a dedicated storage assignment policy is recommended for most components, in order to facilitate component picking/kitting operators memorization and in turn increase the picking/kitting speed as well as reduce the risk for picking errors. (+) The utilization rate of the V.C.s' storage volume is increased since a random storage assignment policy can be applied for some low runner components, which are rarely picked. (+) Multiple vertical storage shafts can be lined up in parallel, be connected, and be operated as a single vertical carousel (-) The possibility of using the V.C.s for overstocking of components (e.g. before the summer leave period) is limited, since the V.C.s' storage volume is recommended to be fitted for normal storage volumes. This to avoid an average overcapacity. (+) The use of V.C.s increases the utilization of the facility's high roof ceiling, which will free up floor space that currently is occupied by flow racks. (+) The floor space being freed up by the use of V.C.s can be used for overstocking components before the summer leave period. This includes the freed up floor space at the AAA:3, CCC:1 and DDD:1, but also at the existing Centralized storage /Kitting area where the new common kitting area for these assembly lines will be located. Also, at the BBB:1 and BBB:2 it can be expected to be freed up floor space even though two V.C's are recommended to be installed there.
Compatibility -with the existing material supply system:	(-) Requires a major reorganization of the existing Centralized storage/Kitting area, in order to make space for the new V.C.s and the manual racks for the P-serie load carriers.

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Continuation of Table 6.18	
Performance Objectives	Strengths (+) and Weaknesses (-)
	(-) Requires a major reorganization at the BBB:1 and BBB:2 assembly line, where the current flow rack system will be replaced by two V.C.s. (+) No major reorganization required at the AAA:3, CCC:1, and DDD:1, since no new major equipment will be installed at these three assembly lines, though space must be made for the new kitting carts that will be necessary. Preferable, this is done by removing most of the existing flow racks, which will not be required anymore. (-) The material feeding principle for the AAA:3, CCC:1, and DDD:1 will be adjusted to kitting supply at a centralized storage, which probably will create implementation issues. (+) V.C.s I/O points are compatible with the existing load carrier lifts, which removes the need for manual lifting and carrying of load carriers.
End of Table 6.18	

6.3.5 Possible but not recommended alternatives

In this subsection, are possible but rejected alternatives for the main recommendations provided. First are possible but rejected general storage policies brought up. Thereafter are possible but rejected material feeding principles explained, followed by a description of possible but rejected warehouse automation system alternatives.

6.3.5.1 Rejected general storage policies

To fully apply Alternative (1), where the storage for all assembly lines are located at the Centralized Storage/Kitting area, is possible but not recommended since it would create congestion at this area and would create an underutilized empty floor, at the BBB:1 and BBB:2 assembly line, that has very good transport connections from both the Goods receiving and from the manufacturing component lines. See Table 6.2, for more benefits and drawbacks with applying Alternative (1).

To use the Maintenance area, between the AAA:2 assembly line and the Shipping area (see Alternative (2)), is possible but not recommended since it would imply congestion and ineffective transports of inbound load carriers, especially those being transported from the components manufacturing lines. See Table 6.3, for more benefits and drawbacks with applying Alternative (2).

It is possible for the case company to implement a fully decentralized storage policy for all assembly lines (see Alternative (3)). Though, this would continue the excessive load carrier handling within the facility and accordingly continue to require a lot of manual work hours. Further, if Alternative (3) is combined with warehouse automation systems, the different types of systems possible to install would be very limited due to the lack of available floor space at the assembly lines. See Table 6.4, for more benefits and drawbacks with applying Alternative (3).

Installing vertical carousels for Alternative (PFSL) would be a good alternative that provides similar benefits and drawbacks as the main recommendations. The major differences between the main recommendations and the Alternative (PFSL) are about transport of finished products that is out of the scope of this thesis. Still, if Alternative (PFSL) are to be implemented in combination with vertical carousels, which would be recommended, most of the strengths and weaknesses of the main recommendations described in Table 6.18, will be valid for Alternative (PFSL) as well. See Table 6.6, for more benefits and drawbacks with applying Alternative (PFSL).

6.3.5.2 Rejected material feeding principles

It would be possible to continue with the current material feeding principle for each assembly line, but this is not recommended since the AAA:3, CCC:1 and DDD:1 assembly lines are characterized by either a high number of sellable product variants assembled or a high number of input line items per finished product, which makes them suitable for centralized kitting supply, as described in section 6.1.2.1. Further, as described in section 6.1.2.1, kitting supply is the recommended material feeding principle if warehouse automation systems are installed at the existing Centralized storage/Kitting area, which is suggested in the main recommendations.

For the BBB:1 and BBB:2 it would be possible to implement kitting supply as well, but as described in section 6.1.2.1, this is not recommended since there are few line items per finished product, the components are highly standardized and are not easily wrongly picked, as well as due to the high rate of automation in the BBB:1 assembly process.

6.3.5.3 Rejected warehouse automation system alternatives

Horizontal carousel is another type of warehouse automation system which could be used effectively on current storage requirements in terms of maximum weight of load carriers in the E-series. However this horizontal carousel system by design requires a large floor space, at least in length ranging from 5.9 meter to 46 meter, for effective storage capacity. Moreover in the horizontal carousel system, the maximum height ranges from 2.2m to 3.5m that would imply under utilization of the available vertical space in the facility. The height and length requirement of a horizontal carousel makes it suitable for rooms up to three metre in height. Thus the current limitation in the facility floor space availability and excess available height could undermine the overall performance of the horizontal carousel. Further in terms of storage units, horizontal carousel is suitable for an environment with SKUs of approximately 2000 to 3500 line items (refer figure 5.1). This is inline with the case company's current situation of 2092 component line items, however storing all these line items in a single centralized storage system might negatively impact the picking process time at peak demand. Also considering the decentralized storage recommendation for the BBB:1 and BBB:2 assembly line, installing a horizontal carousel only for these two assembly lines may lead to under utilizing of the available facility space.

Miniload AS/RS is another possible solution, especially lower versions such as market-available Dematic Rapidstore ML10/ML14/ML20. These versions can handle a maximum weight of 50 Kg per load carrier, which is just above the maximum weight of E-series and makes this suitable for these light weighted load carriers. Further this storage system can accommodate different types and sizes of load carriers as other major storage systems. Miniload AS/RS are suitable for SKU ranging between 3500 and 5500 line items approximately (refer figure 5.1). Considering the recommended centralised storage strategy for AAA and CCC:DDD assembly lines, the number of line items associated with these assembly lines are still lesser than the suitable SKUs. However the minimum height of the miniload AS/RS (Dematic Rapidstore) starts from 10m and ranges up to 20m, which is limited by the available height in the case facility to consider for storage. Swisslog Tornado is another market available, miniload AS/RS, which starts from 5m height, but to match the storage capacity as Dematic Rapidstore system this may require more floor space. Further the throughput capacity (i.e picks per hour), is very low compared to other systems since only one crane could be used in each aisle for retrieving. This is since the available space within the case facility restricts the possibility to have multiple aisle and multiple cranes for simultaneous operation for higher throughput.

Shuttle based AS/RS throughput is as high as 2000 order lines per hour, but depends on the number of shuttles used and the rack system design. Currently the available space in the case facility will impact the number of shuttles that can be used and the rack system design such as single deep storage or double deep storage and may lead to lower storage capacity. Autostore (Swisslog) AGV is another system which also has a high pick rate(i.e 1000 picks per hour), in an ideal condition when combined with picking robots. These throughput rates are relatively high compared to current requirements and makes this system an over capacity. However this system has standardised load carrier sizes which limits the adaptation to current case company's requirements of E-series and F-series. Moreover this system is suitable for a very high number of SKU such as 20000 line items approximately (refer figure 5.1) in a conventional warehouse or consolidation centres, where the probable picking rate could be approximately 1000 per hour, as compared to case company's requirement of 2092 line items.

Vertical lift module (VLM) is an another potential solution which is very similar to the vertical carousel. One of the advantages of the VLM is that it allows sensor-controlled dynamic storage, but the main recommendations for the case company to store the standardized and similar sized load carriers (i.e, the E-serie and F-serie) inside the warehouse automation systems reduces the advantages of the dynamic storage capability. This since the storage shelves height in the VC can be adapted to these standardized load carriers beforehand. Further, the VLM is due to its vertical transport shaft more deep than the VC, which makes a VLM occupy more floor space than a VC with the same storage volume capacity, which is clearly a disadvantage considering the strictly limited available floor space at the case facility. Further, the maximum throughput of a VLM is slight lesser (i.e, about 350 load carriers per hour as compared to about 400 load carriers per hour in vertical carousel (VC)), which makes it less adaptable to future increases in demand. Also, the VLM is not possible to run manually as many VCs are, which will be a great disadvantage if the power supply for the VLM for some reason breaks down. Though, a potential advantage with the VLM, compared to the VC, is that some VLMs can move the presented storage platform closer to the component picker, as well as tilt the platform towards the picking operator to facilitate the picking of components.

The alternative to skip installing warehouse automation systems for the different assembly lines will reduce the productivity and quality in the picking/kitting processes, compared to the main recommendations, due to the often non ergonomic work postures that currently is required by the picking/kitting operators. Further, to skip installing warehouse automation systems would reduce the potential picking/kitting speed, compared to the main recommendations, since picking/kitting from manual racks cannot over time be performed as fast as picking/kitting from a vertical carousel that have components grouped by product. Further, to skip installing warehouse automation systems for all assembly lines will make it more difficult for the company to reach the performance objectives defined in Section 6.1.3. In addition, for the case company top keep the existing low level of automation of its internal material supply operation would constrain the possibility to reduce the need for manual work tasks and accordingly all risks and costs related with such activities.

7
Conclusion

In Chapter 1 - Introduction, it is explained that the purpose of this master's thesis is to explore how the case company can improve its internal materials supply operation, by increasing the level of automation of the component storage systems. This includes identifying and analysing important requirements that should be considered by the case company when selecting warehouse automation system(s) for component storage. Further, the purpose of this master's thesis also includes to provide recommendations for what type of warehouse automation system(s) for component storage the case company should select. In addition, the purpose includes identifying and analysing the consequences for the case company's internal material supply operation of selecting the recommended warehouse automation system(s) for component storage.

The purpose of this master's thesis has been reached by providing answers for the research questions that were defined as:

RQ1: What are important requirements for the case company to consider when selecting warehouse automation system(s) for component storage?

RQ2: What type of warehouse automation system(s) for component storage are recommended for the case company to select?

RQ3: What are the consequences for the case company's internal material supply operation of selecting the recommended warehouse automation system(s) for component storage?

It is concluded that the case company's internal material supply operation is characterized by multiple material supply methods for the seven assembly lines. For example, different types of: storage policies (i.e, centralized and decentralized storage); material feeding principles (i.e. kitting supply and continuous supply), storage assignment policies (i.e., dedicated and random storage); material replenishment methods (i.e., Physical Kanban card, Physical M-card, Two-bin systems, ERP controlled); packaging and unit loads (e.g. standardized EUR boxes and pallets); as well as different sorts of handling and transport equipment (e.g., tug trains, load carrier lifts, pallet jacks, etc.), are utilized within the case company's facility.

Regarding the answer for RQ1, it is concluded that there are multiple important requirements for the case company to consider when selecting warehouse automation systems (see Figure 7.1). This includes requirements imposed by the Operations / Factory Environment, such as: the Production layout; Manufacturing strategies applied; Characteristics of demand (i.e., the Four Vs: Volume; Variation; Variability; and Visibility) that differ between the seven assembly lines; as well as the Characteristics of the assembly lines. Further requirements ,the case company should consider when selecting warehouse automation systems, are imposed by the Material Supply System, mainly the Material feeding principles; Handling equipment; Storage systems; Packaging and unit loads; and Replenishment methods utilized. In addition, there are requirements imposed by the Performance objectives for the internal material supply processes, with respect to requirements for Quality, Speed, Dependability, Flexibility and Ergonomics, which all should be considered by the case company when selecting warehouse automation systems for component storage.

Regarding the answer for RQ2, it is concluded that the warehouse automation system(s) that best meets the requirements, which were identified by answering RQ1, is the Vertical carousel. Further, in order to meet all the identified requirements for the selection of warehouse automation system(s), it is recommended that each of the seven assembly lines are supported by a single Vertical carousel each. Though, a single Vertical carousel can consist of multiple vertical storage shafts that are lined up in parallel, connected, integrated and are operated as a single unit (i.e., a single Vertical carousel). There exists Vertical carousels in many variants and these can be adapted for each of the assembly line's needs, while also taking advantage of the high roof ceiling within the case company's facility.

Regarding the answer for RQ3, it is concluded that there are several consequences for the case company's internal material supply operations of selecting the recommended warehouse automation systems. For example, several of the vertical carousels will be located at distance from the respective supported assembly line that, in this case, basically removes the possibility of applying any other material feeding principle than centralized kitting supply for these assembly lines. Two reasons for this, is the objective to minimize the number of handling tasks of each load carrier (i.e., waste) and the case company's desire to only store each line item at a single location within the facility. Though, also the characteristics of these assembly lines and the input components used, makes kitting supply the recommended material feeding principle for these assembly lines (i.e., independent of the localisation of the vertical carousels). For two of the assembly lines, are the vertical carousels recommended to be located next to the respective supported assembly line. Two reasons for this, is the characteristics of these two assembly lines and the input components used that makes continuous supply the recommended material feeding principle to apply, which in turn requires the vertical carousels to be located next to the respective supported assembly line. This, also in order to minimize the number of handling tasks of each load carrier and the case company's desire to only store each line item at a single location within the facility. Another reason for the vertical carousels to be located next to these two supported assembly lines are the locations' excellent transport connections to both the goods receiving and the internal component manufacturing lines, where inbound component deliveries are made from. Further, the need for manual handling of load carriers will be dramatically reduced, which in turn is expected to reduce the need for manual work hours performed by the goods receiving personnel that currently performs a lot of the load carrier handling. In addition, the internal material supply processes will be more compatible with AMRs, used for load carrier transports, which can be expected to additionally reduce the need for manual work hours related to manual load carrier handling.

In summary, it is concluded that the case company's competitiveness will be strengthened by the selection of Vertical carousels, as warehouse automation systems used for component storage, since these best meet the requirements, which are imposed by the case company's internal and external environment, for high performing internal material supply processes.

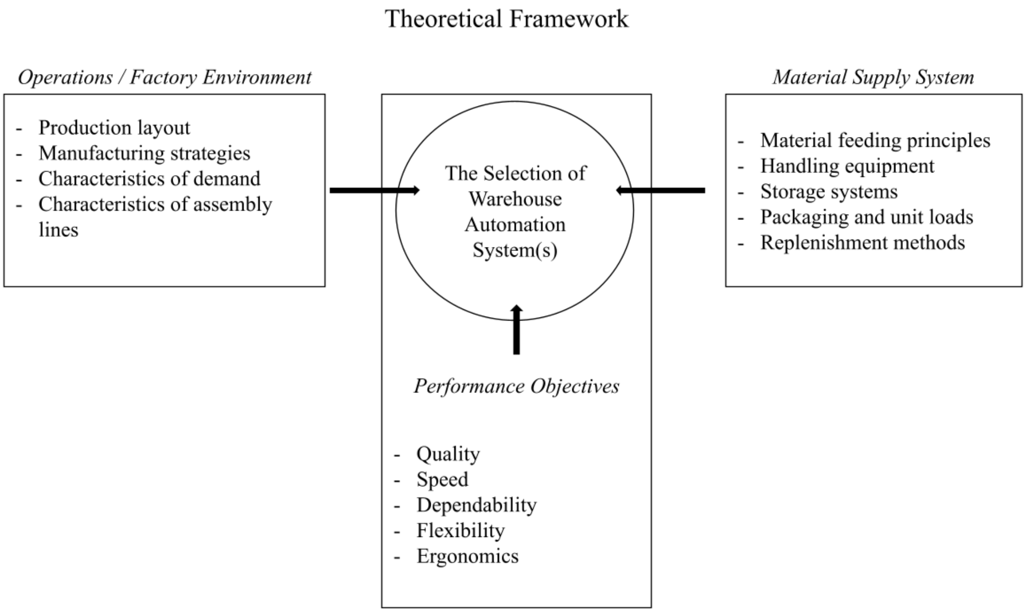


Figure 7.1: *The Theoretical Framework (see Chapter 3), which is applied on the Empirical data (see Chapter 4) in the Analysis (see Chapter 6).*

8

Discussion

The findings presented in Chapter 6 - Analysis show the case company's overall performance will be improved by increasing the level of automation of the internal material supply operation, by selecting vertical carousels as component storage for each assembly line. This, since the vertical carousels and the related internal material supply methods will have positive effects on several inter-mediating performance measurements, which in turn have positive effects on the case company's main KPIs. A major strength of the findings in this thesis, is that the analysis considers the characteristics of end customer demand, through its influence on the assembly processes. This has allowed the company's overall business objective to satisfy end customer needs, to influence the requirements for the selection of warehouse automation system(s). Further, the robustness of the findings in the analysis is high in that sense that the main recommendations provided are valid even if the annual volume of sold products will vary, which it undoubtedly will due to general changes in the macro economic sentiment. The robustness of the findings comes from the main recommendations high compliance with the requirements for the selection of warehouse automation system(s) that are defined in the first part of the analysis. This means that the defined requirements must change rather dramatically before affecting the conclusions about what warehouse automation system(s) that are most beneficial for the case company to select.

The findings presented in the Analysis are highly case specific in that sense that the empirical data, which the findings are based upon, are unique for the case company's situation. Though, the comprehensive theoretical framework that are applied in the Analysis, can be used by basically any manufacturing company that needs decision support when selecting warehouse automation system(s) for component storage. A specific finding in the Analysis that is perceived to be highly generalizable, is that the use of vertical carousels can rather dramatically improve the ergonomic aspects of component picking/kitting procedures compared to if manual racks are used. As pointed out in Chapter 3 - Theoretical Framework, a higher level of ergonomic performance do not only create a better work environment but also increases productivity and quality of the work tasks performed. Accordingly, when any manufacturing industry participant plans to developed an internal material supply operation within a constrained facility space, it is recommended that the vertical carousel is considered in the evaluation process. Though, as shown by the comprehensiveness of this thesis, there are many aspects for a manufacturing company to consider when selecting warehouse automation system(s) for component storage. So, that vertical carousels are the type of warehouse automation system that best fulfills the performance requirements imposed in this specific case, does not mean that vertical carousels always are the best alternative for component storage.

Another finding that is perceived to be highly generalizable is the inter-dependence between the decisions about: What warehouse automation system(s) to use; Which material feeding principle to apply; Where to locate the warehouse automation system(s); and What storage policy to apply. Accordingly, the inter-dependence between these internal material supply decision should be considered simultaneously by any manufacturing company, in a similar context, that plans to make a change to their internal material supply operation regarding any of these decisions. Also, another finding perceived to be generalizable is that the use of warehouse automation systems that are based on vertical storage technique, such as the vertical carousel, may allow consolidating the storage locations that in turn may reduce the amount of internal transports needs. This, due to both reduced internal transport distances, as well as due to increased possibilities to co-ordinate internal material transports.

Both the reliability and validity of the findings in the analysis are high, due to the high reliability and validity of the empirical data used and because of the comprehensiveness of the theoretical framework applied. The comprehensiveness of the theoretical framework has enabled an equally comprehensive analysis, which should be valuable for the case company even if it finally decides that another solution than the main recommendations provided in this thesis should be implemented. One reason for why the case company could end up choosing another type of warehouse automation system(s) for component storage, is that the direct financial aspects related to investment, implementation, operation, maintenance, and liquidation have not been covered in the analysis. Consequently, for the case company to also consider direct financial aspects may lead to another type of warehouse automation system finally being selected. Though, since any selected warehouse automation system(s) will have a major impact on the performance of the supported assembly processes, which in turn have major impact on the end customer satisfaction, the case company should be very careful to allow short term financial goals to hinder solutions that best meets the requirements that are defined in this thesis.

As desired by the case company, the main recommendations will reduce the need for multiple storage locations for each line item and consequently reduce the need for M-card handling. Though, due to the large component inventory build up before each summer, it is expected that some areas being freed up at the Centralized storage/Kitting area and at assembly lines will have to be used for overstocking. Since the need for the existing flow racks will be heavily reduced, or even eliminated, these freed up areas can be used for such summer overstocking needs.

Before looking into how to implement the main recommendations, the first step for the case company is to make a highly detailed analysis of: exactly which components to store in the vertical carousels; which small sized high-runner low-value components to store at the assembly lines (e.g., using two-bin systems); and which high-runner large sized components to store in manual flow racks next to each vertical carousel. This job will be resource consuming and will require a lot of attention from the production technicians at each assembly line, which probably have the best knowledge about what component type to store where. Next the case company, should acquire/secure competences within storage assignment optimization since this will be crucial for an effective group by product implementation.

Further, to facilitate implementation of the main recommendations provided in the analysis, the case company could start to implement the recommendations for the AAA:1 and AAA:2 assembly line. This since the kitting procedure for these two assembly lines already fully takes place in the Centralized storage/Kitting area, which will reduce some implementation issues that can be expected to occur. For example, it can be expected to occur massive congestion in the Centralized storage/Kitting area if the existing kitting procedures for the AAA:1 and AAA:2 are supposed to continue to take place within that area at the same time as vertical carousels designated for other assembly lines are being installed at the same location. In addition, successive implementation of the main recommendations will allow the case company to gain valuable knowledge and experience that can be used when implementing the main recommendations for the other assembly lines.

To further improve the performance of the internal material supply processes, the case company should replace the physical Kanban cards with electronic Kanbans (E-Kanban) that are integrated with the ERP system. This would remove the risk of Kanban cards disappearing and also allow real time signaling for replenishment needs. This can be extra valuable if AMRs are implemented for load carrier transport tasks, between the component manufacturing lines and the different vertical carousels, since there would be no need for physical handling of Kanban cards if E-Kanbans are implemented. If possible, it could also be beneficial if the number of E-Kanban collaborations with external suppliers are increased, since this could reduce the component storage capacity requirements and the average component inventory levels.

Regarding the case company's early plans of a more radical change of the production layout, in this thesis referred to as Alternative PFSL, most of the benefits and drawbacks related to the main recommendations in the analysis are valid also for this potential future state layout. This since the planned common kitting area, associated with Alternative PFSL, are located just next to the existing Centralized storage/Kitting area, where the vertical carousels for all but two assembly lines are suggested to be located according to the main recommendations. The major differences between the main recommendations in the analysis and the Alternative PFSL consider transports of finished products, which is out of the scope of this thesis.

Regarding sustainability, the research methods applied in this master's thesis project have not had any negative impact on either ethical, societal, nor ecological aspects for any stakeholder or third party. Regarding the outcome of this master's thesis project, there may instead be some positive consequences regarding sustainability for the operators at the case company's facility. This, since the work environment can be expected to be improved if the main recommendations provided in this thesis are implemented. For example, since implementing the main recommendations will improve the component picking/kitting operators' work posture during the component picking/kitting procedures, which is expected to reduce worker fatigue and related negative long term consequences of bad work postures.

References

Antunes, D.S.L., Sousa, S., & Nunes, E.P. (2013). Using Project Six Sigma and Lean Concepts in Internal Logistics. *Proceeding of the World Congress on Engineering 2013*, Vol I, WCE 2013, July 3-5, 2013, Imperial College London, London, U.K.

Azadeh, K., de Koster, R., & Roy, D. (2019). Robotized and automated warehouse systems: Review and recent developments. *Transportation Science*, Vol. 53, No. 4, pp. 917-945.

Bagadia, K.(1985). "Definitions and classifications", In: Kulwiec, R.A. (ed.) Materials handling handbook, 2nd ed. John Wiley Sons, New York. Ch.4.

Baines, T. (2004). An integrated process for forming manufacturing technology acquisition decisions, *International Journal of Operations & Production Management*, Vol. 24, No. 5, pp. 447-467.

Baudin, M. (2002). Lean Assembly: The Nuts and Bolts of Making Assembly Operations Flow. CRC Press, Boca Raton, FL.

Baudin, M. (2004). Lean Logistics: The nuts and Bolts of Delivering Materials and Goods. CRC Press, Boca Raton, FL.

Bennett, D. J., & Forrester, P. L. (1993). Market-focused production systems: design and implementation. Prentice Hall International, Hoboken, NJ.

Blackstone John, H., & Cox James, F. (2004). American Production and Inventory Control Society. APICS, Inc., Falls Church, VA, USA.

Boysen, N., Fliedner, M., & Scholl, A. (2007). A classification of assembly line balancing problems. *European Journal of Operational Research*, Vol. 183, No. 2, pp. 674-693.

Boysen, N., Fliedner, M. & Scholl, A. (2008). Assembly line balancing: Which model to use when?. International Journal of Production Economics, Vol. 111, No. 2, pp. 509-528.

Bozer, Y. A. & McGinnis, L. F. (1992). Kitting versus line stocking: A conceptual framework and a descriptive model. *International Journal of Production Economics*, Vol. 28, No. 1, pp. 1-19.

Brynzér, H., & Johansson, M. I. (1995). Design and performance of kitting and order picking systems. *International Journal of production economics*, Vol. 41, No. 1-3, pp. 115-125.

Bukchin, Y. & Meller, R. D. (2005). A space allocation algorithm for assembly line components. *IEE Transactions*, Vol. 37, No. 1, pp. 51-61.

Cardarelli, E., Digani, V., Sabattini, L., Secchi, C., & Fantuzzi, C. (2017). Cooperative cloud robotics architecture for the coordination of multi-AGV systems in industrial warehouses. *Mechatronics*, Vol. 45, No. 1, pp. 1-13.

Caplice, C. & Sheffi, Y. (1995) - A Review and Evaluation of Logistics Performance Measurement Systems. *The International Journal of Logistics Management*, Vol. 6, No. 1, pp. 61-74.

Caputo, A. C., & Pelagagge, P. M. (2011). A methodology for selecting assembly systems feeding policy. *Industrial Management & Data Systems*, Vol. 111 No. 1, pp. 84-112.

Caputo, A.C., Pelagagge, P.M. & Salini, P. (2015). A model for kitting operations planning. *Assembly Automation*, Vol. 35 No. 1, pp. 69-80.

Ceroni, J. A. (2009). Economic Rationalization of Automation Projects, in Nof, S. Y. (Ed.), Springer Handbook of Automation, pp. 699-714, Springer, Berlin, Heidelberg.

Crandell, R. E. & Burwell, T. H. (1993). The effect of work-in-progress inventory levels on throughput and lead times. *Production and Inventory Management Journal*, Vol. 34, No. 1, pp. 6-10.

Cruz Di Palma, R. J. & Basaldúa, M. S. (2009). Production, Supply, Logistics and Distribution in Nof, S. Y. (Ed.), Springer Handbook of Automation, pp. 947-960. Springer, Berlin, Heidelberg.

Custodio, L., & Machado, R. (2020). Flexible automated warehouse: a literature review and an innovative framework. *The International Journal of Advanced Manufacturing Technology*, Vol. 106, No. 1, pp. 533-558.

Daim, T. U. & Kocaoglu, D. F. (2008). Exploring technology acquisition in Oregon, Turkey and in the U.S. electronics manufacturing companies, *Journal of High Technology Management Research*, Vol. 19, No. 1, pp. 45-58.

Dallari, F., Marchet, G., & Melacini, M. (2009). Design of order picking system. *The international journal of advanced manufacturing technology*, Vol. 42 No. 1-2, pp. 1-12.

Dekker, R., de Koster, M. B. M., Roodbergen, K. J., & van Kalleveen, H. (2004). Improving order-picking response time at Ankor's warehouse. *Interfaces*, Vol. 34, No. 4, pp. 303-313.

de Koster, R., Roodbergen, K. J., & Van Voorden, R. (1999). Reduction of walking time in the distribution center of De Bijenkorf. In New trends in distribution logistics (pp. 215-234). Springer, Berlin, Heidelberg.

de Koster, B. M., & van de Velde, S. L. (2002). Linking warehouse complexity to warehouse planning and control structure: An exploratory study of the use of warehouse management information systems. *International Journal of Physical Distribution & Logistics Management*, Vol. 32, No. 5, pp. 381-395.

de Koster, R., Le-Duc, T., & Roodbergen, K. J. (2007). Design and control of warehouse order picking: A literature review. *European journal of operational research*, Vol. 182, No. 2, pp. 481-501.

Dematic. (n.d). Dematic RapidStore ASRS. [Brochure]. Retrieved from: `http://www.warehouse-logistics.com/Download/Flyer/EN_Flyer_Produkt_Dematic_WMS_003.pdf`.

Devaraj, S., Hollingworth, D. G., & Schroeder, R. G. (2004). Generic manufacturing strategies and plant performance. *Journal of Operations Management*, Vol. 22, No. 3, pp. 313-333.

Durrani, T. S., Forbes, S. M., Broadfoot, C. & Carrie, A. S. (1998). Managing the technology acquisition process, *Technovation*, Vol. 18, No. 8/9, pp. 523-528.

Dörnhöfer, M., Schröder, F., & Günther, W. A. (2016). Logistics performance measurement system for the automotive industry. *Logistics Research*, Vol. 9, No. 1, pp. 1-26.

Engström, T., Jonsson, D., & Medbo, L. (1996). Implications for improving the flexibility of the external material flow system based on theories and experiences from transforming the assembly line. *Unpublished draft*. 1996, CH. 3-6, pp. 1-9.

Engström, T., & Karlsson, U. (1982). Alternativ montering. *Institute for Management of Innovation and Technology*, Göteborg (in Swedish).

ERP 1. (2021). Oracle JD Edwards World Documentation Release A9.4. Retrieved from:"`https://docs.oracle.com/cd/E59116_01/index.htm`"

ERP 2. (2021). JD Edwards World Advanced Warehouse Management Guide. Retrieved from:"`https://docs.oracle.com/cd/E59116_01/doc.94/e58759/toc.htm`"

ERP 3. (2021). Better Integration for JD Edwards World. Retrieved from: "`https://www.toolbox.com/tech/erp/blogs/better-integration-for-jd-edwards-world-032114/`"

Finnsgård, C., Wänström, C., Medbo, L., & Neumann, P. (2011). Impact of materials exposure on assembly workstation performance. *International Journal of Production Research*, Vol. 49, No. 24, pp. 7253-7274.

Fragapane, G., de Koster, R., Sgarbossa, F., & Strandhagen, J. O. (2021). Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda. *European Journal of Operational Research*, Vol. 294, No. 2, pp. 405-426.

Frohm, J., Lindström, V., Winroth, M. & Stahre, J. (2006). The industry's view on automation in manufacturing. *Proceedings of the 9th IFAC Symposium on Automated Systems Based on Human Skills and Knowledge, 22-24 May 2006, Nancy, France, pp. 453-458.*

Fullerton, R.R., & Wempe, W.F. (2009). Lean manufacturing, Non-Financial Performance Measures, and Financial Performance. *International Journal of Operations*

& Production Management, Vol. 29, No. 3, pp. 214-240.

Granlund, A. (2014). Facilitating automation development in internal logistics systems. (Doctoral dissertation, Mälardalen University).

Goetschalckx, M., & Ashayeri, J. (1989). Classification and design of order picking. Logistics World. *Logistics Information Management*, Vol. 2, No. 2, pp. 99-106.

Goldsby, T., & Martichenko, R. (2005). Lean Six Sigma Logistics: Strategic Development to Operational Success. J. Ross Publishing, Inc, Boca Raton, FL.

Granlund, A. (2014). Facilitating automation development in internal logistics systems. (Doctoral dissertation, Mälardalen University).

Groover, M. P. (2008). Automation, Production Systems, and Computer-Integrated Manufacturing, 3rd edition. Prentice Hall, Upper Saddle River, NJ.

Gunasekaran, A., Patel, C., & McGaughey, R. E. (2004). A framework for supply chain performance measurement. *International Journal of Production Economics*, Vol. 87, No. 3, pp. 337-347.

Gupta, T. & Dutta, S. (1994). Analysing Materials Handling Needs in Concurrent/Simultaneous Engineering. *International Journal of Operations & Production Management*, Vol. 14, No. 9, pp. 68-82.

Hales, H. L., & Andersen, B. J. (2001). Industrial engineering support for materials management. *Maynard's industrial engineering handbook*, 5, 3-10.

Hanson, R. (2009). On the options available in the design of in-plant materials supply systems. Chalmers University of Technology.

Hanson, R. (2012). In-plant materials supply: Supporting the choice between kitting and continuous supply. Chalmers University of Technology.

Hayes, R. H. & Upton, D M. (1998). Operations-Based Strategy. *California Management Review*, Vol. 40, No. 4, pp. 8-25.

Hinz, P. (2013, April). Order picking in the warehouse. Adaptalift Group. Retrieved from: https://www.adaptalift.com.au/blog/2013-04-11-order-picking-in-the-warehouse).

ISO, International Organization for Standardization. (2003). Ergonomics - Manual handling - Part 1: Lifting and carrying (Preview). Reference number: ISO 11228-1:2003(E). Retrieved from: www.sis.se

ISO, International Organization for Standardization. (2007a). Ergonomics - Manual handling - Part 2: Pushing and pulling (Preview). Reference number: ISO 11228-2:2007(E). Retrieved from: www.sis.se

ISO, International Organization for Standardization. (2007b). Ergonomics - Manual handling - Part 3: Handling of low loads at high frequency (Preview). Reference number: ISO 11228-3:2007(E). Retrieved from: www.sis.se

Jarvis, J. M., & McDowell, E. D. (1991). Optimal product layout in an order picking warehouse. *IIE transactions*, Vol. 23, No. 1, pp. 93-102.

Johansson, E. S. E. (2006). Materials supply systems design during product development projects. Chalmers University of Technology.

Johansson, E. & Johansson, M. (2006). Materials supply systems design in product development projects. *International Journal of Operations and Production Management*, Vol. 26, No. 4, pp. 371 - 393.

Johansson, M. I. (1989). Product design and materials handling in mixed-model assembly. *Department of Transportation and Logistics*, Chalmers University of Technology.

Johansson, M. I. (1991). Kitting systems for small size parts in manual assembly systems. In: M. Pridham and C. O'Brien (Eds.), Production Research: Approaching the 21st Century. Taylor and Francis, London.

Johansson, M. I., & Mathisson-Ojmertz, B. (1996). Packaging as a Carrier of Materials Flow Effectiveness. Volume 4: Transport Management. In: World Transport Research. Proceedings of the 7th World Conference on Transport Research World Conference on Transport Research Society.

Jones, D.T., Hines, P, & Rich, N. (1997). Lean Logistics. International Journal of Physical Distribution & Logistics Management, Vol. 27, No. 3/4, pp. 153-173.

Jonsson, P. (2000). Towards an holistic understanding of disruptions in Operations Management. Journal of Operations Management, Vol. 18, No. 6, pp. 701–718.

Jonsson, P., & Mattsson, S-A. (2009). Manufacturing Planning and Control. McGraw-Hill Education, Maidenhead, Berkshire.

Kang S, & Kim K (2017) Multiple concurrent operations and flexible robotic picking for manufacturing process environments. In: 2017 14Th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI), IEEE, pp 380–381.

Kardex 1. (n.d). Horizontal Carousel Module. Retrieved from: `https://www.kardex.com/en/products/horizontal-carousels`.

Kardex 2. (n.d). The new Vertical Carousel Module. Retrieved from: `https://www.kardex.com/en/products/megamat-vertical-carousels`.

Kardex 3. (n.d). Vertical Carousel vs. Vertical Lift Modules. [Brochure]. Retrieved from: `https://cdn.bfldr.com/EL3HU3A3/as/f5hwg9xw8k9t7v4pmntmq3xj/Buyers_Guide_`

VLM_vs_VCM_EN.

Kardex 4. (n.d). Vertical Lift Module. Retrieved from: https://www.kardex.com/en/products/shuttle-vertical-lift-modules.

Kardex 5. (n.d). Kardex Remstar Megamat® RS: Automatiska paternosterverk för effektiv, skräddarsydd lagring och uthämtning. [Brochure]. Retreived from: https://www.kardex-remstar.se/se/lagerautomat/paternoster-se/megamat-rs-650.html

Kartnig, G., Grösel, B., & Zrnic, N. (2012). Past, State-of-the-Art and Future of Intralogistics in Relation to Megatrends. FME Transactions, Vol. 40, No. 4, pp. 193-200.

Klenk, E., Galka, S., & Günthner, W. A. (2015). Operating strategies for in-plant milk-run systems. IFAC-PapersOnLine, Vol. 48, No. 3, pp. 1882-1887.

Kuan-Yu H., & Chang T.-S. (2010). An innovative automated storage and retrieval system for B2C e-commerce logistics. The International Journal of Advanced Manufacturing Technology, Vol. 48, No. 1-4, pp. 297-305.

Kueng, P. (2000). Process performance measurement system: a tool to support process-based organizations. Total quality management, Vol. 11, No. 1, pp. 67-85.

Kulwiec, R. A. (1985). Materials Handling Handbook. John Wiley Sons, Hoboken, NJ.

Le-Duc, T., & de Koster, R. (2005). Layout optimization for class-based storage strategy warehouses. Supply Chain Management-European Perspective, 191-214.

Linck, J., & Cochran, D. S. (1999). The Importance of Takt Time in Manufacturing System Design (No. 1999-01-1635). SAE Technical Paper Series.

Liu C.-H., Chiu C.-H., Chen T.-L., Pai T.-Y., Hsu M.-C., & Chen Y. (2018). Topology optimization and prototype of a three-dimensional printed compliant finger for grasping vulnerable objects with size and shape variations. Journal of Mechanisms and Robotics, Vol. 10, No. 4.

Loos, M. J., Merino, E., & Rodriguez, C. M. T. (2016). Mapping the state of the art of ergonomics within logistics. Scientometrics, Vol. 109, No. 1, pp. 85-101.

Manzini, R. (2012). Warehousing in the global supply chain: Advanced models, tools and applications for storage systems. Springer Science Business Media, Berlin.

Manzini R, Gamberi M, & Regattieri A. (2006). Design and control of an AS/RS. The International Journal of Advanced Manufacturing Technology, Vol. 28, No. 7-8, pp. 766-774.

Mapes J., Szwejczewski M. & New, C. (2000). Process variability and its effect on plant performance. International Journal of Operations & Production Management, Vol. 20, No. 7, pp. 792-808.

Marchet, G., Melacini, M. & Perotti, S. (2014). Investigating order picking system adoption: a case study- based approach. International Journal of Logistics Research and Applications: A leading Journal of Supply Chain Management, Vol. 18, No. 1, pp. 82-98.

McCrea, B. (2020, July 8). Reader Survey: There's No Stopping Warehouse Automation. Logistics Management. Retrieved from: `https://www.logisticsmgmt.com/article/theres_no_stopping_warehouse_automation`

Michalos, G., Makris, S., Papakostas, N., Mourtzis, D. & Chryssolouris, G. (2010). Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach, CIRP Journal of Manufacturing Science and Technology, Vol. 2, No. 2, pp. 81-91.

Medbo, L. (2003). Assembly work execution and materials kit functionality in parallel flow assembly systems. International Journal of Industrial Ergonomics, Vol. 31, No. 4, pp. 263-281.

Mierzejewska, A., Castaneda-Vega, J.I, & Cochran, D. (2002). Systematic Approach to Takt Time Calculation in Achieving Required Manufacturing System Capacity. Proceedings of the 33rd CIRP International Seminar on Manufacturing Systems, Stockholm, Sweden June 5-7, 2000.

Neumann, P., Kihlberg, S., Medbo, P., Mathiassen, S. E. & Winkel, J. (2002). A case study evaluating the ergonomic and productivity impacts of partial automation strategies in the electronics industry. International Journal of Production Research, Vol. 40, No. 16, pp. 4059-4075.

Neumann, W.P., Winkel, J., Medbo, L., Magneberg, R., & Mathiassen, S. E. (2006). Production system design elements influencing productivity and ergonomics: A case study of parallel and serial flow strategies. International Journal of Operations & Production Management, Vol. 26, No. 8, pp. 904-923.

New, C. (1993). The Use of Throughput Efficiency as a Key Performance Measure for the New Manufacturing Era. The International Journal of Logistics Management, Vol. 4, No. 2, pp. 95-104.

Nilsson, A., & Elmar Merkle, D. (2018). Technical solutions for automation of warehouse operations and their implementation challenges. (Master dissertation, Linnaeus University).

Novara, V. (2020). A New Decision Making Tool for Automated Industrial Storage Systems Selection. (Doctoral dissertation, Politecnico di Torino).

Oleari, F., Magnani, M., Ronzoni, D. & Sabattini, L. (2014). Industrial AGVs: Toward a pervasive diffusion in modern factory warehouses. In: Intelligent Computer Communication and Processing (ICCP), 2014 IEEE International Conference on. Cluj Napoca, Romania, 4-6 September 2014. IEEE.

Olhager, J. (2010). The role of the customer order decoupling point in production and supply chain management. Computers in Industry, Vol. 61, No. 9, pp. 863-868.

Park, B. C. (2012). Order Picking: Issues, Systems and Models. In: Manzini R. (eds) Warehousing in the Global Supply Chain. pp.1-30. Springer, London.

Porter, M. E. (1996). What is Strategy?. Harvard Business Review, Vol. 74, No. 6, pp. 61-78.

Rossi, D., Bertolini, E., Fenaroli, M., Marciano, F., & Alberti, M. (2013). A multi-criteria ergonomic and performance methodology for evaluating alternatives in "manuable" material handling. International Journal of Industrial Ergonomics, Vol. 43, No. 4, pp. 314-327.

Rushton, C., & Croucher, P.(2006). The handbook of logistics and distribution management. Kogan Page Publishers, London, UK.

Rüttimann, B.G. (2018). Lean Compendium: Introduction to Modern Manufacturing Theory. Springer International Publishing, Cham, Switzerland

Sambasivarao, K. V. & Deshmukh, S. G. (1995). Selection and implementation of advanced manufacturing technologies: classification and literature review of issues, International Journal of Operations & Production Management, Vol. 15, No. 10, pp. 43-62.

Scholl, A. (1999). Balancing and Sequencing of Assembly Lines, (2nd edn). Physica-Verlag, Darmstadt, Germany.

Sharp, G. P., Il-Choe, K., & Yoon, C. S. (1991). Small parts order picking: Analysis framework and selected results. In Material Handling'90 (pp. 317-341). Springer, Berlin, Heidelberg.

Slack, N. & Lewis, M. (2011). Operations Strategy (3rd Edition). Pearson Education Limited, Harlow, UK.

Slack, N. & Lewis, M. (2015). Operations Strategy (4th Edition). Pearson Education Limited, Harlow, UK.

Spath, D., Braun, M. and Bauer, W. (2009). Integrated Human and Automation Systems, in Nof, S. Y. (Ed.), Springer Handbook of Automation, pp. 571-598. Springer, Berlin, Heidelberg.

SSI Schaefer. (n.d). SSI Flexi Shuttle. Retrieved from: `https://www.ssi-schaefer.com/en-th/products/storage/small-load-carriers/storage-shuttle-systems-bins-cartons-trays/ssi-flexi-shuttle-446212`.

Stricker, N., Echsler Minguillon, F., & Lanza, G. (2017). Selecting key performance indicators for production with a linear programming approach. International Journal of

Production Research, Vol. 55, No. 19, pp. 5537-5549.

Swisslog 1. (n.d). Tornado: A versatile miniload crane for automated warehousing. Retrieved from: `https://www.swisslog.com/en-us/products-systems-solutions/asrs-automated-storage-,-a-,-retrieval-systems/boxes-cartons-small-parts-items/tornado-miniload-crane`.

Swisslog 2. (n.d). CycloneCarrier: Dynamic shuttle storage and retrieval system for small loads. Retrieved from: `https://www.swisslog.com/en-us/products-systems-solutions/asrs-automated-storage-,-a-,-retrieval-systems/boxes-cartons-small-parts-items/cyclonecarrier-shuttle-system-logistics`.

Swisslog 3. (n.d).AutoStore: Space saving storage and order picking system for small parts. Retrieved from: `https://www.swisslog.com/en-gb/products-systems-solutions/asrs-automated-storage-retrieval-systems/boxes-cartons-small-parts-items/autostore-integrator`.

Säfsten, K. (2002). Evaluation of assembly systems: An exploratory study of evaluation situations. (Doctoral dissertation, Linköping University).

Säfsten, K., Winroth, M. & Stahre, J. (2007). The content and process of automation strategies. International Journal of Production Economics, Vol. 110, No. 1-2, pp. 25-38.

ten Hompel, M. & Schmidt, T. (2007). Warehouse Management: Automation and Organization of Warehouse and Order Picking Systems. Springer, Berlin, Heidelberg.

Tompkins, J. A., White, J. A., Bozer, Y. A., & Tanchoco, J. M. A. (2003). Facilities planning. John Wiley & Sons, Hoboken, NJ.

van Zante-de Fokkert, J. I, & de Kok, T. G. (1997). The mixed and multi model line balancing problem: a comparison. *European Journal of Operational Research*, Vol. 100, No.3, pp. 399-412.

Vollmann, T. E., Berry, W. L., Whybark, D. C., & Jacobs, F. R. (2005). Manufacturing Planning and Control Systems for Supply Chain. Irwin, NY.

Wang M, Guo L, Zhang Y, & Liang X. (2015). A method of mobile robotic drilling trajectory planning for large-scale components. In: *ASME 2015 International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers.*

Wikner, J., & Rudberg, M. (2005). Introducing a customer order decoupling zone in logistics decision-making. *International Journal of Logistics: Research and Applications*, Vol. 8, No. 3, pp. 211-224.

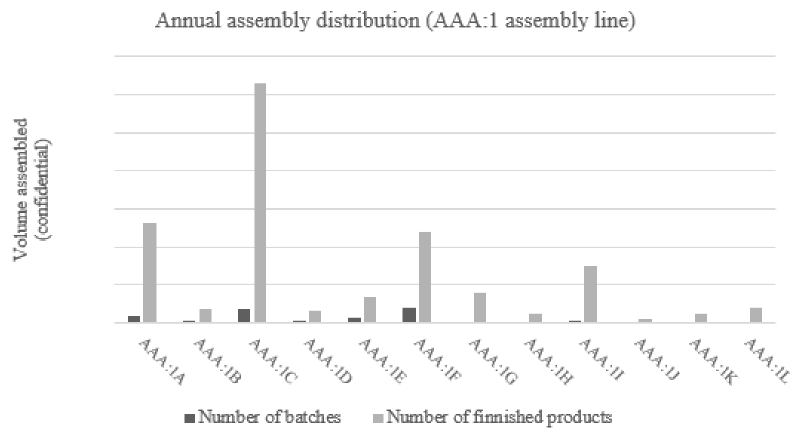
Woodside, A. G. (2010). Case Study Research: Theory, Methods and Practice. Emerald Publishing Limited, Bingley, UK.

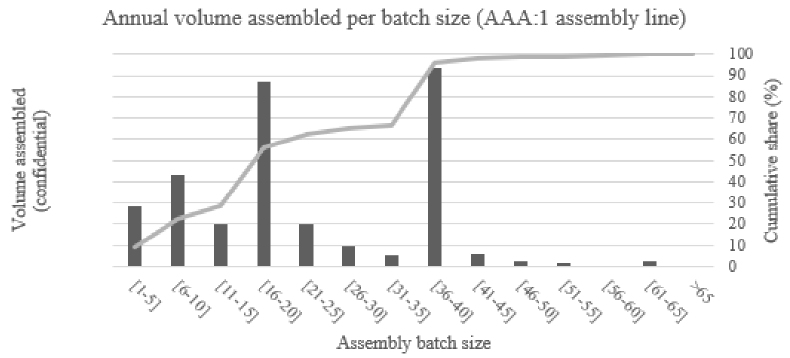
Wänström, C., & Medbo, L. (2009). The impact of materials feeding design on assembly process performance. *Journal of Manufacturing Technology Management*, Vol. 20, No. 1, pp. 30-51.

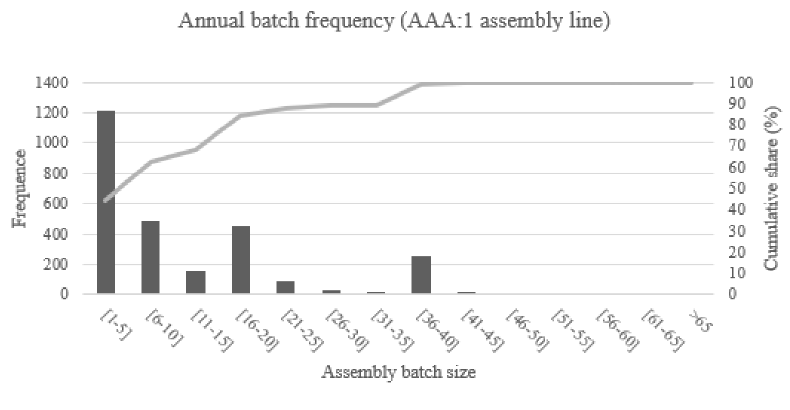
Öjmertz, B. (1998). Materials Handling from a Value-Adding perspective. *Department of Transportation and Logistics*, Chalmers University of Technology.

A

Appendix - Annual production data (AAA:1 assembly line)

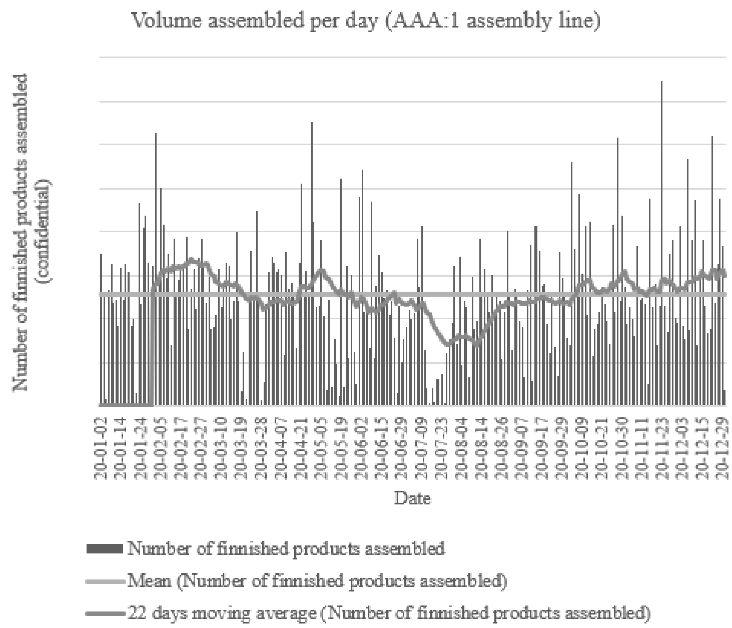


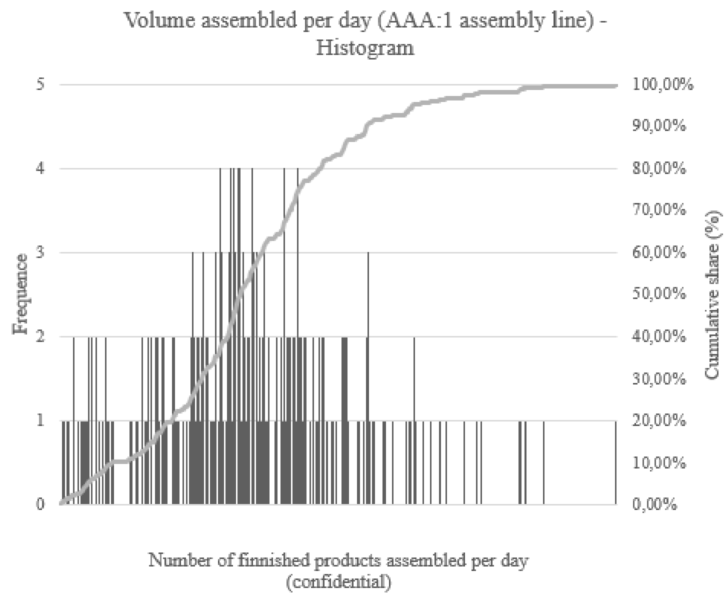




B

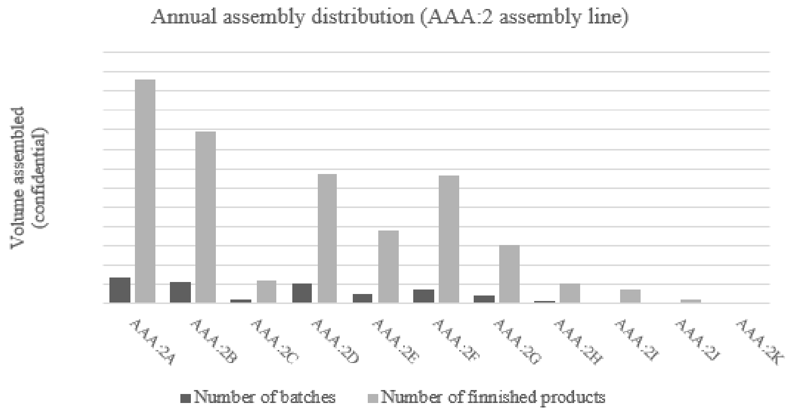
Appendix - Variation in volume assembled (AAA:1 assembly line)

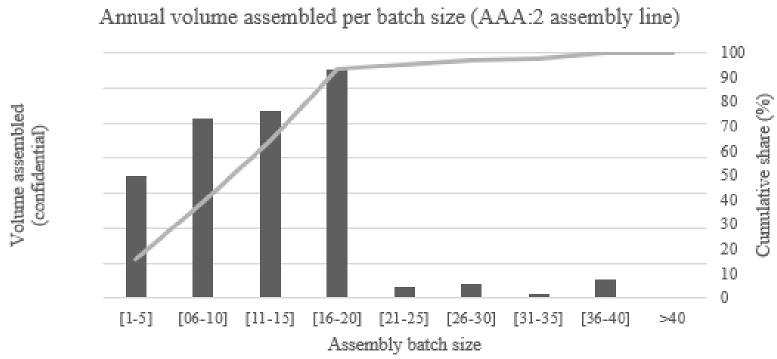


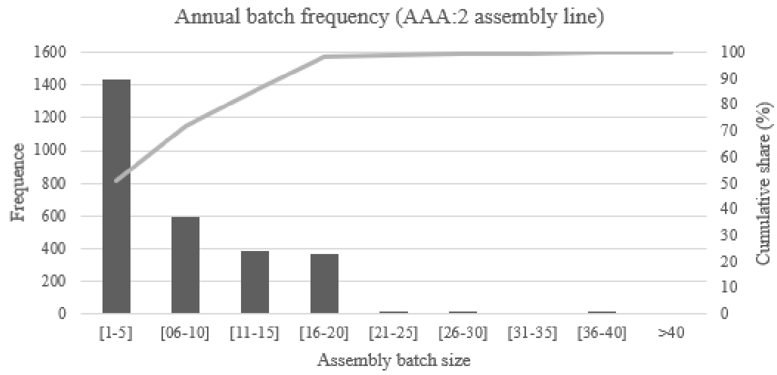


C

Appendix - Annual production data (AAA:2 assembly line)

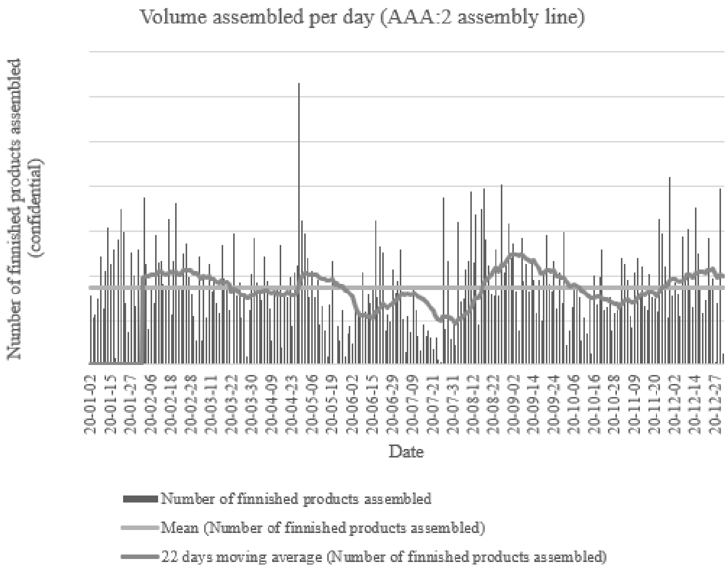


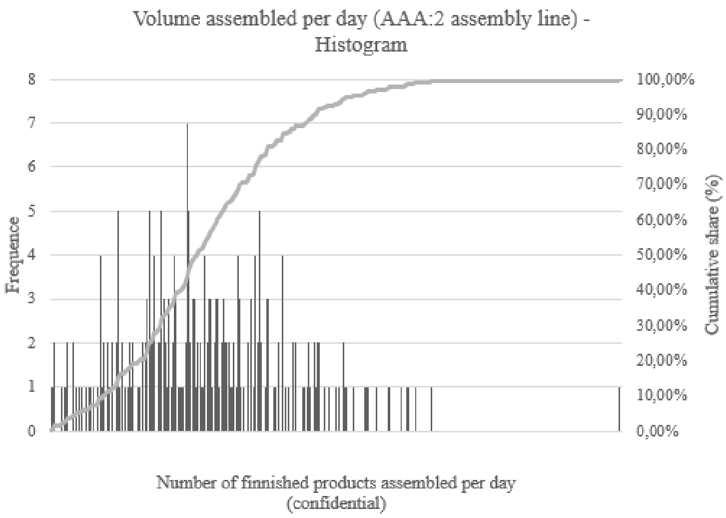




D

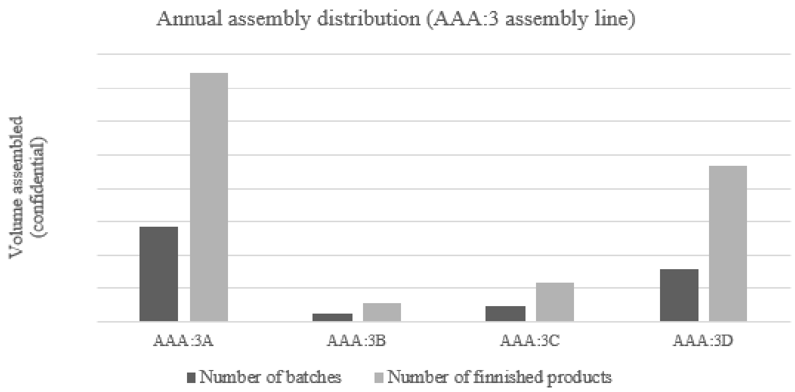
Appendix - Variation in volume assembled (AAA:2 assembly line)

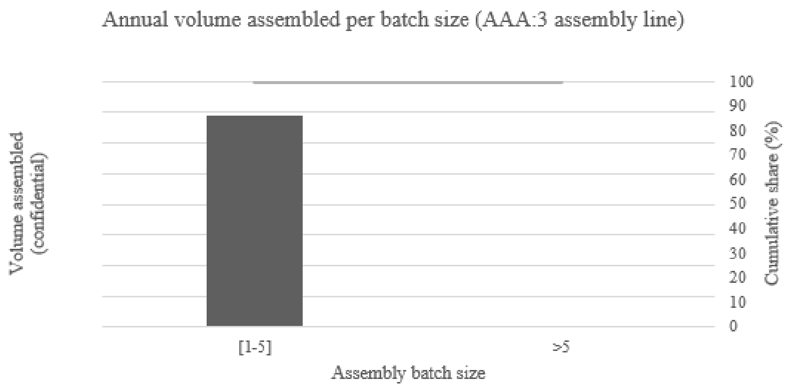


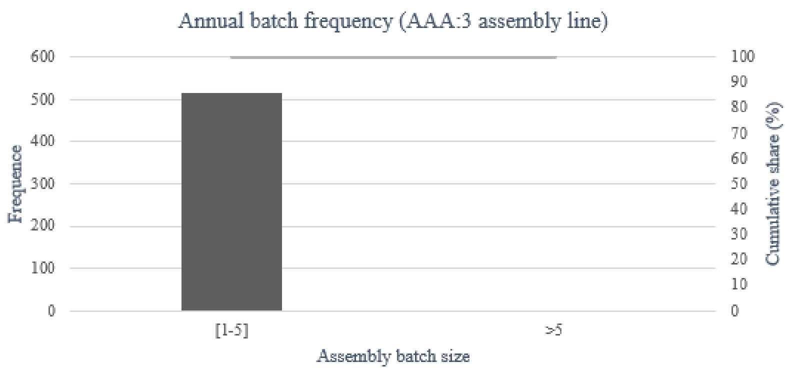


E

Appendix - Annual production data (AAA:3 assembly line)

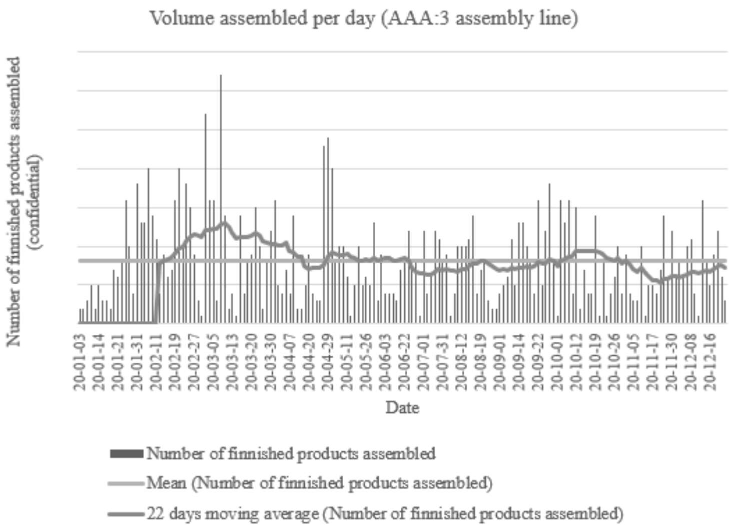


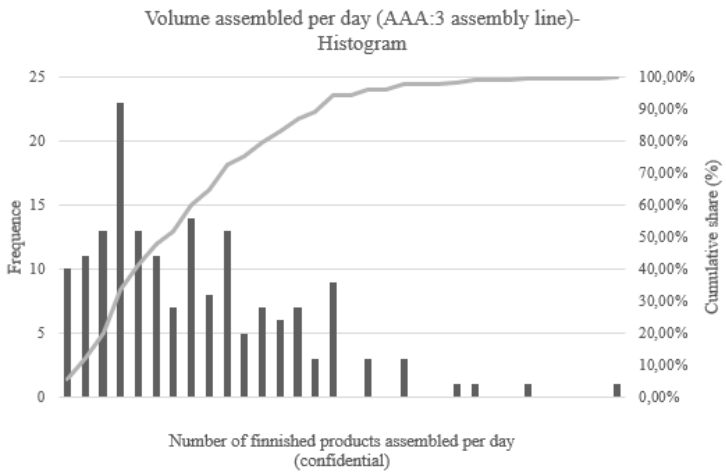




F

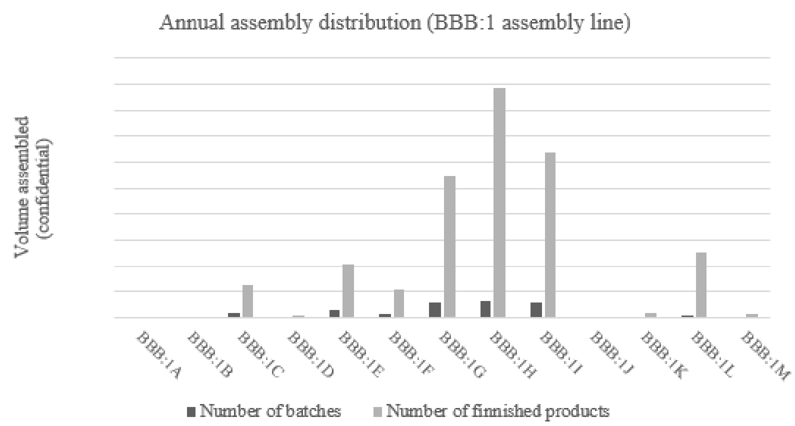
Appendix - Variation in volume assembled (AAA:3 assembly line)

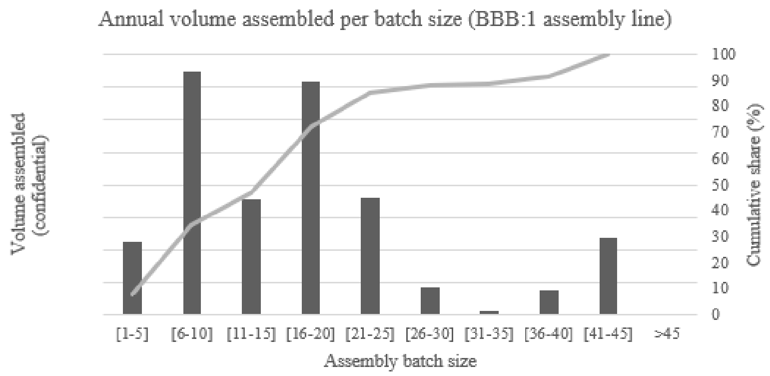


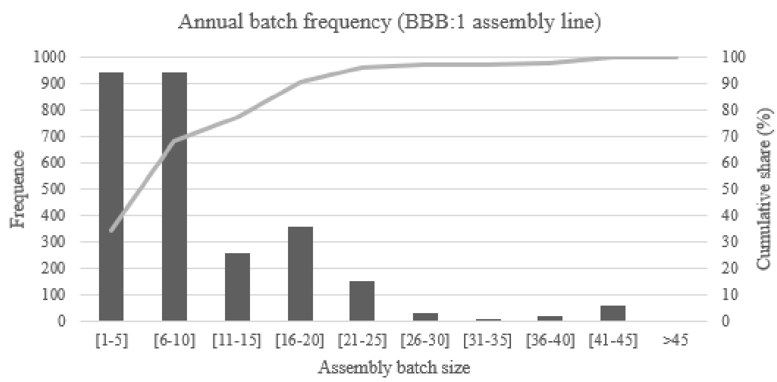


G

Appendix - Annual production data (BBB:1 assembly line)

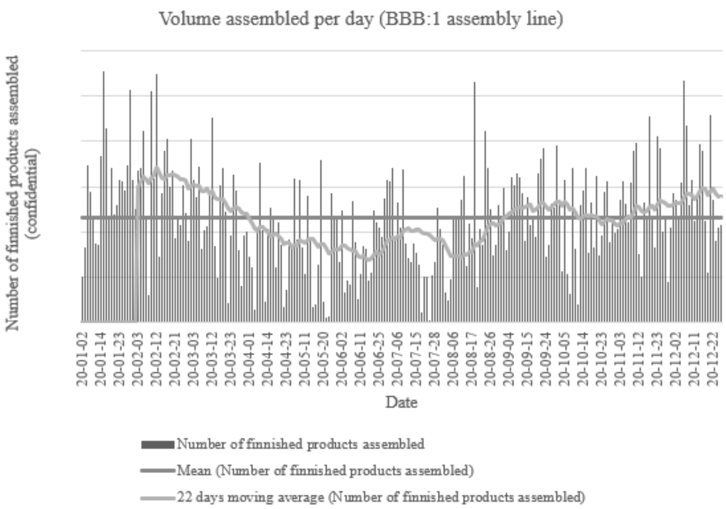


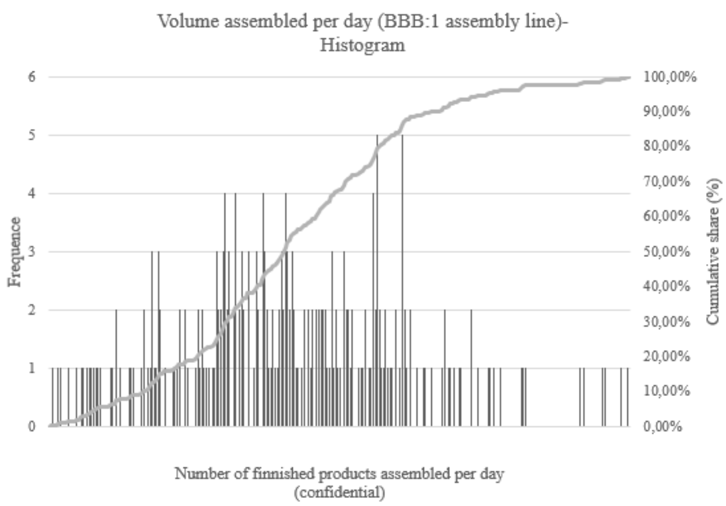




H

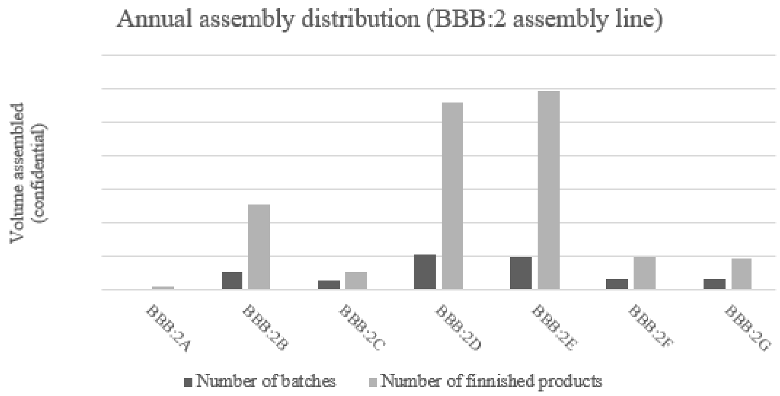
Appendix - Variation in volume assembled (BBB:1 assembly line)

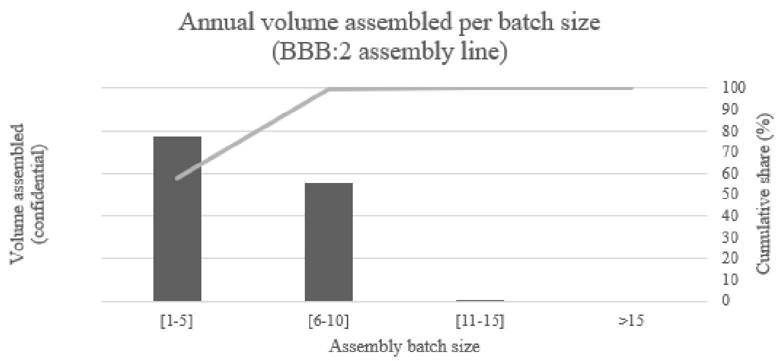


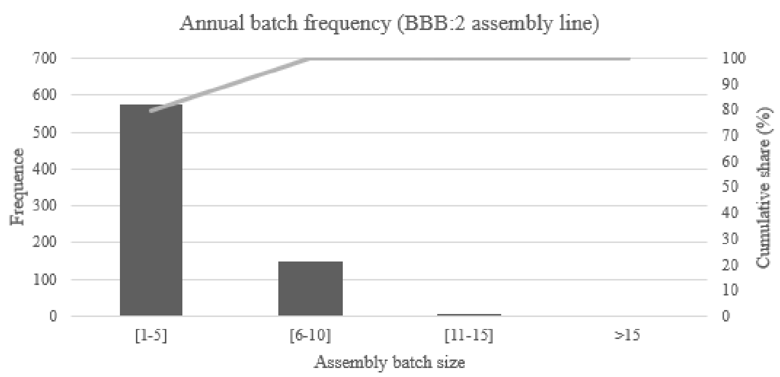


I

Appendix - Annual production data (BBB:2 assembly line)

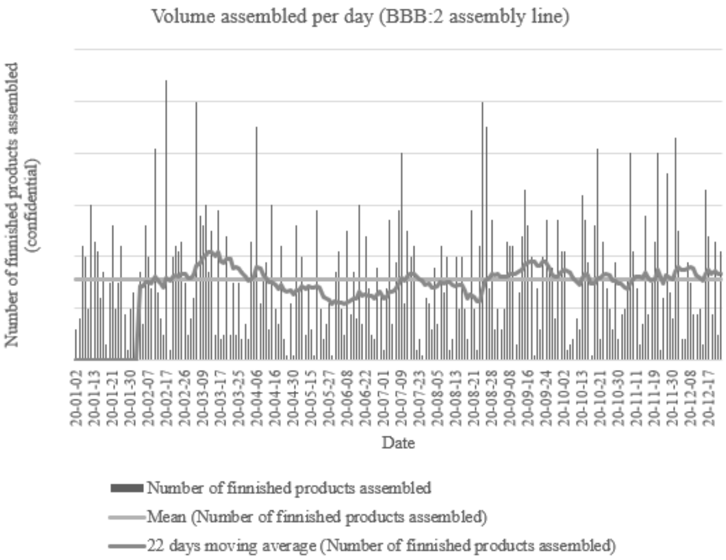


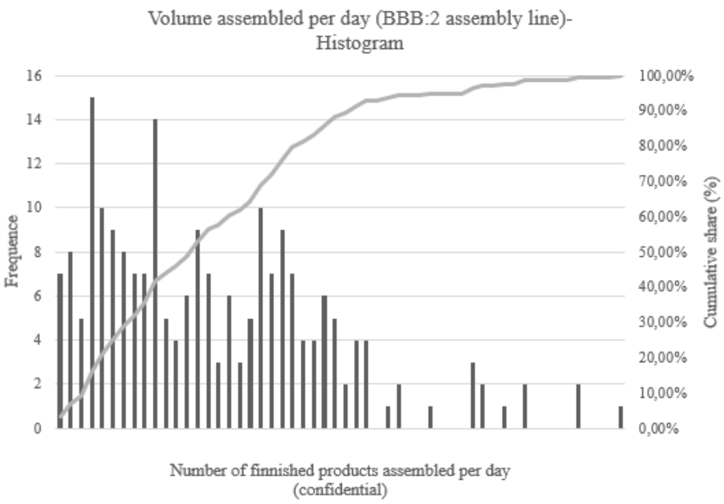




J

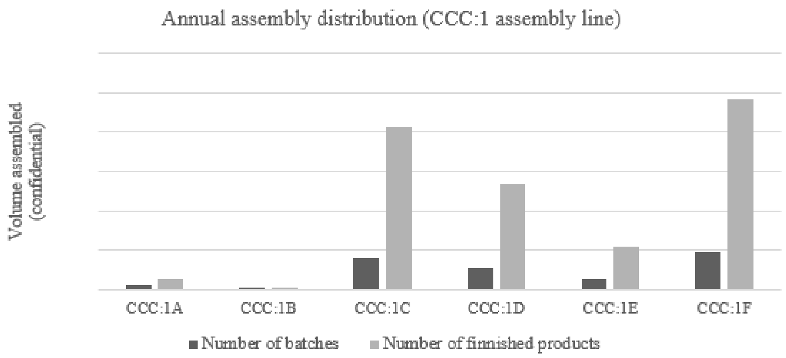
Appendix - Variation in volume assembled (BBB:2 assembly line)

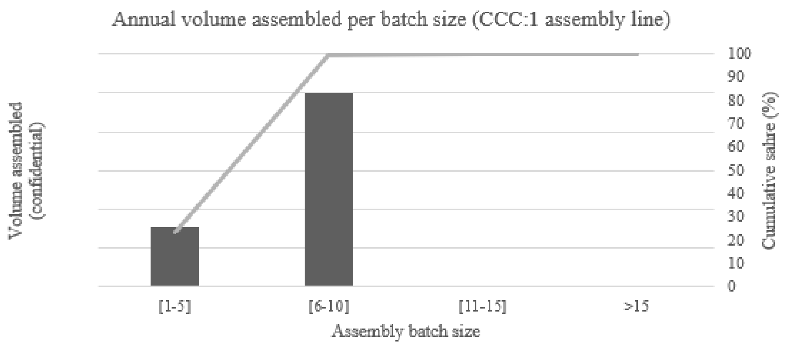


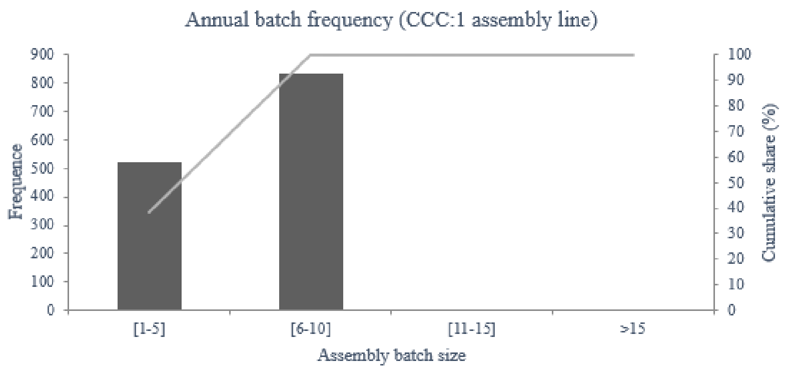


K

Appendix - Annual production data (CCC:1 assembly line)

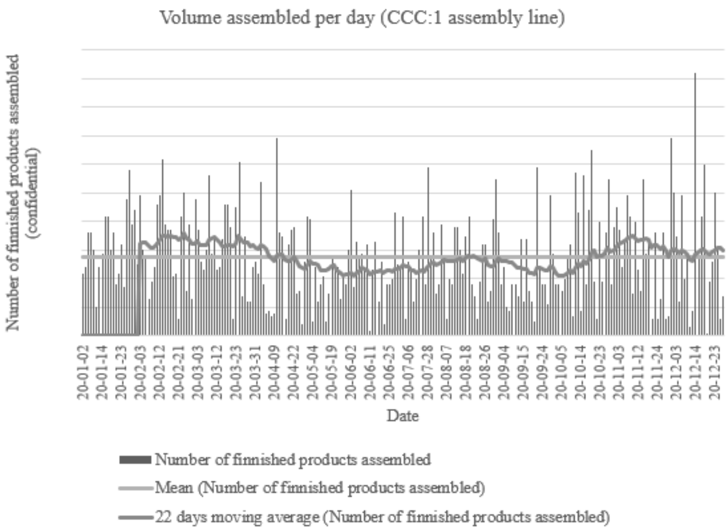


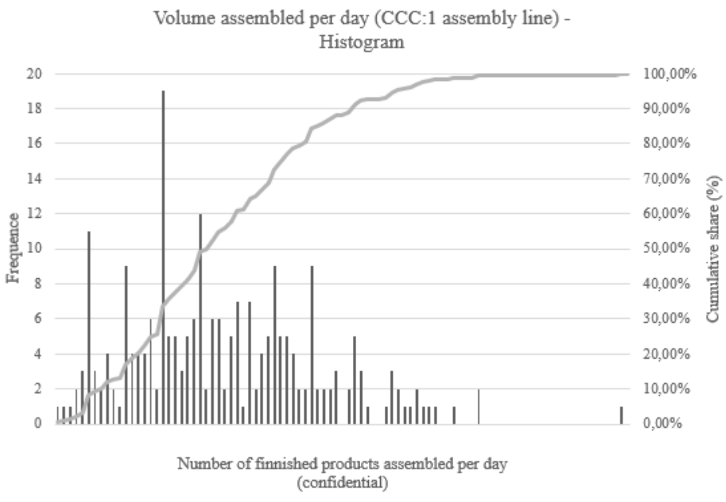




L

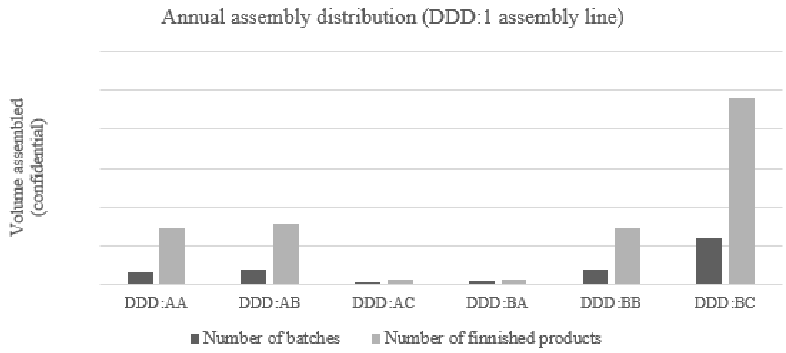
Appendix - Variation in volume assembled (CCC:1 assembly line)

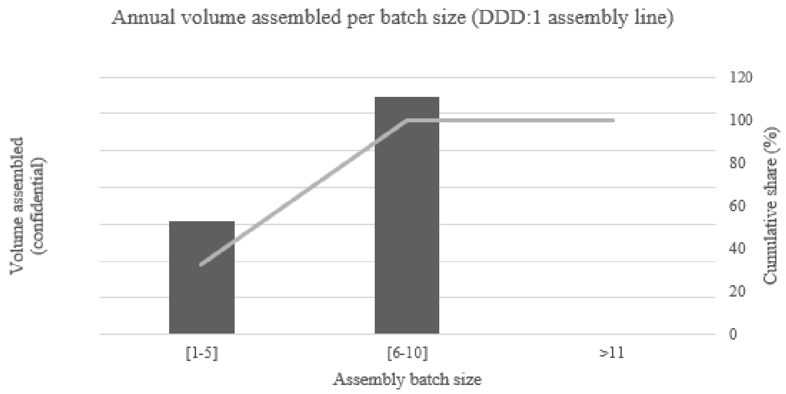


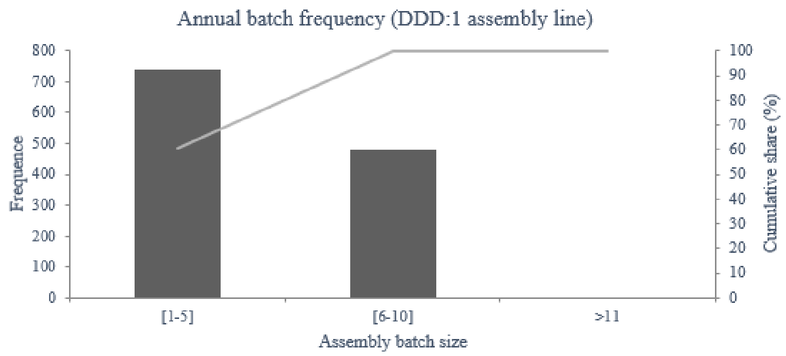


M

Appendix - Annual production data (DDD:1 assembly line)

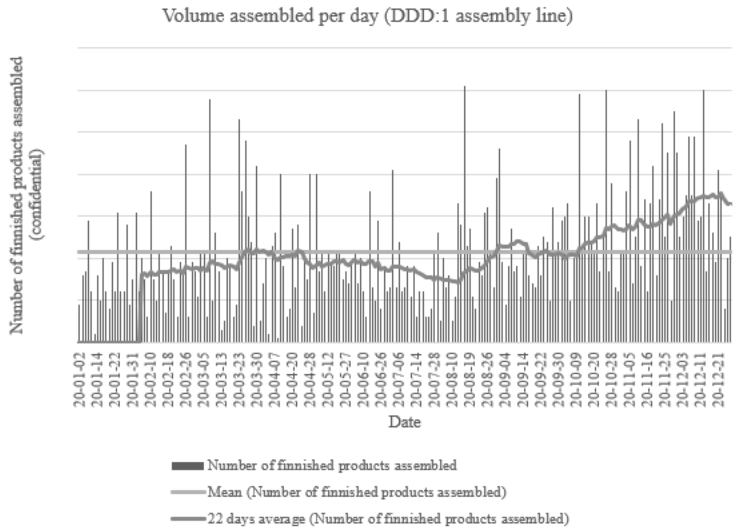


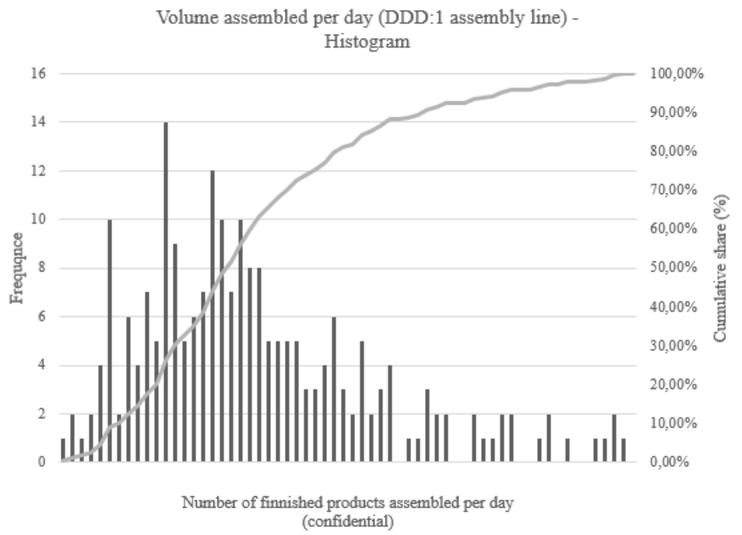




N

Appendix - Variation in volume assembled (DDD:1 assembly line)





O

Appendix - Numerical Calculations (1 of 3)

Assembly line/ Volume measurement (unit)	*Calculations performed by using extracted ERP data*
Annual total number of finished products assembled *(finished products per year)*	NFP_{annual} = *Annual total number of finished products assembled* *(Directly extracted from the ERP system)*
Annual number of assembly batches *(batches of finished products per year)*	NAB_{annual} = *Annual total number of assembly batches* *(Directly extracted from the ERP system)*
Weighted average number of line items per product *(component types per finished product, i.e., the quantity per item line is NOT considered)*	$w.avg.number\ of\ line\ items\ per\ product, NLI_{w.avg.} = \sum_i^K S_i * N_i$, *where i represent product subgroup* *S = Share of the annual total volume of finished products assembled* *N = Number of item lines* *K = All product subgroups*
Average number of finished products assembled per day *(finished products per production day)*	$avg.number\ of\ finished\ products\ per\ day, NFP_{avg.per\ day} = \frac{NFP_{annual}}{pd}$ NFP_{annual} = *Annual total number of finished products assembled* *pd = Number of production days per year*
Maximum number of finished products assembled per day *(finished products per production day)*	*Directly extracted from the ERP system*
Average number of line items assembled per day *(component types per production day)*	$avg.number\ of\ line\ items\ assembled\ per\ day, NLI_{avg.per\ day} = NLI_{w.avg.per\ finished\ product} * NFP_{avg.per\ day}$ $NLI_{w.avg.}$ = *weighted average number of line items per finished product* $NFP_{avg.per\ day}$ = *average number of finished products assembled per production day*
Maximum number line items assembled per day *(component types per production day)*	$Max.number\ of\ line\ items\ assembled\ per\ day, NLI_{max\ per\ day} = NLI_{w.avg.per\ product} * NFP_{max.per\ day}$ $NLI_{w.avg.per\ product}$ = *weighted average number of line items per finished product* $NFP_{max.per\ day}$ = *maximum number of finished products assembled per production day*
Average number of assembly batches per day *(assembly batches per production day)*	*Avg. number of assembly batches per day,* $NAB_{avg.per\ day} = \frac{NAB_{annual}}{pd}$ NAB_{annual} = *Annual total number of assembly batches* *pd = Number of production days*
Maximum number of assembly batches per day *(assembly batches per production day)*	$NAB_{max.per\ day}$ = *Max. number of assembly batches per day* *(Directly extracted from the ERP system)*

P
Appendix - Numerical Calculations (2 of 3)

Estimated likely number of load carriers & packages being picked from an average sized assembly batch *(load carriers & packages per assembly batch)*	*For each assembly line:* $Est.\ likely\ number\ of\ load\ carriers\ \&\ packages\ being\ picked\ from\ an\ avg.\ sized\ batch,\ LCB_{avg.per\ avg\ batch} = \sum_i^X SB_i * LNLC_{avg.batch,i}$ *, where i represent product subgroup* *For each product subgroup:* $SB = Share\ of NAB_{annual}$ $NAB_{annual} = Annual\ total\ number\ of\ assembly\ batches$ $LNLC_{avg.batch} = Likely\ number\ of\ unit\ loads\ picked\ from\ per\ the\ average\ sized\ batch = LNLC_{min} + LNLC_{Extra}$ $LNLC_{min} = Minimum\ number\ of\ unit\ loads\ of\ components\ picked\ from\ per\ average\ assembly\ batch = \sum_k^M NLC_{min.per\ avg.batch,k}$ *where k represents each line item* $LNLC_{Extra} = Extra\ unit\ loads,\ being\ needed\ due\ to\ none\ full\ unit\ loads\ at\ the\ start\ of\ the\ picking\ procedure = \left\lceil \sum_k^R NLC_{extra\ per\ avg.batch} \right\rceil$, *where k represents each line item* $\lceil \square \rceil$ *represents the closest integer above the real value* *For each line item:* $NLC_{min.per\ avg.batch} = \left\lceil \left(\frac{NCO_{per\ avg.batch}}{BQ_{max}}\right) \right\rceil,$ $\lceil \square \rceil$ *represents the closest integer above the real value* $NCO_{per\ avg.batch} = Required\ number\ of\ components\ of\ an\ line\ item\ per\ average\ batch\ size$ $BQ_{max} = Bin\ quantity\ (i.e., maximum\ number\ of\ components\ per\ unit\ load)$ $LNLC_{Extra} = \left(\frac{NCO_{per\ avg.batch}-1}{BQ_{max}}\right) - \left\lfloor \left(\frac{NCO_{per\ avg.batch}-1}{BQ_{max}}\right) \right\rfloor,$ $\lfloor \square \rfloor$ *represents the closest integer below the real value* *(OBS: The calculation of $LNLC_{Extra}$ assumes that each unit load (i.e., load carrier or other package), at the picking location, contains a quantity of components in the interval [1-BQ_{max}]. This means that it is assumed that a specific load carrier never is empty at the start of the picking procedure because an empty load carrier will always and immediately be removed from the picking location when it becomes empty. The calculation of $LNLC_{Extra}$ also assumes that the existing quantity of components in each unit load is independent of the existing quantity of components in all other unit loads of other line items.)*

Q

Appendix - Numerical Calculations (3 of 3)

Estimated likely average number of load carriers & packages being picked from PER DAY *(load carriers & packages per production day)*	***Estimated likely <u>average</u> number of load carriers & packages being picked from <u>per day</u> =*** $LCB_{avg.per\ day} = LCB_{avg.per\ avg\ batch} * NAB_{av.g\ per\ day}$ $LCB_{avg.per\ avg\ batch}$ $= Est.\ likely\ number\ of\ load\ carriers\ \&\ packages\ being\ picked\ from\ an\ avg.sized\ batch$ $NAB_{av.g\ per\ day}$ *= average number of assembly batches per day =* $\frac{NAB_{annual}}{pd}$ $NAB_{annual} = Annual\ total\ number\ of\ assembly\ batches$ *pd = Number of production days per year*
Estimated likely average number of load carriers & packages being picked from PER HOUR *(load carriers & packages per production hour)*	***Estimated likely <u>average</u> number of load carriers & packages being picked from <u>per hour</u>*** = $LCB_{avg.per\ hour} = LCB_{avg.per\ day} / ph_{avg.per\ day}$ $LCB_{avg.per\ day} =$ *Estimated likely average number of load carriers & packages being picked from per production day* $ph_{avg.per\ day} = average\ number\ of\ prodcution\ hours\ per\ production\ day$
Estimated likely maximum number of load carriers & packages picked from PER DAY *(load carriers & packages per production day)*	***Estimated likely <u>maximum</u> number of load carriers & packages picked from <u>per day</u> =*** $LCB_{max.per\ day} =$ *The same calculation as for the "Estimated likely <u>average</u> number of load carriers & packages being picked from an <u>average</u> sized assembly batch", except that* $LNLC_{avg.batch}$ *is replaced by* $LNLC_{max.batch}$, *where* $LNLC_{max.batch}$ $= Likely\ number\ of\ unit\ loads\ picked\ from\ per\ the\ maximum\ sized\ batch$
Estimated likely maximum number of load carriers & packages picked from PER HOUR *(load carriers & packages per production hour)*	***Estimated likely <u>maximum</u> number of load carriers & packages being picked from <u>per hour</u>*** = $LCB_{max.per\ hour} = LCB_{max.per\ day} / ph_{avg.per\ day}$ $LCB_{max.per\ day} =$ *Estimated likely maximum number of load carriers & packages being picked from per production day* $ph_{avg.per\ day} = average\ number\ of\ prodcution\ hours\ per\ production\ day$
Takt time *(time available, at each assembly line, for producing a single product)*	***Takt time*** *(minutes per product)* = $Takt\ time_{minutes} = \frac{\frac{ph_{week}}{5}}{\frac{NFP_{annual}}{pd}} * 60$ NFP_{annual} *= Annual total number of finished products assembled* *pd = Number of production days per year* $ph_{week} = The\ number\ of\ production\ hours\ per\ week$ *5 = The number of production days per week* *60 = Number of minutes per hour*
Production pace *(Number of finished products assembled per hour)*	***Production pace*** *(finished product per hour)* = $\frac{1}{Takt\ time_{minutes}} * 60$

R
Appendix - Unit Load Calculation

$$\text{Required number of unit loads} \quad = \frac{\text{inventory of the line item}}{\text{quantity per load carrier (LC)}}$$

$$\text{Total unit loads} = \sum_{i=1}^{n} \text{required number of unit loads for a line item } i$$

where i represent an unique line item

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