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Balancing inventory levels and setup times

An analysis and outline of a decision-making model

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Henning and Mohsen

Abstract

Title

Balancing inventory levels and setup times - An analysis and outline of a decision-making model

Course

Degree Project in Production Management – MIOM01

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Background and Research Question

Historically, Lindab has largely focused its efforts on the production, but as a part of recent development in company strategy, supply chain management has gained more attention. In this regard, more attention has been given to stock reduction and minimizing total setup times to get a leaner production. Therefore, the company wants to investigate the current production scheduling and sequencing in two well-defined production lines to analyze parameters influencing inventory management and production planning decisions. Furthermore, based on the findings, a model is outlined to support planners in decision making within production.

Methodology

The presented analysis and model outline was conducted in cooperation with Lindab AB. The study followed an abductive research approach and focused on collecting qualitative as well as quantitative data through several methods. The quantitative data collected originated from several databases and was supplemented with semi-structured interviews.

Theoretical Framework

This study is based upon the established theory on inventory management and production scheduling and sequencing. Furthermore, approaches described in theory are used to investigate the company and outline a production planning model.

Conclusion

Throughout the analysis, it could be shown that the company bases their inventory management as well as production scheduling and sequencing on the most relevant parameters. However, the values of these parameters are often not optimal and improvements could be made to further reduce the costs associated with this area. Although, the current approach of utilizing the experience of production operators to improve a production lines performance shows some potential, the obtained results vary between operators and could be improved by further structuring their approach to production scheduling and sequencing. A standardized approach is suggested by this study, to increase savings in the areas of average inventory levels and total setup time.

Keywords

Inventory Management, Setup Times, Average Stock on Hand, VMI, Production Scheduling and Sequencing

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1 Introduction

This section introduces the general structure of the thesis. The background, problem description and purpose of this study are presented and lastly the delimitations are discussed.

1.1 Background

Operations management plays a central role in improving manufacturing in the dimensions of cost, quality and speed (Hopp and Spearman, 2001). In an ideal world, products are always readily available and if not they can be produced without any difficulties or lead times. However, in reality this is not possible due to many reasons, where one is the cost involved in producing and storing such high numbers that every demand can always be satisfied immediately. Therefore, companies strive to find a middle-ground in those dimension, which enables them to satisfy customer demands while maintaining costs as low as possible. Similarly, a company's goal might be to satisfy customer requirements while keeping quality or speed at an appropriate level. (Hopp and Spearman, 2001)

By assuming that product quality is relatively constant for a given production setup, it can be seen that a company is faced with the challenge of producing the right product at the right time and quantity at minimum costs. The economic order quantity, introduced by Harris (1913), represents a first step in balancing fixed setup costs with holding costs and capital tied up in stock. This model provides a guidance and can help in reducing costs associated with production. But other aspects such as producing the right product at the right time cannot be expressed by this approach. Here, forecasting, production scheduling and sequencing play a central role. Approaches like material requirements planning (MRP) and several scheduling and sequencing methods, such as shortest-process-time (SPT) or earliest-due-date (EDD), allow companies to face the challenge of meeting customer demands when they arise. However, simply applying these different approaches individually does not lead to an optimal solution and might even result in a poor overall solution for the production system (Hopp and Spearman, 2001). Therefore, a more holistic perspective on managing operations is necessary.

1.2 Problem Description

This thesis was carried out in cooperation with the Supply Chain Center of Excellence at Lindab AB. Traditionally, Lindab has focused their efforts on producing and selling products. Over the past years, as part of the "efficient availability" strategy, the importance of logistics and supply chain management has been emphasized. As part of this, a new information and planning systems, called Lindab Inventory Control System (LICS) and Lindab Inventory Production System (LIPS), has been introduced. Figure 1 schematically shows how these systems interact with each other through Lindab's ERP system Axapta.[1] These systems are built and maintained by the Supply Chain Center of Excellence. Currently, LICS and LIPS are used at many of Lindab's production sites and are continuously improved and expanded.

[1] A more detailed description of Lindab's different information systems and their interaction can be found in Section 4.3

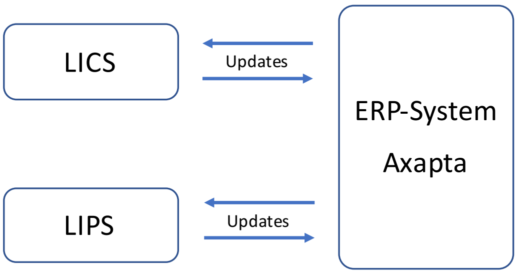

Figure 1: Interaction between Lindab's information systems

One part of the system is a production scheduling logic that helps operators to produce required quantities but also to produce additional products based upon current stock levels. The aim of this approach is to increase machine utilization to lower the total costs of production. This approach is used for example when producing finished goods to be put on stock. The decision logic, which is seen as an internal vendor managed inventory (VMI) system, is built upon a (R,Q)-policy with an quantity Q obtained from the EOQ-formula[2]. Through the calculated batch quantity and current stock levels, operators can steer the production towards more efficient utilization of raw materials and machines. The pairing of this approach with placed customer orders and operators' experience results in a system similar to a vendor managed inventory system.

One of the main features of LIPS is displaying real-time information about stock levels for each product assigned to a given production line. Additionally, the system allows operators to choose the next product to be produced. This is done by selecting a product and then entering the desired production quantity, for which LICS provides a suggestion to operators. The LIPS system provides this information and functionality through a computerized system with indicators, which display products that could be produced next because of low stock levels.

While the system provides several options, the decision of what to produce is made by the individual operators based on parameters such as inventory levels, setup time and machine utilization. The effectiveness of the current system is dependent on the operator's experience. As a result, the output of the system, including stock levels and resource utilization varies. The output from the production line is further influenced by the seasonality of products, likely resulting in varying utilization and output rates throughout the year.

Although Lindab is aware of several parameters influencing inventory cost, they are currently not aware if these are among the most crucial parameters and if their approach for determining them is aligned with reality. The ambition is to analyze key parameters affecting the total inventory and production planning decisions as well as an estimation of the actual values. Furthermore, the company perceives the current approach for production scheduling and sequencing as good, but also what to investigate more structured approaches to further improve the current approach.

[2] Concepts are presented and discussed in Section 3.2

1.3 Purpose

The objectives of this master thesis are to

(i) identify and analyze key parameters affecting total inventory and production planning decisions for two well defined productions lines and

(ii) to outline a quantitative production planning tool to help operators make better and more consistent decisions.

1.4 Delimitations

The purpose of this thesis, as described in the previous section, is extensive and relatively complex. To be able to provide adequate results within the given time frame, the scope has been narrowed down. Firstly, Lindab AB is a large, international company with many production sites and warehouses across Europe. This results in many different scenarios, which cannot be considered in this study. The two production lines focused on in this study produce a limited number of products, which limit this study to different sizes and colors of gutter outlets and small ventilation bends.

The production lines have been selected by the company for several reasons, among which are the different kinds of products manufactured, the progress in improving production efficiency and share in the sales volume. This thesis focuses on aspects related to inventory management and production scheduling and sequencing to find potential areas for improvements.

2 Methodology

The aim of this chapter is to describe the approaches and methods selected to conduct this thesis. Moreover, a description of the data collection and the working procedure selected is presented.

2.1 Research Design

The research design outlines the approach chosen to study and analyze the problem. It also describes what kind of data was collected and how it was analyzed. Prominent designs in business research include experiments, case studies and longitudinal studies (Bryman and Bell, 2011). These research designs are used to obtain insights into one or several different companies so that a certain problem is identified or explained. Especially case studies focus extensively on a certain research question and how it can be answered with the help of one or several case companies. Depending on the type of case study, different perspectives regarding the research question and case companies can be adopted (Yin, 2009). Operations research, in contrast, focuses on increasing the understanding of operations management problems through mathematical modeling, and the goal is often to solve previously identified problem through the means of optimization and modeling (Hillier and Lieberman, 2010).

2.2 Research Strategy

Research is often separated into quantitative or qualitative approaches (Kotzab and Westhaus, 2005). Quantitative studies center around measurable data that can be analyzed or evaluated through mathematical or statistical methods. This kind of data is collected through field surveys or experiments with the purpose of verifying a theory by testing significance and strength of relationship between variables. Qualitative studies, in contrast, consider data sources that cannot be (easily) expressed by numbers. Instead, qualitative studies focus on words, procedures and descriptions to study a phenomenon. Due to these characteristics, common forms of data collection are questionnaires, interviews or documents. (Kotzab and Westhaus, 2005)

A third research strategy is a so called balanced approach presented by Kotzab and Westhaus (2005). This research strategy combines qualitative and quantitative approaches to provide all available and relevant information on a phenomenon to solve it. The research process for this type of research strategy can be described as follows (Figure 2). This strategy is related to the so called abductive research approach and tries to bridge the gap between qualitative and quantitative research strategies.

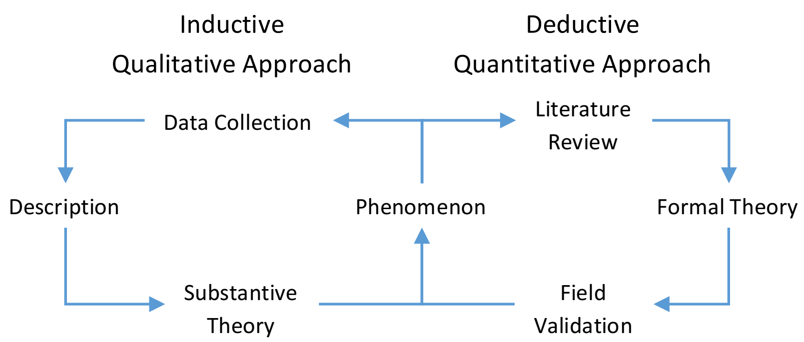

Figure 2: Approach for the balanced research strategy (Kotzab and Westhaus, 2005, p. 20)

2.3 Research Approach

Next to the research strategy the research approach plays a central role in how a research question is addressed. Generally, research approaches can be separated into deduction, induction and abduction/ iterative (Bryman and Bell, 2011). Deductive research is best described by an initial theory that is later tested against data/ findings, and therefore it sometimes also called the theory-testing process. Inductive research follows the same process, but from the opposite direction. Here, the aim is to distill a general theory out of findings or observations (Bryman and Bell, 2011). The third approach, abduction, represents a middle ground, where both deduction and induction are applied. This can be achieved by applying both approaches iteratively, e.g. starting with deduction followed by a phase of induction.

2.4 Research Purpose

The research purpose describes the way a study aims to contribute to existing body of knowledge in a certain area (Bryman and Bell, 2011). Among the most common research purposes are exploratory, description, explanatory and normative studies (Kotzab and Westhaus, 2005). Depending on the research questions and areas studied one or more of those purposes are applicable. Explorative studies are used for research questions in areas where little knowledge is available and fundamental knowledge has yet to be attained. A descriptive study builds upon existing knowledge to illustrate causes or effects, but does not put an extensive focus on explaining them. Explanatory studies aim to do just that by analyzing the system to find root causes and deepening the knowledge further. Lastly, normative studies strive to find generalizing aspects and to provide predictions for future events (Bryman and Bell, 2011).

2.5 Quality Assurance

The purpose of the thesis is not to promote or prove the efficiency of a method. Rather, it is to observe the results and try to understand and explain why the results are as they are. Furthermore, the literature utilized in the theoretical framework (see Section 3) are not selected to prove a certain point. Instead it is selected to illustrate what academic research has been conducted in the relevant areas. The representativeness of a study indicates to what extent the results can be generalized and applied in other cases than the one investigated. Single company case study often poses little with regard of generalizability, nonetheless, some aspects can be translated into other context where similar characteristics can be found. Therefore, a thorough description of the context increases the representatives of a study.

The reliability of research refers to the credibility and authenticity of collected data, analysis and obtained results. In order to obtain reliable data, it is essential to collect data in structured way, preferably through established and recognized methods (Bryman and Bell, 2011). Therefore, approaches and methods should be determined beforehand to ensure reliable data collection. Similarly, the analysis of data should be conducted in a well-structured way to ensure consistent results that can be replicated and are deemed credible by others. Here, differentiated discussions are critical to ensure that results have not been obtained by chance Through this replicability of the study can also be ensured (Hillier and Lieberman, 2010).

Before it is possible to rely on the results of a study, one must assure the quality of it. Model verification and validation are essential elements for quality assurance (Laguna and Marklund, 2013). The verification of a model is the process of removing any errors or flaws from the model so that it operates as expected, meaning the implemented logic operates as designed. An approach for verifying a model is building a model incrementally. This means that a model is build piece by piece and each piece is checked individually to be verified that it operates as expected (Laguna and Marklund, 2013). By doing this, it can be assumed, once the model is completed and every single piece operates as expected, that the entire model operates correctly. Another verification method is to reduce the model to simple cases that replicates easily predictable outcomes. Once the model is verified, the validation of a model starts which aims at determining whether the model produces accurate results for the real system (Laguna and Marklund, 2013). Usually this is done by comparing results obtained from the model with those from the real process. Here, it is essential that both systems operate based on the same metrics and under the same conditions. This can be achieved by using historical data for the model and comparing it to the results from the real system (Laguna and Marklund, 2013). If the results from both systems are within a reasonable range, it can be assumed that the model is valid.

2.6 Methodology of this Study and Data Collection

In correspondence with scientific principles, this section is dedicated to describing and motivating the methodology used in this study. The purpose of this study is to investigate how key parameters influence inventory management decisions in the specified system and to design a quantitative model or heuristic for production scheduling and sequencing. Therefore, this study is heavily rooted in operations research and focuses on solving a specific problem. Nonetheless, some aspects of other research designs, such as case study research, are also used in this study. For example, the study focuses on a single company, more specifically two production lines, for which the factors influencing inventory management are largely unknown.

As described in the previous section, the research strategy can vary between the extremes of qualitative and quantitative research. In this study, the data collection and the results are based on both qualitative and quantitative aspects. As it is explained earlier, the first objective of this study is to identify parameters in decisions regarding production sequencing, which has to be of a more qualitative nature. However, designing a decisions support tool based on the identified parameters requires a quantitative modelling approach. Therefore, a balanced approach will be suitable for this study.

When it comes to a research approach for this study, an abductive approach is chosen. Since it suggests an iterative or cyclic process between the inductive and deductive approach, which facilitates hypothesis testing, but also theory building based the observations. This research begins with a deductive phase by analyzing literature to create a theoretical framework, which is used as a basis for the data collection and the subsequent analysis. This latter part of the study follows an inductive approach, where based on the data and observations, some theory will be derived and analyzed. In this way, important parameters in the current theoretical framework are analyzed, discussed and afterwards observed or analyzed in practice. Subsequently, the gathered information is used to form a theory.

Considering the different purposes research can have, the first part of this study is descriptive, while later parts can be considered as explorative and explanatory. Because of the objective of this study to find, describe and understand influencing factors in production sequencing, a clear connection to descriptive studies can be seen. Furthermore, the data gathered is used to illustrate causes and effects on the production lines at hand.

The chosen data collection methods for this study are aligned with the balanced approach, where interviews are conducted to learn about the current decision making method for production sequencing and quantity, while required quantitative data will also be collected from LICS and Microsoft Dynamics AX (formerly Axapta). The qualitative, but also some of the quantitative, data required is obtained through several interviews. These interviews are based upon the approach described by Yin (2009) and are designed to be semi-structured focused interviews, which rely on a prepared interview guide. The interviews are conducted with operators, technical experts and production planners at Lindab's production plants in Grevie and Förslöv. The interviews are held in meeting rooms outside the production lines. Furthermore, results from these interviews are validated through several later queries at later stages.

Since the focus of this study is limited to two pre-defined production lines, namely line 206 (producing gutter outlets) in Lindab's profile factory and line Böj 110_6 (producing small ventilation bends) in the ventilation factory, personnel involved in those lines will be interviewed. Furthermore, interviews with employees from Lindab's supply chain department are conducted in a similar fashion, to learn more about the current inventory system and productions system, LICS, LIPS and Axapta.

Apart from these interviews, relevant documents, manuals, and reports, will be used to complement findings. In addition, various types of information and data sets will be collected, for example forecasts, production schedules and sequences, machines setup times, changeover times and other technical features available in LICS or related systems. Furthermore, data about the items produced, such as demand, physical specifications, tools requirements, processing times, price/value and profit margin, will be collected.

2.7 Working Procedure

The working procedure for this study is closely related to the 'Operations Research Modeling Approach' described, for example, in Hillier and Lieberman (2010). This approach consists of six phases or steps that can be summarized as follows:

1) Problem definition and data collection
2) Formulation of mathematical model representing the problem
3) Deriving solution from the model
4) Testing and refining of model
5) Preparation for ongoing application of model
6) Implementation

Generally, the approach is applicable to a great number of operations research projects or studies. Because of this broad focus of the approach and the limitation in time, the approach has been adapted accordingly. Most notably the last two phases are excluded since they are not relevant to the research question. The adapted approach contains the following phases, which will be explained in greater details below.

1) Problem definition and data collection
2) Data analysis and formulation of a model
3) Deriving solution from the model
4) Testing and refining of model

Phase 1- Problem definition and data collection

The first phase centers around defining the problem and (initial) data collection. Generally, this is very similar to the approach described by Hillier and Lieberman (2010). The problem definition for this study is originated from discussion with Lindab and supervisor at the Production Management department at LTH. Lindab is interested in investigating parameters affecting the inventory and production planning decisions and how to potentially support operators within the production in making better decisions. Consequently, the purpose of this study is to analyze key parameters affecting the inventory and production panning decisions for two well defined productions lines and to outline a quantitative production planning tool to help operators to make better decisions.

To gather relevant data a review of available research literature was performed, which can be found in Section 3. The areas considered include operations management, inventory management and production scheduling and sequencing. The purpose of this is to gain a deeper understanding of relevant areas to the problem. After reviewing the literature, the data collection is performed. By collecting parameters from both literature and documents from Lindab a list of potentially interesting aspects is created. This is used to create a semi-structured interview guide, for interviews with operators and production planners at the different production lines. Additionally, the list of parameters is used to collect data available from databases and documents within Lindab.

Phase 2 – Data analysis and formulation of a model

As described by Hillier and Lieberman (2010), the second phase progresses from a formulated problem towards a model or idealized representation. An important step is analyzing the gathered data and formulating a mathematical model from which solutions can be derived in later steps. In the adapted approach used in this study, the analysis of the data plays a more central role than described by Hillier and Lieberman (2010). Nonetheless, a central step during this phase is the reformulation of the problem so it can be analyzed from a mathematical perspective. In this study, the analysis was conducted based on the following structure (Figure 3).

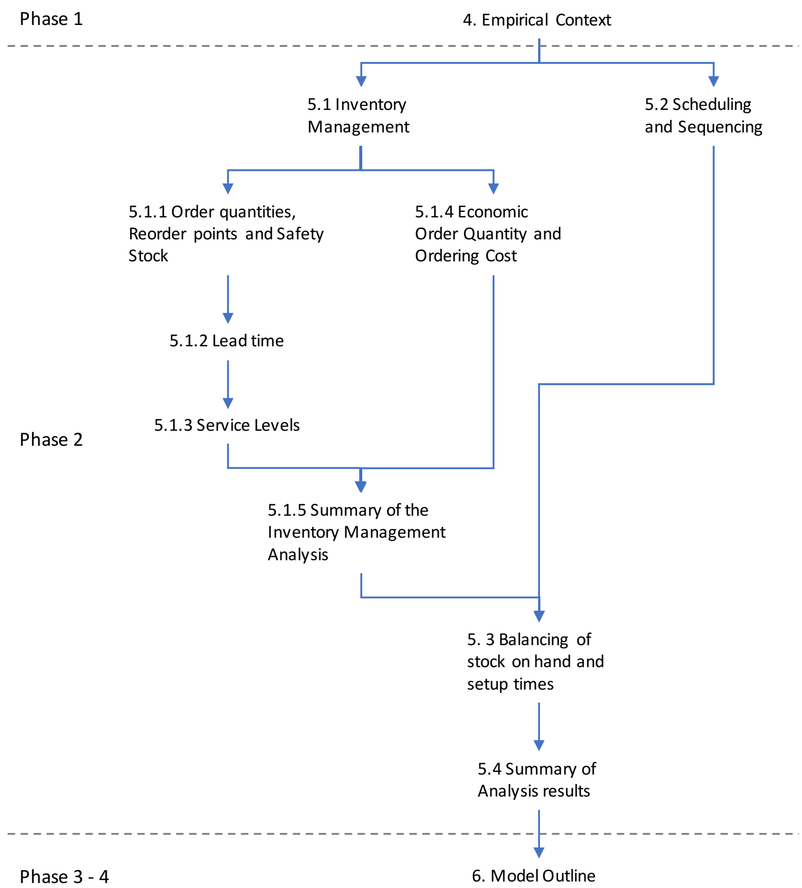

Figure 3: Structure of the second phase and the resulting report

From this perspective, a model is created that consists of decision variables, constraints and parameters. The characteristics are used to describe the problem in greater detail. A key challenge in this step is finding the correct parameters and variable for a model (Hillier and Lieberman, 2010). This challenge can be overcome by gathering relevant data, which requires a detailed analysis of the problem and topics associated with it. The approach for the development of the model can be seen as an iterative approach, where first a simple model is created to capture some of the most basic and relevant aspects. During later iterations the model is continuously refined so that it describes the reality more accurately. Here, it is important to note that not necessarily all aspects can be captured in single model to describe a problem (Hillier and Lieberman, 2010).

Phase 3 – Deriving solutions from the model

After the formulation of a model a procedure for solving the problem is generated. For this phase, several different approaches or methods exist and each of these leads to different procedures. However, it is important to note that Hillier and Lieberman (2010) consider this phase to be vital but neither the most complex nor longest in a project. For this study, the model was created and used to outline the effect both on inventory management and production scheduling and sequencing. Regarding inventory management, the focus was put on deriving different scenarios from the system so that effects of various strategies towards inventory management. As for production scheduling and sequencing, a dedicated model was used to outline and potentially find a near optimal solution for a given time period.

Phase 4 – Testing and refining of the model

The fourth and last phase within this adapted approach has the goal to validate the obtained model and results. Furthermore, the model is refined so that it can support the scheduling and sequencing process. The process to achieve this is based on steps described in the Quality Assurance (see Section 2.5), where first the model is verified and later validated. Within this study, the fourth phase stretched out over a period of time and some iteration between this and the previous phase occurred so ensure robust results. The testing of the model was based on historical data and was conducted in cooperation with experts from Lindab.

3 Theoretical Framework

The aim of this chapter is to present literature and theoretical frameworks relevant to the research question at hand and to provide relevant methods to solve the problem. The chapter is structured into four different section, beginning with a more general overview of operations management and research literature to form a basis for the following topics. Those are production scheduling and sequencing and inventory management, which can be seen at the core of this study. Lastly, additional topics such as vendor-managed-inventory (VMI) systems or single minute exchange of die (SMED), are presented.

3.1 Operations Management

Operations management plays a vital role in creating value and satisfying customer demands (Lowson, 2003). According to Bozarth and Handfield (2008), operations management is directly linked to the overall business strategy. As a result, the aim of operations is to translate this strategy into a viable functional strategy that provides products or services to the targeted customer segments. In accordance to this Lowson (2003) defines operations management as,

> *"the design, operation and improvement of the internal and external systems, resources and technologies that create product and service combinations in any type of organization."*

A company's success and growth is dependent on the alignment between its functions and targeted markets, which can be achieved by aligning marketing and operations strategies with the corporate strategy of a company (Hill and Hill, 2009). Deriving from the strategic considerations, appropriate operations processes and infrastructures guide a company to reach to a higher profit and market share (Hill and Hill, 2009).

As for the process choice, parameters such as variety and volume of products are among the most critical one to define the production process, ranging from project and job shops via batch production to production lines and continuous processing (Hill and Hill, 2009; Bozarth and Handfield, 2008). Line and continuous processing are more suitable for production environments that are characterized by medium to high production volumes of (highly) standardized products, with the aim of achieving as low as possible production costs (Bozarth and Handfield, 2008). Benefits of these production processes include low cycle time and relatively low production costs per produced unit. However, drawbacks of these processes are their relative inflexibility in the production process and long setup times for lines. Additionally, changes to other products normally lead to significant investments (Bozarth and Handfield, 2008). A further differentiation can be made based upon the principle products are produced under, based on existing or anticipated demand. The production principle that is based upon a work schedule, which is built upon anticipated demand and releasing a job is not dependent on the current work in progress, is called a push system. Contrasting, a pull system explicitly limits the work in process (Hopp and Spearman, 2011). According to this definition, in a pull system, upstream processes are activated based on signals received from downstream processes, while pre-defined production schedules control the activities in a push system (Hopp and Spearman, 2011). Based on this, traditional MRP and (R,Q)-policies are considered push models, while Kanban, CONWIP (constant work-in-process) and MRP with constant WIP are built based on a pull philosophy. Lastly, a differentiation is also possible between production approaches. Here, make-to-order (MTO) and made-to-stock (MTS) represent two common approaches, where in the first production is only triggered once customers demand exists while the other is based on anticipated demand (Chopra and Meindl, 2007).

3.2 Inventory Management

Inventory management represents a major topic in today's supply chains and its strategic importance is fully recognized by academia and in practice (Axsäter, 2006). This is due to the investment inventory represents, its potential cost savings that can be achieved by lower stock on hand (Chopra and Meindl, 2007) and the possibility to overcome uncertainties (Axsäter, 2006). Therefore, the purpose for creating and maintaining inventory are seen as twofold, economies of scale and safeguard against uncertainties.

Chopra and Meindl (2007), based Harris' (1913) economic order quantity, see inventory as a means to achieve economies of scale and thus lower costs. This effect can be seen when a different product is manufactured or purchased and the costs for doing so are relatively high. Therefore, the aim should be to produce as many units as possible so that the initial costs are justified. Another important aspect influencing the overall cost is the inventory holding cost, which counteracts the increase in production volume to reduce initial cost of setting up the production.

The other purpose of inventory is to safeguard against uncertainties in supply and demand (Axsäter, 2006). Especially variability in demand and lead times inevitably creates safety stocks, which can be used to bridge periods of longer than expected lead times.

There are numerous inventory models available in literature for different types of inventory systems and settings. The following sections of this chapter will present aspects with inventory management relevant to this study.

3.2.1 Inventory Management Systems

In a supply chain, inventory is described by different characteristics such as its location within the supply chain as well as its primary use. Inventory locations in a supply chain, to a certain degree, describes the type of goods stored in it (Chopra and Meindl, 2007). An example would be raw material inventory, which usually is focused upstream from production facilities, or finished goods inventories, which are located downstream and close to potential customers.

A further distinction can be made by the complexity of inventory system that is being analyzed. Here, the main differentiation is between a single inventory location, also called a single-echelon system, and multiple inventory locations, called multi-echelon systems (Axsäter, 2006). The focus of this study is put on single-echelon systems and therefore no models for multi-echelon systems will be presented or applied.

3.2.2 Costs in Inventory Management

The main costs components considered in inventory management are the following (Axsäter, 2006):

- Holding costs

  In the classical definition, represents cost incurred when storing a single item for a period of time, one part of this is the cost of capital tied up in inventory. Commonly, the holding cost h is simply calculated by multiplying the product cost c_r, including purchasing or production costs, with a carrying charge r. For calculation of the capital cost, depending on the industry, the rate varies from 12 to 34% and a common figure used in practice is 25% (Berling and Rosling, 2005; Silver et al., 1998). According to the opportunity cost approach, the carrying charge should reflect, the highest expected return for an alternative investment, while based on the weighted average cost of capital, the carrying cost “ is set equal to the firm’s weighted average cost of capital” (Berling, 2005).

  $$h = r * c_r \qquad (1)$$

  Apart from the capital costs (opportunity cost of money invested), components included are inventory service costs, storage space costs and inventory risk costs (Berling 2005; Silver et al., 1998). Inventory service costs includes insurance and tax, while storage space cost consists of costs for handling, distribution, transportation and physical storage facilities. Finally inventory risk cost includes depreciation and obsolescence (Berling 2005). However, in many calculations only the opportunity costs for capital tied up is considered as the cost of carrying items, simply because it is assumed to make up the largest portion of the carrying cost (Silver et al., 1998). In contrast to this assumption, some researches agree that the cost of carrying an item does not make up the dominating part of the holding cost for all goods and in some cases, it even might be negative (Berling and Rosling, 2005).

- Order or Setup costs

  The order or setup cost describes the costs associated with placing a purchase order or setting up a machine to produce a batch. This cost is independent from the size of the order or batch of products. The exact definition of this cost is dependent on the product and from where it originates, Berling and Rosling (2005) and Silver et al. (1998) suggest the following definitions:

  - Order cost

    All costs that are incurred during the order process of products from outside suppliers, including order handling, transportation and inspections.

  - Setup cost

    This cost only occurs when a company produces goods within its own production facilities. Aspects included in this cost are order cost for raw materials, wages, cost for decreased production speed or interruption during the first phase after a setup and opportunity costs.

  Usually, order and setup costs are assumed to be relatively stable and Chopra and Meindl (2007) go as far as considering them to be constant. Nonetheless, Axsäter (2006) states that learning effects can influence setup costs and facilitate in lowering them. In contrast to the holding cost, this cost is independent of the number of units purchased or produced.

- Shortage or Stock-out costs

  This cost only occurs when a product is not available in the quantity required by customers or downstream process steps. Contributing factors to this cost are discounts for compensation of late deliveries, lost sales or penalty fees. In addition to these, aspects such as loss of customer goodwill or future lost sales can be added to shortage cost. Because of these considerations, it can be very difficult to determine an exact value for these costs per se (Axsäter, 2006).

- Additional costs

  Apart from the above-mentioned costs, several other costs can be attributed to inventory management activities. Axsäter (2006) lists costs for information systems, administration, risk of obsolescence and insurance.

3.2.3 Ordering Systems

A main goal of inventory management is to satisfy the demand by building up appropriate buffers, but at the same time being cost efficient by avoiding unnecessary inventory. In other words, customer demand can be satisfied without unnecessary delays and excessive costs. Therefore, inventory management focuses on determining where, when and how much should be produced (Axsäter, 2006). With this in mind, key aspects are stock on hand, outstanding orders (orders placed but not yet delivered), backorders, inventory position and inventory level (Axsäter, 2006, p. 46).

$$\textit{Inventory position} = \textit{Stock on Hand} + \textit{Outstanding Orders} - \textit{Backorders} \qquad (2)$$

$$\textit{Inventory level} = \textit{Stock on Hand} - \textit{Backorders} \qquad (3)$$

An additional aspect in an inventory system is how it is monitored, which can be performed either continuously or periodically. In a system with continuous review and reorder point policies, an order is placed immediately when the inventory position reaches the reorder point. After placing an order, the expected delivery occurs after the lead time L. However, in a periodic review system, the inventory position is monitored only once during a certain time interval T (Silver et al., 1998). Thus, orders are placed at fixed points in time and if a review period has been missed, the next delivery occurs at T+L.

Another defining aspect in an inventory system is the ordering policy. One of the most common ordering policies is the (R,Q)-policy, where an order Q is released once the inventory position reaches the reorder point R (Axsäter, 2006). Commonly, in a (R,Q)-policy, first the optimal order quantity Q* is determined and then R calculated with the help of stochastic models. Determining these values is highly depended on the product and demand behavior. However, other approaches exist, where Q* and R* are determined simultaneously. Products with relatively large, frequent and stable demand can be approximated to follow a normal distribution. In contrast, products with irregular and varying demand can usually be best expressed using discrete distributions such as, for example, the Poisson distribution (Figure 4). (Silver et al., 1998)

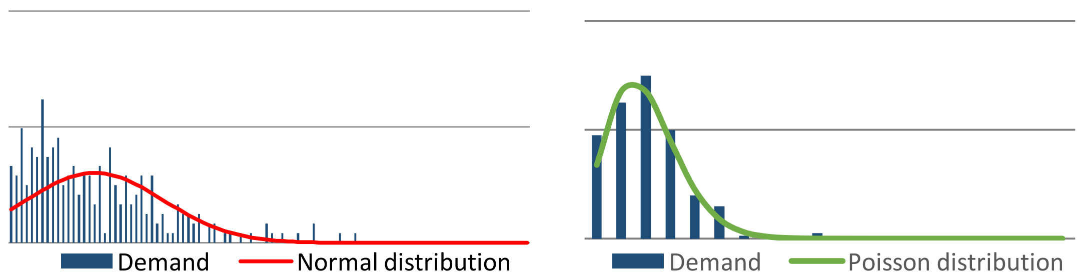

Figure 4: Comparison between normally distributed and compound Poisson demand

A common and well-known model for determining the batch quantity Q* is the economic order quantity (EOQ) due to Harris (1913). The EOQ model is based on the following assumptions:

- Continuous and constant demand
- Order and holding costs are constant over a certain period
- No shortages are allowed
- The whole ordered quantity is delivered at the same time
- The ordered quantity does not need to be an integer[3]

[3] For products with discrete demand Q* is rounded to the next integers and for both possible solutions the inventory costs must be calculated. The one with the lowest costs represents the best possible order quantity given by the specified model assumptions.

Under these assumptions, it is possible to calculate Q* using (4). This model balances the cost of capital per time unit being tied up, with the ordering/ setup costs per time unit.

$$Q^* = \sqrt{\frac{2\ A * D}{h}} \tag{4}$$

where,

Q*	Optimal order quantity
A	Order/ setup cost
D	Annual demand
h	Holding cost per unit

Along with the determination of reorder points and order quantities, the achievable service level associated with these values is a crucial aspect in inventory management (Axsäter, 2006). The types of service levels relevant to this study are the cycle service level (S_1), the fill rate (S_2) and the ready rate (S_3) (Axsäter, 2006, p. 94). The cycle service level S_1 is defined as the probability of no stock outs per order cycle and it is commonly used in continuous review systems, where a batch of Q is always ordered. Assuming a continuous review (R,Q)-policy with constant lead times L and normally distributed demand S_1 can be calculated using (5).

$$S_1 = (D(L) \leq R) = \Phi(\frac{R - \mu'}{\sigma'}) \tag{5}$$

$$\mu' = \mu * L \tag{6}$$

$$\sigma' = \sigma * \sqrt{L} \tag{7}$$

where,

R	Reorder point
L	Lead time
μ	Average demand per time unit
σ	Standard deviation of demand per time unit
μ'	Average demand during lead time
σ'	Standard deviation of demand during lead time.

The ready rate S_3 corresponds to the probability of having a positive inventory level, see (8).

$$S_3 = P(IL > 0) \tag{8}$$

For normally distributed customer demand, S_2 and S_3 are equal and can therefore for continuous review (R,Q)-policy systems with constant lead times be obtained from (9) (Axsäter, 2006, p. 98).

$$S_2 = S_3 = 1 - F(0) = 1 - \frac{\sigma'}{Q}\left[G\left(\frac{R - \mu'}{\sigma'}\right) - G\left(\frac{R + Q - \mu'}{\sigma'}\right)\right] \tag{9}$$

The fill rate increases with increasing reorder points and order quantities.

The reorder point defines an inventory position which triggers an order to replenish the stock on hand. This value can be, in accordance with the initial assumptions for Q*, non-integer. To determine the reorder point under normally distributed demand, one can rearrange the formula for S_1 shown in (5) or (9) solve for R, depending on the available information or data.

For compound Poisson distributed demand, the determination of R and Q is more complex. For these types of distributions, demand is considered to be discrete and stochastic. This means that customers arrive according to a Poisson process with an intensity λ and the amount of customer demand is a stochastic variable. It follows that the probability for k demand occurrences during the period t is (Axsäter, 2006, p. 78):

$$P(k) = \frac{(\lambda t)^k}{k!} e^{-\lambda t}, k = 0, 1, 2, \ldots \tag{10}$$

The average demand and the variance of the number of demand occurrences are both equal to λ*t in this model (Axsäter, 2006, p. 78). As mentioned before, the demand size is a stochastic variable and the probability of demand size j is expressed as f_j. Accordingly, the probability that k customer orders in j units is denoted f_j^k. The stochastic demand during a time interval can then be calculated as follows. (Axsäter, 2006, p. 79)

$$P(D(t) = j) = \sum_{k=0}^{\infty} \frac{(\lambda t)^k}{k!} e^{-\lambda t} f_j^k \tag{11}$$

Using (11), it is possible to determine the average and the standard deviation of the demand during a given time period, such as the lead time. According to Axsäter (2006, p. 79.-80) the average demand per time unit μ and the standard deviation per time unit σ can be calculated using (12) and (13).

$$\mu = \lambda \sum_{j=1}^{\infty} j\, f_j \tag{12}$$

$$\sigma = \sqrt{\lambda \sum_{j=1}^{\infty} j^2 f_j} \tag{13}$$

Having calculated the average and standard deviation of demand per time unit, it is possible to determine the average and standard deviation of demand during the lead time. The formulas used are the same as those used for normally distributed demand.

Lastly, an important aspect influencing both Q and R is the fluctuation of demand and lead time due to seasonality, trends and change in market prices. Companies must regularly recalculate the values for Q and R for these changed parameters. With regard to demand fluctuations, forecasting methods using seasonal indices can help improving the demand approximation (Axsäter, 2006).

3.3 Production Scheduling and Sequencing

3.3.1 General Considerations

Production scheduling and sequencing describes the decision-making process of arranging, controlling and optimizing work and workloads in a production process. The main objective is meeting due dates originating from customer orders or material requirements for subsequent process steps (Hopp and Spearman, 2001). Here, a main challenge is balancing due dates with maximizing resource utilization, lowering inventory levels and total costs. A distinction between different production scheduling and sequencing approaches is made based upon the production strategies, for example make-to-order (MTO) or make-to-stock (MTS). In a MTO environment due dates for the delivery to the customers are available and these dates are a major driver and pull orders through the production. In contrast, customer orders are usually not available in a MTS environment. Thus, inventory positions and levels are major drivers for production (Hopp and Spearman, 2001).

According to Pinedo (2016), there are other differences between scheduling and sequencing of jobs: While production scheduling focuses on allocating jobs to different machines, meaning what and where to produce jobs, production sequencing focuses on only a few machines, often a single one, and aims at optimizing the production of jobs towards an objective. As it can be seen from these definitions, scheduling is concerned with a broader environment which may include many different influencing factors. On the other hand, sequencing, because of its narrower focus, includes fewer influencing factors but can provide a more in-depth perspective (Pinedo, 2009).

3.3.2 Performance Measures and Objectives

Within production scheduling and sequencing, several performance measures have been identified. Depending on the type of production strategy, different sets of objectives and measures are relevant. Some of the most predominant measures include (Hopp and Spearman, 2001; Pinedo, 2009; Silver et al., 1998):

- Service level

  A measure that is commonly used in MTO environments to measure the fulfillment of orders before or at the requested due dates. The service level measure counts jobs that are completed before or at their planned due date and is generally expressed as the fraction of on-time jobs versus all jobs.

- Fill rate

  The fill rate represents the MTS equivalent to service level. Here, it defines as the fraction of demand that can be fulfilled immediately from inventory on hand.

- Lateness

  Defined as the difference between the job/order completion date and the due date. The lateness L_j is calculated by subtracting the due date d_j from the completion time c_j of a job j.

$$L_j = c_j - d_j \qquad (14)$$

It is important to note that lateness can be both positive, a job was completed too late, or negative, a job was completed ahead of schedule.

- Tardiness

  This measure describes the actual lateness of a job, meaning the value is zero, when the job is completed before or on time, and otherwise it is equal to the job lateness. Commonly, this is expressed as follows.

$$T_j = \max(c_j - d_j, 0) = \max(L_j, 0) \tag{15}$$

- Machine utilization

  As previously described, maximizing machine utilization is one key objective in reducing costs and increasing return on investment. Furthermore, the throughput rate, equivalent to the output rate, represents an important measure within production, which many strive to maximize. This can be achieved by improving the bottleneck utilization, which should ideally have as little as possible idle times and as few as possible setups.

- Cost-related measures

  In addition to the measures discussed above, there exist several other measures that are more directly related to costs occurring in production. For instance setup costs, work-in-progress inventory costs and (finished goods) inventory costs are some of the more commonly used measures. Reducing setup times results in faster changes between different jobs and usually lower setup costs. The relationship between setup times and costs has been proven to not necessarily be proportional, hence measuring both is recommended. Another important measure is the work-in-progress (WIP) inventory. WIP inventory ties up capital, which could be used somewhere else, and obstructs operations.

In classical scheduling or sequencing problems, focus most often is to find (near) optimal solutions for one or more of the above-mentioned measures. Due to the complexity of this problem, this is usually done for a limited number of machines (one to three). Both scheduling and sequencing problems generally are NP-hard problems, which cannot be solved in polynomial time, and that even relatively small numbers of jobs result in complex and lengthy calculations. To keep the complexity to a minimum, the following assumptions have usually been made (Hopp and Spearman, 2001):

- All jobs are available in the beginning of the scheduling period
- Process/ production times are deterministic and independent from each other
- Machines don’t experience breakdowns
- Jobs are not interrupted or cancelled

These assumptions, as with the EOQ formula, serve to reduce the complexity and some of them are excluded in more advanced models. However, real systems rarely fulfill these assumptions, which therefore leads to a very limited applicability of general scheduling and sequencing models (Hopp and Spearman, 2001). As a result, specialized models and heuristics have been developed to provide more applicable solutions.

3.3.3 Notation and Classification

Scheduling and sequencing problems usually use a fixed notation, where the number of jobs is denoted by n and the number of machines by m (Pinedo, 2016). An additional and common notation is $\alpha|\beta|\gamma$, where α describes the shop (machine) environment, β processing characteristics and γ the measure/ objective to be minimized (Allahverdi et al., 2008; Pinedo, 2016). Among the possible shop environments (α) are: single machine, flow shop, flexible (hybrid) flow shop, assembly flow shop, parallel machines, job shop and open shops (Allahverdi et al., 2008; Pinedo, 2016). The different processing characteristics (β) can display two different kinds of information, shop characteristics and setup information. Shop characteristics include release dates (r_j), preemptions (premp) and precedence constraints (prec). The setup information, where some of the most commonly are: setup times or costs, sequence-dependent or sequence-independent, non-batch or batch/ family setup or family removal (Figure 5).

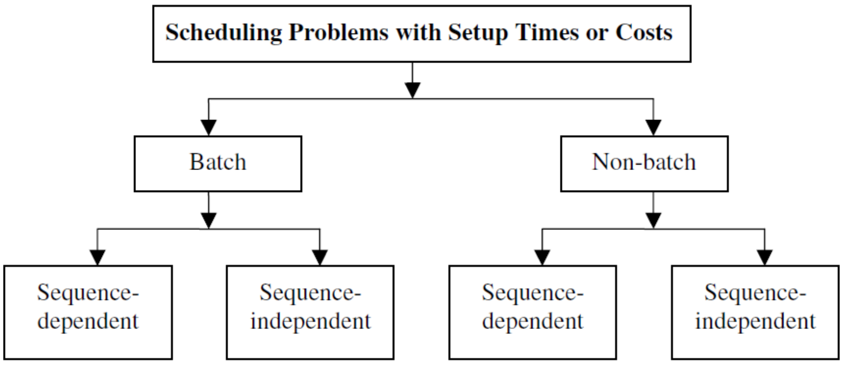

Figure 5: Classification of setup time or cost scheduling problems (Allahverdi et al., 2008)

Lastly, the objective γ describes the measure that should be minimized. Often these are selected from the previously described measures, which include among other lateness, tardiness or total setup time (Allahverdi et al., 2008).

Since the selected production lines at Lindab produce in batches and also experience sequence dependent setup time/cost, some models focusing on this are addressed in the following section. Generally, these types of problems are distinguished based upon the objective function, reducing setup times or setup costs (Allahverdi et al., 2008). Based on this distinction, sequence dependent batch setup time problems are denoted as $ST_{sd,\ b}$ and sequence-dependent batch setup cost as $SC_{sd,\ b}$.

Karabati and Akkan (2006) suggest a branch and bound algorithm to solve a $ST_{sd,\ b}$ problem in a single machine scenario with the objective to minimize the overall completion time ($\sum C_j$ Problem). The method is applicable to a group of jobs that can be clustered into families based on the similarity of the processing requirements. They showed that a branch and bound algorithm can be applied to problems with up to 60 jobs and 12 families. Similarly, Sourd (2005) addressed the general problem of one machine scheduling problem with setup and earliness–tardiness penalties with the objective of minimizing the earliness–tardiness and setup costs. It was concluded that a branch and bound algorithm in this case cannot be applied to problems with no more than 20 jobs and for problems with the higher number of jobs, a multistart heuristic was suggested.

3.3.4 Single Machine Models

In the following, the focus is put onto single machine problems with n jobs, because the considered production lines at Lindab can be considered as single machines from a scheduling and sequencing perspective.

Single machine problems are less complex compared to other types of problems and some basic heuristics are available that can be applied on the certain problems. Many single machine problem models fall into the category which is called offline scheduling problems. Within these problems, all data such as processing times, due date, release date is available in advance some part of and can be used in the scheduling (Pinedo, 2016). Unlike offline models, in online models some part of the problem data (e.g., release date) is not known before starting the processing.

Some of the sequencing heuristics, commonly known as dispatching rules, include Shortest Processing Time first (SPT), Weighted Shortest Processing Time first (WSPT) and Earliest Due Date first (EDD) (Hopp and Spearman, 2001; Pinedo, 2016; Allahverdi et al., 2008). Specifically, SPT and WSPT aim at reducing the overall processing time by dispatching jobs based on processing time. EDD, on the other hand, reduces the total number of late or tardy jobs by dispatching jobs with regard to their due date. These dispatching rules result in optimal sequence for a single machine and a given set of jobs, if the assumptions described by Pinedo (2016) are applicable. It is important to note that each of these heuristics works under certain assumptions which makes their optimality limited to certain environments. For instance, EDD, which dispatches jobs based on their due date from the earliest to the latest, assumes that ”size and routings are fairly consistent” (Hopp and Spearman, 2001). Unlike EDD, SPT does not consider due dates and jobs are dispatched based on their processing time from the shortest to the longest. Nevertheless, SPT’s average due date performance is generally good and it is also quite good in decreasing average manufacturing times and improving machine utilization (Hopp and Spearman, 2001).

3.3.5 Greedy Methods and Tabu Search

As stated earlier, the sequencing of several jobs in an optimal order, can quickly result in very lengthy calculations that are likely infeasible. Therefore, several heuristics were developed and applied in order to sequence jobs, to find (near) optimal solutions quickly (Hopp and Spearman 2011).

A group of well-known heuristics that can be applied are different types of greedy algorithms, which focuses on the best choice available at a given point in time (Cormen, 2009). A greedy algorithm aims at optimizing towards an objective through a stepwise selection of items out of a set of items and checking if an improvement is achieved. To create a greedy algorithm the following functions or components should be available (Cormen, 2009):

- A set of items, often called candidate set
- A function that selects the best option from the candidate set
- A function that checks the feasibility of a set
- An objective function
- A solution function, which will indicate when a solution is obtained

A greedy algorithm, using the selection function, selects an item from the candidate set and (temporarily) adds it to the solution function. If this leads to an infeasible solution then the item is rejected, otherwise it is added to list and the process restarts for the next item (Cormen, 2009).

For sequencing problems, the candidate set is a number of jobs that can be sequenced and a greedy algorithm is applied to find a jobs sequence that leads to an improvement in production process by interchanging jobs. The interchange that leads to the largest reduction in, for example, make span is executed and the search for the next interchange with the largest improvement begins (Hopp and Spearman, 2011). This process quickly leads to a local optimum, which means the solution found is better than any adjacent solution. However, overall performance is not ideal, which tabu search attempts to address. Tabu search is a heuristic that finds (near) optimal solutions, where other methods, for example the greedy algorithm, would find a local but not global optimal solution (Glover, 1990). The heuristic forces the search away from local optima towards a global optimum by prohibiting recently considered actions. Actions that ended up in the tabu list, are prohibited for a limited time until the algorithm moves on to other actions. In sequencing problems, actions can be defined as the placement of jobs within a sequence (Hopp and Spearman, 2011). Essential components of a tabu search are different types of memories or tabu lists, that help in guiding the search towards the optimum. Glover (1990) defines these different memories as follows:

- Short-term memory
  This memory contain action previously taken. An action in this list are prohibited until a predetermined number of actions have past, then it is available again.
- Intermediate-term memory
  Contains prohibited actions that steers the search towards potentially promising areas for an optimum.
- Long-term memory
  Rules that drives the search in different regions, for example once it finds a (potentially) local optimum or is stuck on a plateau.

For scheduling and sequencing problems, especially for single machine scheduling problems, the tabu algorithm has shown to produce optimal solutions in most cases (Barnes and Laguna, 1993). Depending on the objectives considered in the problem, it can be seen as an asymmetric traveling salesman problem, which focuses on finding the right permutation, or a more complex tabu search across many possible options. It is notable that in a tabu search for single machine scheduling, beside pairwise interchanges of jobs, insertion moves are also allowed which means moving a single job in a new position (Barnes and Laguna, 1993). This additional type of action also improves the performance of the search and it has been shown to be feasible for up 100 jobs (Barnes and Laguna, 1993).

3.4 Additional Topics

In addition to the previously discussed topics, the aspects such as vendor managed inventory and single exchange of die (SMED) are also relevant for the context of this study, although to a lesser extent. Reason being that several characteristics of the observed and analyzed production lines are influenced or characterized by them.

3.4.1 Vendor Managed Inventory

An additional aspect, influencing the inventory management at Lindab is a so-called vendor managed inventory (VMI) system.

Theory describes VMIs as a partnership between two companies in different stages of a supply chain (Chopra and Meindl, 2007). While a basic partnership is limited to information sharing about different aspects of operations and inventory management, a more developed partnership, namely a VMI, represents a much closer cooperation. In many cases, the supplier owns the consignment until it is sold or used by the other company and manage it throughout the channel (Chopra and Meindl, 2007). In other words, in a VMI-consignment, the consignor (the owner of goods) takes the full responsibility for maintaining product availability for customers and delivers it to the consignee to be used or sold (Dong and Xu, 2002; Simchi-Levi et al., 2003). Considering the retailer-supplier partnership (RSP) strategy, a VMI system is one of the most developed partnerships. The supplier dominates decision-making about inventory plan and has access to real-time information about point-of-sale data and stock level and utilizes available data to perform the demand forecasting and chose the inventory level and inventory policy for each item (Simchi-Levi et al., 2003; Tyan and Wee, 2003).

Many researchers emphasize the beneficiary role of VMI in reducing the distortion of demand information, the so-called bullwhip effect (Disney and Towill, 2003; Çetinkaya and Lee, 2000; Lee et al., 1997). This is due to the reduction in the number of the layers in the decision-making process, which leads to a shorter lead time and a more efficient flow of material and information through the supply chain. Furthermore, the intensive information sharing minimizes information delays and leads to a more accurate demand forecasting (Disney and Towill, 2003). Moreover, using a VMI can reduce inventory carrying cost and the total cost of the channel. As the supplier manages the stock in the whole channel, it is easier to optimize the stock level and location and consequently obtain more cost-efficient solutions. In addition, the supplier has a chance to obtain more accurate data and therefore improve its operations (production, transportations and inventory management). However, it takes longer time for the supplier than the retailer to enjoy the cost benefit of VMI implementations, due to additional costs of inventory owning and operational costs related to inventory control and forecasting. (Dong and Xu, 2002)

Within Lindab the production is seen as a supplier to the finished goods warehouse and is responsible for managing the production according to the defined inventory system in such a way that leads to a sufficient stock level for different items. Hence, this approach can be described as an internal VMI system.

3.4.2 Single Minute Exchange of Die

A central aspect in increasing production flexibility and allowing for smaller order quantities is the reduction of setup times. Lowered setup times and increased flexibility in production, enable a company to sequence a wider range of products within a production schedule (Hopp and Spearman, 2001). A well-established method for reducing setup times is Single Minute Exchange of Die (SMED), which is part of the lean and total productive maintenance tools (McIntosh et al., 2000). SMED was "invented" by Shigeo Shingo during the 1980s and was initially implemented in Japanese manufacturing companies (Shingo, 1985). The aim of the method is to reduce machine setup times between products to less than 10 minutes, which allows the production to be more flexible (Agustin and Santiago, 1996). An important concept in this method is the differentiation between internal and external setups. External setups are activities that occur outside of a machine and don't require it to halt, internal setups represent the opposite (Shingo, 1985). Shingo's (1985) method includes the following four stages, which can also be seen as the process to achieving SMED.

0. Internal and external setups are not differentiated
1. Separation between internal and external setups
2. Shift from internal to external setups
3. Improvement of operational elements related to setups

Moving through the different stages can help a company to reduce setup times within manufacturing significantly. The documented results vary between over 90% (Shingo, 1985), up to 85% (Agustin and Santiago, 1996) and up to 80% (McIntosh et al., 2000) reduction from initial setup times.

4 Empirical Context

This chapter describes the investigated company, Lindab AB, and focuses on the characteristics relevant to this study. These aspects include a short company profile and a description of the supply chain adjacent to the production lines. Furthermore, the current information systems, inventory management and scheduling and sequencing approaches are described.

4.1 Company Profile

Lindab AB, is an international company that develops, manufactures and distributes products for construction and indoor climate control. The company was founded in 1956 in Lidhult, Sweden, but later moved its production and headquarters to Grevie, where it is still located today. Until today, Lindab has expanded its operation into 32 countries. With its products Lindab currently serves around 24 000 customers in 60 countries, through its own branch network, a web shop and external retailers. The main markets to Lindab, measured by sales are Northern and Western Europe. Sweden, Denmark and the United Kingdom represent the largest sales volumes in 2015. In addition to several local warehouses and production sites, Lindab operates ten central production sites, which produce a large range of products on automated machinery.

Historically and today, manufacturing has been a key focus of the company. In general, Lindab's offerings can be segmented into products and solutions. An additional segment, called building systems, exists, but it is excluded from this study, due to relatively low sales volumes and separate administration. The segment of products and solutions, which accounts for 89% of net sales, includes six different product groups are included. Among these groups, ventilation products and rainwater systems are the focus of this study.

4.2 Supply Chain and Production Processes

As this study considers two production lines within Lindab's profile and ventilation factories, this section describes their supply chain. These range from steel mills, located at the most upstream part, to retailers and customers at the most downstream end.

Steel mills are responsible for providing full steel coils in different colors and materials, which are raw material to Lindab Steel. The lead time from an order to its delivery varies significantly and lies between 20 and 80 days. Lindab Steel slits the coils into different widths to be used to produce different kinds products. Once Lindab Steel receives an order from a production site, the processing and transporting of coils to the profile or ventilation raw material warehouse requires three to five days. When Lindab profile and ventilation have processed the coils into finished products, the finished goods are stored in warehouses and await distribution to customers. Customers can be categorized to three groups, internal or external customers and building sites. The lead times from production sites to the customers ranges from eight to eleven days, consisting of about five days production lead time and three to six days transportation lead time. The supply chain structure in Figure 6 illustrates this.

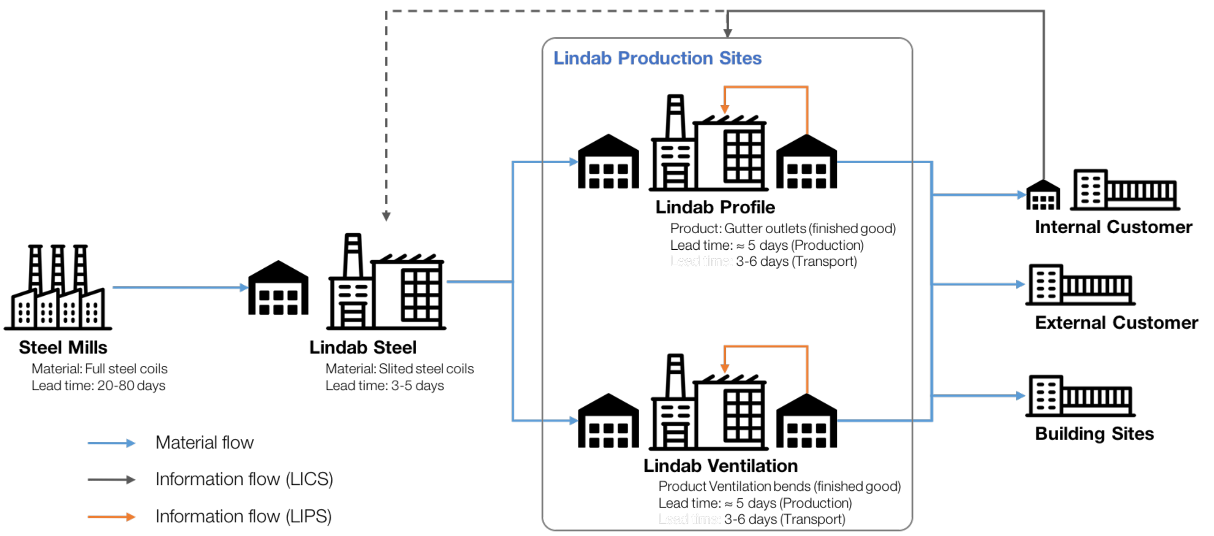

Figure 6: Supply chain structure relevant to this thesis

The information flow across the different entities within the supply chain is managed by Axapta, LICS and LIPS, where the ERP-system Axapta plays the main role in this matter. All data, including point of sale (POS) and stock on hand for the internal customers, are visible in these systems and are used in upstream entities. The information mostly flows upstream from the internal customers back to the production facilities and Supply Chain Center of Excellence. Additionally, information from the production sites, in this study from the profile and ventilation factories, can been accessed by the supply chain center.

The two production lines under consideration are line 206 and line 110_6. Production line 206 at Lindab Profile, later referred to as the *profile line*, produces gutter outlets, of which 83 different variations based on sizes and color are offered. Production line 110_6 at Lindab Ventilation, from now on referred to as the *ventilation line*, produces ventilation bends in several sizes and specifications, in total 28 variations. The following figure (Figure 7) gives an outline of the different products and product variations produced at the two production lines.

Profile line

Size	Colour/ Material	
100-75	387 (Coffee Brown)	MGRÅ (Dark Grey)
100-87	ALUZ (Aluminium)	MRÖD (Dark Red)
125-100	AMET (Anthracite Metallic)	SMED (Silver Metallic)
150-87	AVIT (White)	SVRT (Black)
150-100	BRUN (Brown)	TRÖD (Tile Red)
150-111	GALV (Galvanized Metal)	ZM (Zinc Magnesium)
150-120	KMET (Copper)	

Ventilation line

Size	Material	Barcode	Code
125-15	GALV (Galvanized Steel)	Yes	B (no rubber gaskets)
125-30		No	BU (Rubber gasket on each end)
125-45			BMU (Rubber gasket on one end)
150-30			BKML (Small radius with special rubber gasket)
150-45			BKMU (Small radius with one rubber gasket)
150-90			BEJ (plain bend with any add. finishing)
160-15			
160-30			
160-90			

Figure 7: Overview over the products and product variations

The profile factory usually operates with just one shift of eight hours per day and no production during weekends. But during peak seasons, from mid-spring until early autumn, some production occurs in 1½ shifts per day. Additionally, not all production lines operate continuously as operators only start up a production line if required. As a result, operators are shared between production lines and in some situations, there are not enough operators to produce products in all line at the same time.

The production in the ventilation factory operates with three shifts each day, which are generally eight hours long and contain roughly 7,5 hours of productive time. Additionally, the production in the ventilation factory also operates during the weekend, where two shifts run each day. Furthermore, the production undergoes scheduled maintenance every third week for a couple of hours, usually less than half a shift.

Production Process – Profile Line

After the production line has been set up for a new product, the production process starts with the cutting of the metal coil into small metal sheets. In the next station, metal sheets are pressed into halves of the gutter outlet. Then, these halves are transferred to the next station, where halves are pressed together. The final step, the finished gutter outlets are transferred to packaging station where they are packed manually and sent to the warehouse. Figure 8 illustrates the production process schematically.

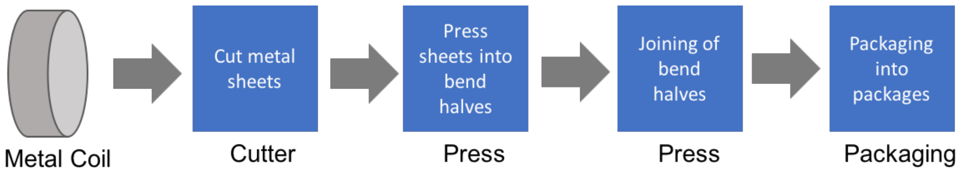

Figure 8: Production process of the profile line

The production process of the profile line consists of a number of products steps, where most are automated. Due to this semi-automated process, the cycle times per unit on this production line vary only slightly and they could theoretically be within the range of 22 to 26 seconds. However, due to some external factors, such as raw material of poor quality or unexpected delays, the actual cycle times are usually higher than that. The factor by which the actual cycle time is higher, is determined by a KPI called overall equipment effectiveness (OEE). For the profile line the OEE generally lies around 50% and therefore this value is chosen for this study.

The setup time of the profile line is defined by three main aspects, namely product size, coil width and product color. Depending on the kind of product that has to be produced next, the setup times can range from just 15 minutes, for changing to another coil width or color, up to 60 minutes, for also setting up the machine to produce another product size. An exception to this is represented by setups for gutter outlets made from so called naked metal, like copper, zinc magnesium or aluminum. The special characteristics of these materials lead to much longer setup times, which generally are around 120 minutes. A detailed overview over the setup times between different products can be found in the Appendix 11.1.

Production Process – Ventilation Line

The production process of the ventilation line is illustrated in Figure 9. In a first step, a metal coil is fed into the cutter to create metal sheets, which are then pressed into halves of a bend. In the next step, the halves are manually transferred to the welding station, where the halves are welded together on an automated welding station. Then the welded bends are transferred via a conveyor system to a station called SUE. Here, the bends receive, if required, folds and rubber gaskets as well as a small label. Depending on the type of product the entire SUE station or some of it is omitted. After the SUE station, the product is transferred to the end of the production line, where it is packed. In this step, the bends are simply dropped into the package from a conveyor and operators occasionally check if manual packaging is required. Afterwards, the finished products are picked up and transferred to the finished goods warehouse. A schematic representation of the production process is given in Figure 9.

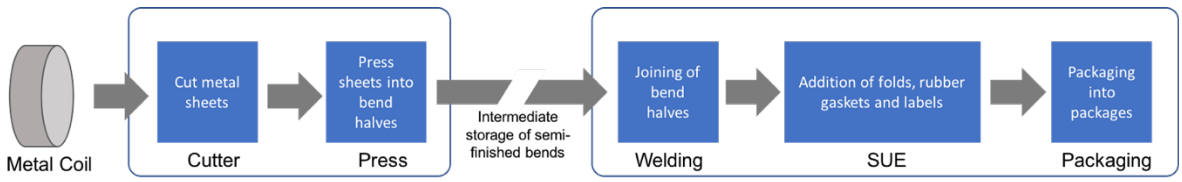

Figure 9: Production process of the ventilation line

Similar to the production process of the profile line, the process steps for the ventilation line are mostly automated. The theoretical cycle time for this production line is 10 to 13 seconds and therefore almost twice as fast as the one in the profile factory. Furthermore, the OEE of the ventilation line is on average at 63%, which results in significantly faster actual cycle times ranging from 16 to 21 seconds.

The setup times of the ventilation line is mainly dependent on three aspects, which are the dimension, angle and code of a product. In case of a dimension change, for example from 125 to 160 millimeters, a relatively complex setup of five tools is required. Consequently, the total setup up time for such a change is usually 20 minutes. Similarly, changing between angles, for example from 150-30 to 150-90, requires several tool changes and is done in a shorter time frame, roughly 10 minutes. However, changing from one code to another, e.g. B to BEJ, can constitute in a fast changeover of just one minute, but may take up to 180 minutes if the machines have to be setup for more complex products, for example code BKML and BKMU. A detailed overview over the setup times between different products can be found in the Appendix 11.2.

4.3 Information Systems

The supply chain map in Figure 6 shows that Lindab not only manages material but also information flow across several stages of its supply chain. Key systems relevant for this thesis project are Axapta, LICS and LIPS, whose basic interaction is illustrated in Figure 10.

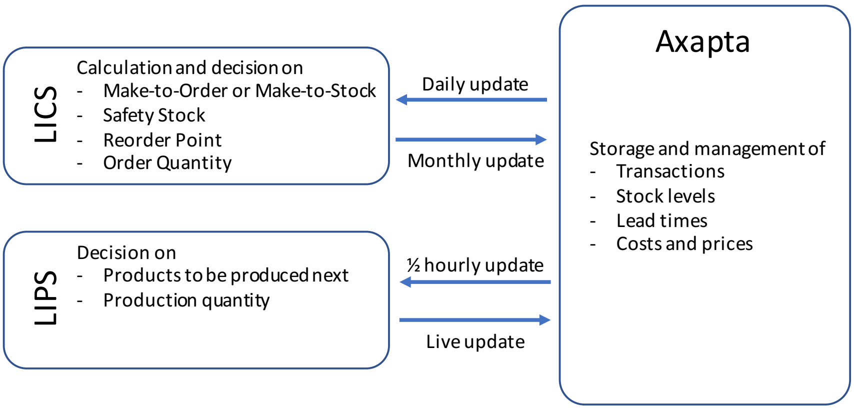

Figure 10: Interactions and interfaces between Axapta, LICS and LIPS

The central IT system is Microsoft Dynamics AX (formerly Axapta), an enterprise resource system. Axapta is used to administer information in nearly all functions and is implemented in all Lindab organizations across Europe. With regard to inventory management, Axapta contains nearly all information, including stock levels, lead times and transactions among other, but is not directly involved in calculations regarding inventory management, production scheduling and sequencing. However, Axapta has been used to manage Lindab's inventory before the introduction of LICS a few years ago.

LICS, Lindab Inventory Control System, is connected to Axapta through several interfaces and both systems exchange information on a regular basis. LICS employs (R,Q)-policies and was introduced in 2014 in an effort to improve customer service and lower the costs related to inventory. The main functionality of LICS is the determination of what products should be kept on stock and in what quantity. Furthermore, reorder points and order quantities as well as safety stocks are also determined by LICS.

LIPS or Lindab Inventory Production System is another key information system used by the company. It represents a production scheduling and sequencing tool, which is used by operators within production, and has the aim to visualize the current status so that the production can be scheduled more effectively. This is achieved by displaying the inventory level for each product at a production line in combination with outstanding customer orders, safety stock and planned production. LIPS allows operators to decide for themselves what products should be produced and what quantity. Furthermore, it allows them to do all this without extensive support from other systems or personnel. Figure 11 shows a screenshot from the main user interface for a production line from LIPS.

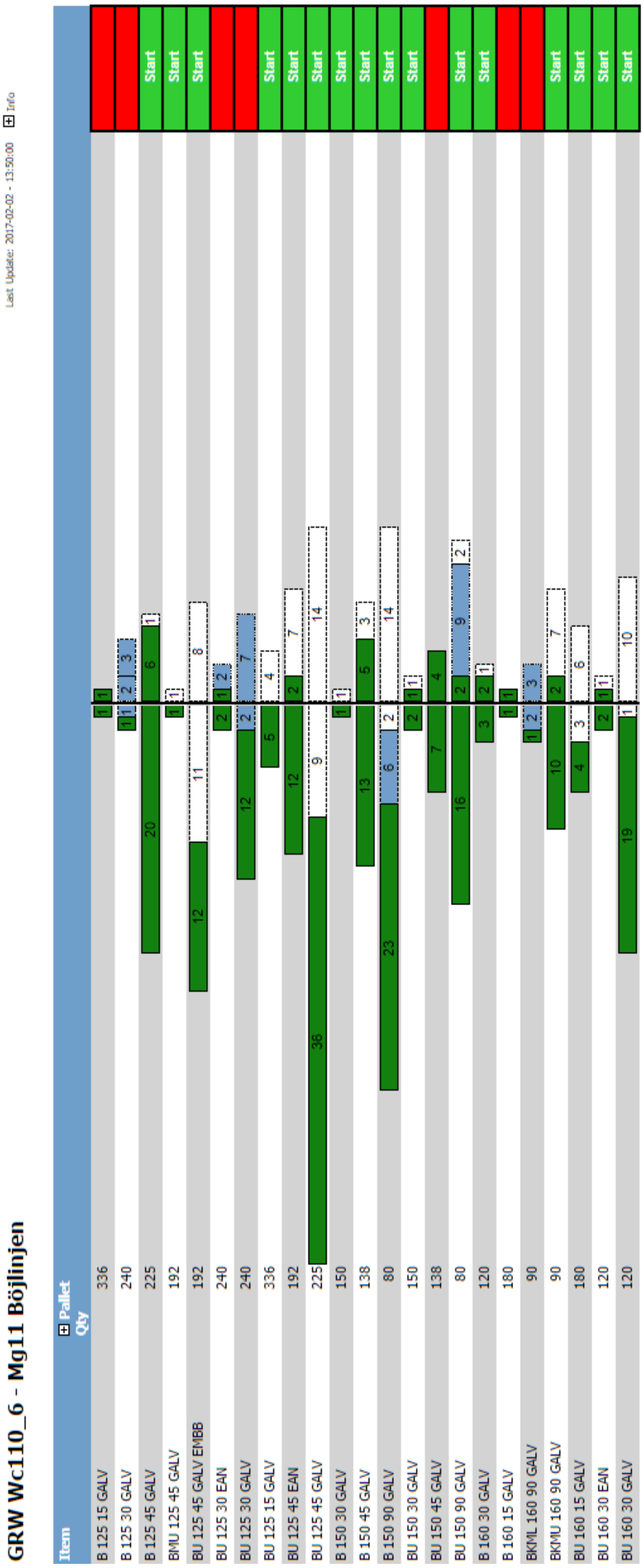

Figure 11: Main user interface of LIPS

LIPS allows operators to start a production order for any product where the inventory level is below safety stock plus the order quantity (green symbolizes the inventory level and blue placed production orders). The white space represents the available space in inventory (measured in pallets) and the black line symbolizes the safety stock level. The reorder point is not visible in this tool and the quantity displayed on the right-hand side of the safety stock line equals the order quantity from LICS. As mentioned before, the above described systems interact with each other through several interfaces and build upon each other to manage the inventory and production within Lindab.

4.4 Inventory Management

The following section will focus on Lindab's approach to inventory management. The company manages several warehouses for different types of goods across its supply chains. From a supply chain process perspective, the inventories considered in this study are located directly after the production and hold finished goods. Lindab uses (R,Q)-policies to manage these types of inventories through LICS. The company bundles these activities into a company-wide strategy with the aim of optimizing availability, meaning a reduction of tied up capital while maintaining or potentially improving the customer service. As a result, one of the key performance indicators (KPI) within the supply chain department is availability, which is defined as having at least two-days of demand or stock for an average customer order on hand.

LICS applies the classical EOQ formula to determine the order quantity for each product. The reorder point is determined to satisfy a targeted fill rate. In these calculations, a normal distribution is used for products with frequent demand, which Lindab refers to as flow products, and for products that experience a (very) irregular demand, called transaction products, LICS assumes a compound Poisson distribution to determine the reorder point. By using two different distributions for high and low frequent products, Lindab aims to achieve a better approximation of demand behavior. Furthermore, to simplify calculations and inventory management, Lindab has classified and grouped products based on three criteria, namely price class, transaction class (demand during a year) and value volume (COGS). This classification is used for definition of different service targets, which are expressed in safety stock or reorder points, depending on the type of product (Table 1). For flow products, the LICS matrix defines the service targets as safety stock in expected number of days of stock on hand. For transaction products, the LICS matrix shows the reorder point, which is displayed as the number of transactions (orders).

Table 1: LICS matrix displaying service targets for each transaction and price class

			Price Class			
			a	b	c	d
Transaction Class	Transactions per year	Product Type	0- 30 SEK	30-100 SEK	100-300 SEK	>300 SEK
A	≥3000	Flow	13	12	11	10
B	1000-2999	Flow	14	13	12	11
C	300-999	Flow	15	14	13	13
D	100-299	Flow	17	15	13	13
E	52-99	Flow	23	19	17	17
F	24-51	Flow	26	20	18	18
G	12-23	Transaction	2	1,5	1,5	1,5
H	6-11	Transaction	2	1,5	1,5	1
I	4-5	Transaction	1,5	1,5	1	1
J	2-3	Transaction	1,5	0	0	0
K	1	Transaction	0	0	0	0
L	0	Transaction	0	0	0	0

Table 1 illustrates that products in some transaction or price classes have no specified reorder point or safety stock level. Historically, these products experienced too irregular and low demand to justify keeping them in stock. As a result, the LICS matrix also provides information if a product is made-to-order or made-to-stock.

For each transaction/price class there is a target fill rate, defined by Lindab, which is used for calculating safety stocks and associated reorder points. This is done by assuming a general 5-day lead time for all groups. This general assumption is made to simplify the calculations and in the further steps, each product's safety stock is determined according to expression (16).

$$safety\ stock = LICS\ value * daily\ demand * \sqrt{\frac{actual\ lead\ time}{5}} \qquad (16)$$

Lindab defines the reorder point of a product as safety stock plus the demand during lead time in accordance with the literature (Axsäter, 2006). Since Lindab calculates its inventory in days on hand, meaning current inventory level divided by average daily demand, the calculation can be expressed as days of safety stock plus lead time. As previously described, for flow products a normal distribution is assumed and with the help of average demand (arithmetic mean) and the lead time, the demand during the lead time is determined. For transaction products, demand is presumed to follow a compound Poisson process (see Section 3.2). The actual lead times used in these calculations are based upon data from Axapta, which stores information about production, purchase and transfer time for each product.

In order to meet customer demand accurately while keeping costs to a minimum, Lindab bases its demand forecasts on several aspects, which are regularly updated and refined. Firstly, Lindab has direct access to POS data, thanks to its network of stores across Europe, and can forecast on actual demand without large influence of information distortion. Additionally, the forecast is based upon demand from previous years and is calculated with demand from the previous three years. Lastly, seasonality in the demand is also considered through the inclusion of a seasonality indices.

Profile Line

For the profile line, the inventory is managed centrally by production planners, who are responsible for production scheduling and sequencing. To manage the inventory level and maintain the targeted service levels planners mostly rely on Axapta and data from LICS. The production scheduling and sequencing tool LIPS is currently not in use at this factory and is being implement at the same time as this study was conducted.

The production planners for this factory have had some education in inventory management and recognize the implications given by a (R,Q)-policy and the EOQ formula. However, in practice the planners are deviating from the (R,Q)-policy, while they are aiming at maintaining an inventory level above the safety stock and place new production orders, when they assume that the reorder point has been reached or that it will be reached in the coming days. The quantity of the products to be produced is based on the economic order quantity from LICS Q_{LICS}. Generally, planners see Q_{LICS} as a guideline for how much to produce for MTS products, while for MTO products, the Q_{LICS} doesn't necessarily apply and planners first and foremost satisfy known customer orders.

Comparing the information gathered from interviews with data from LICS and Axapta, the aforementioned approach to scheduling is generally followed which means that production at the profile line is scheduled similar to a (R,Q)-policy. Interestingly, inventory management for this production line is only similar to the policy, because the inventory level for a number of products constantly remained above the maximum level of R_{LICS} plus Q_{LICS} and production occurred at much higher inventory levels than necessary. Nonetheless, the saw tooth shape of a (R,Q)-policy can be observed, although at higher inventory levels. An example for this is product 100-75 AVIT which was produced on the 03.02.2016, while still having an inventory position well above the reorder point and no large upcoming customer orders (Figure 12).

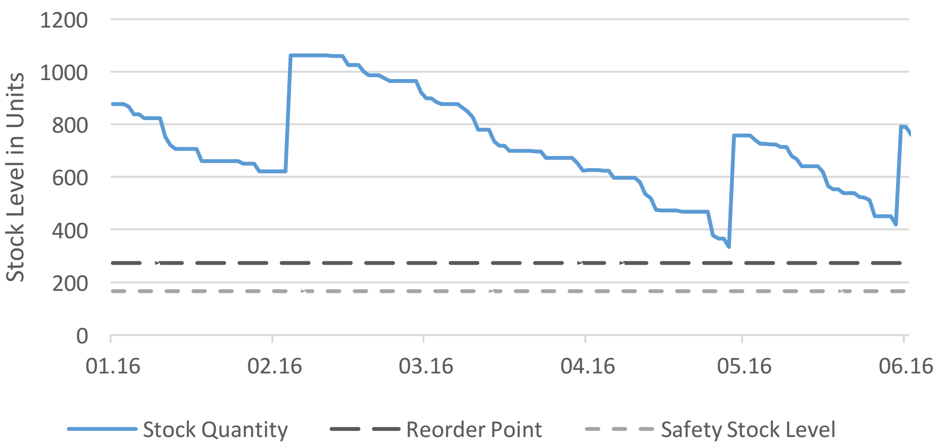

Figure 12: Stock level of product 100-75 AVIT in the first half of 2016

The batch quantities entered into the system on average reflect Q_{LICS}, but several, large deviations from it exist, which are hidden by the overall average. Here, the product 150-100 SVRT is one example. This product is among the most frequently demanded and produced on this production line. The actual production quantity should be close to Q_{LICS} or multiples of it, but the average quantity usually 46% is higher than that.

In summary, the profile line follows the LICS determined (R,Q)-policy in many but not all aspects. On average the line seems to yield to the parameters given by LICS, but a closer investigation of individual products often paints a different picture.

Ventilation Line

While the profile factory seems to follow their own interpretation of the (R,Q)-policy, which is managed through IT systems such as LICS and Axapta, the ventilation factory implemented an additional tool to manage their inventory. LIPS moves the responsibility of inventory management and production planning into the hands of production line operators. As LIPS is connected to Axapta and indirectly to LICS, it allows the production within the ventilation factory to also operate similar to the designed (R,Q)-policy. As mentioned, reorder points and safety stock levels are generated by LICS based on the corresponding target fill rates and statistical distribution, flow products are estimated by normal distributions, while compound Poisson distributions are used for transaction products. As discussed in Section 4.3, LIPS somewhat deviates from the traditional (R,Q)-policy, since it only displays the safety stock level rather than the reorder point. In other words, safety stock is used as a reference line for placing an order in LIPS, since production lead time is very small and can be ignored, according to operators. Therefore, the safety stock level will be very close to the reorder point. However, the total lead times in LICS for this production line are approximately six days including production lead time and on average one day warehousing operations. Resulting from this, operators aim at maintaining an inventory level close to the displayed safety stock and produce at almost random inventory levels, which results in similarly random production quantities to increase the inventory level back to safety stock level. Furthermore, operators have had limited training in the implications given by a (R,Q)-policy and the EOQ formula.

To achieve the required service targets set in LICS, operators closely observe the inventory level of the warehouse downstream through LIPS and upcoming customer order in Axapta. It is important to note that Axapta still is a central tool for managing inventory levels in the production line, since it allows operators to not just see today's requirements, but also further ahead. Based upon imminent customer demand and potential shortages, operators schedule the production to avoid stock outs. The approach described by operators at this production line is confirmed by the available production data and nearly every production run features products that would have experienced stock outs in the near future.

An example of this approach to inventory management can be found in product BU 125-45 GALV. The product remained below safety stock level for ⅔ of the year and never reached the reorder point. Furthermore, the production quantity remained at roughly 40% of Q_{LICS}. In order to avoid stock outs and backorders, the production line had to produce this product almost every day.

In conclusion, the ventilation line operates at random and does not follow the (R,Q)-policy outlined by LICS.

4.5 Scheduling and Sequencing

In this section, Lindab's current approach for scheduling and sequencing of the two selected production lines are discussed. Because of their differences, each production line is discussed separately. Some of these differences are a result of the fact that during this study, LIPS has not been implemented in the profile factory, while the ventilation line has been using it for several years. However, the implementation of LIPS for the profile factory began during this study and scheduling and sequencing task will be transferred to operators in the foreseeable future. Currently, scheduling and sequencing of the production in the profile factory is carried out by production planners.

Profile Line

As mentioned previously, the production at the profile factory is managed by production planners, who among other things schedule and sequence the profile line. These planners schedule and sequence the production every second week, but re-scheduling and re-sequencing is done as soon as unexpected shortages or customer orders appear. Currently, the IT tools that are used are Axapta and Microsoft Excel.

The regular scheduling and sequencing process begins with the extraction of data from Axapta into Excel. This data includes upcoming customer orders and the availability of products during the two-week period. This is done by dividing a product's stock on hand by the average daily demand for that product. The average demand for a product is determined by considering the total demand quantity during a rolling 12-month period. The determination of the production schedule is based upon the likelihood of a stock out during the planning cycle. Products, where this likelihood is high enough, are added to the production schedule of this period (two weeks). Furthermore, products with existing customer order that cannot be met by current inventory levels, listed on the so-called shortage list, are added to the schedule. Additionally, customer orders for MTO products are included into the schedule. Lastly, products with a similar production setup but theoretically sufficient inventory for the upcoming planning horizon are included into the schedule so that the overall setup time can be reduced. Of course, available production capacity is a limiting factor and the entire production schedule should not exceed the maximum overall capacity during those two weeks. Here, the scheduled production quantity as well as setup times play a central role, which has been discussed in previous sections.

After possible products have been selected, the sequencing of products begins. Here, products that have a higher risk of stock-out will be identified and sorted by considering how long they last until stock-out or when the next customer orders exists. During the sequencing process, customer orders or shortages have the highest priority followed by regular MTS products.

Besides the current stock level, a primary parameter for sequencing is the setup time required to change from one product to another. The aim is to sequence the production in a way so that the total setup time is reduced. For this purpose, products in the production schedule with the same dimensions are preferred to be sequenced successively, then products requiring the same material or coil and lastly those that don't match with other products. An important consideration during the sequencing is that products made from naked metal (e.g. zinc magnesium or aluminum) are sequenced last, because of lengthy calibrations and cleaning procedures. The process for production scheduling and sequencing can be summarized as follows.

1. Checking of shortage list for upcoming shortages or customer orders
2. Determination of products likely to fall below the reorder point during the planning horizon
3. Selection of products that should be produced (≤ 2 weeks of stock) and other suitable products (e.g. similar size or fast mover)
    - Not necessarily to full capacity of the production line
4. Sequencing based on due date for shortages or customer orders, then product size and availability of raw material
    - Raw metals are produced together and preferably last

Similar to the scheduling procedure, the logic for determining a production sequence for a planning horizon is mostly reflected in the data. During several periods in 2016 the production iterated between several product dimensions, with the effect that several potentially unnecessary setups occurred (Table 2).

Table 2: Production schedule of week 16 in 2016 on the profile line

Week	Day	Product
Week 16	11.04.16	**150-87** ALUZ
		150-87 SMET
	12.04.16	**150-87** SVRT
	13.04.16	**125-100** MGRÅ
		150-87 BRUN
		150-87 MGRÅ
	14.04.16	**100-75** ZM
		150-87 KMET
	15.04.16	**100-75** GALV
		125-100 AMET
	16.04.16	**100-75** SMET
		125-100 ZM

However, the production generally follows the planned sequence and rarely deviate from it. Some of these changes can be explained by cancellations of orders, lack of raw materials or lack of experienced operators. Because of the long planning horizon, availability of raw material is currently not a big concern, due to short production lead time from Lindab Steel of roughly three to five days. However, it is feared that the introduction of LIPS in the profile factory will lead to more frequent raw material shortages. In addition, it is likely that during some shifts, without experienced operators, setups cannot be performed due a lack of knowledge and skills.

Ventilation Line

The production in the ventilation line is scheduled every morning for the three shifts on that day. An exception of this is the schedule for the weekend shifts, which is done on Fridays. In contrast to the profile factory, the line operators are responsible for scheduling and sequencing production on their machines. Here, LIPS, which is used to release production orders, and also Axapta, which is used to gather customer orders and shortages, play central roles.

Similar to the profile line, customer orders that are due within the next two to three days are included and prioritized in the production schedule. In addition to those customer orders, products with a low inventory level are included in the schedule. The interpretation of what stock level is to be considered low varies between operators. According to the operators in the ventilation factory, the shortage list represents a major part in their daily schedules and other products are included into the production to utilize the available capacity as much as possible. Similar to the product selection, the quantity to be produced is determined differently among operators. Some operators strive to maintain equal inventory levels across all products, which is usually at the safety stock level displayed within LIPS.

Even though the production is scheduled every day and aims at satisfying the imminent demand as well as some additional products, stock outs, especially with existing customer orders, are (very) rare. The subsequent production sequencing is based upon the priority a product has in the schedule. Customer orders have the highest priority, while regular MTS products are ranked after those based upon the current inventory level. Unlike the profile factory, due to (usually) small differences between setup times, setup considerations are of lower importance. Nonetheless, operators strive to reduce setup times. An additional parameter within sequencing is difficulty of production. Some products classes, for example BKMU or BKML (ventilation bends with a short radius, large angle and rubber gaskets), are usually produced during the morning shifts, due to lengthy calibration and trial runs. In short, the scheduling process can be summed up into the following steps.

1. Checking of shortage list for upcoming shortages or customer orders
2. Selection of products that need to be produced
3. Selection of products similar to shortage products or frequently demand products to complete the schedule for the day
    - Close to full capacity of the production line
4. Sequencing according to due date, with products from shortage or customer orders first, then other products

Moreover, the ventilation factory shares tools with other production groups, which has led to some complications for scheduling and sequencing of each line. The ventilation factory also supplies the Lindab factory in the Czech Republic with some of its semi-finished products, for example bend halves. As a result, some parts of the production line are occasionally dedicated to those orders and this may be an obstacle for other production orders.

4.6 Summary of the Empirical Context

The empirical context and the two focused production lines can be summarized in the following table (Table 3).

Table 3: Summary of the Empirical Context

	Profile Line	**Ventilation Line**
Product	Gutter outlets	Small ventilation bends
Number of product variations	83 variations based on size and color	28 variations based on different sizes and attributes
Shifts per day	1 shift per day of 8 hours	3 shifts of 8 hours per day (Mon.-Fri.), 2 shifts of 8 hours during weekends
Theoretical cycle time for producing a product	22-26 seconds	10-13 seconds
OEE	50%	63%
Main IT systems	Axapta, Excel, LICS	Axapta, LICS, LIPS,
Inventory policy	Related to (R,Q)-policy from LICS, but with deviations	Loosely based on (R,Q)-policy from LICS, but rarely considered by operators
Avg. order quantities	On average multiples of Q_{LiCS}	Independent of Q_{LICS}
Total lead time in LICS	On average 11 days	On average 6 days
Production planning horizon	10 production days (two weeks)	1 production day
Setup times	Between 15 and 180 minutes	Between 1 and 180 minutes

5 Analysis

This chapter will analyze the gathered information and data to determine important parameters influencing inventory management and production in the two considered production lines at Lindab. The aim of this analysis is to not only identify parameters influencing the inventory and production management but to also outline their value and impact.

5.1 Inventory Management

In the following section the findings in the area of inventory management are analyzed with regard to the research question presented. The aim of this section is to analyze key parameters influencing the inventory levels. Because of the contrasting approaches, the two production lines are not considered separately but rather compared directly in several different aspects.

As described above, the profile line is responsible for the production of 83 different types of gutter outlets. Most of those products are MTS, only five are MTO. On average, the cycle time for each product batch is 2,1 hours, for a production quantity equal to Q_{LICS}. Across all products, the average time between individual customer orders is 24,4 days, some products are only ordered a handful of times during the year. In contrast, the ventilation line produces 28 products, which have an average cycle time of four hours for production quantities according to Q_{LICS}. Next to the number of products, the average interarrival times between orders is also significantly smaller, for 2016 only 7,2 days passed between individual customer orders. Furthermore, all products at this production line are MTS. The two production lines show different approaches with regard to the order quantity used. While the profile line on average is close to Q_{LICS} or multiples of it, the ventilation line is on average 38% below Q_{LICS}. These general characteristics are summarized in Table 4.

Table 4: Key characteristics of the studied production lines and their products[4]

Production Line	MTS/MTO	Avg. Q_{LICS} Cycle Time	Avg. Q_{LICS}	Avg. Q_{actual}	Avg. Interarrival Time
Profile Line	78 MTS 5 MTO	1,9 h	165	318 (+93% from Q_{LICS})	24,4 days
Ventilation Line	28 MTS 0 MTO	4,2 h	803	498 (-38% from Q_{LICS})	7,2 days

The products at each production line have been grouped into different product groups for the analysis of these different aspects. These groups are related to an ABC classification and derived from Axsäter (2006) and is based on the demand quantity as well as the demand frequency. Group A includes the most frequently and highly demanded products of each production line, while group B and group C include products with less frequent or low demand.

[4] These values are given by or based on LICS and Axapta and have been determined by Lindab

For the purpose of illustration, a number of products have been selected from each group. These products highlight key finding from the analysis, which can be observed for (almost) all products within a group. In total five products per production line were chosen, two from group A and B respectively and one from group C. The selection of these products was based on how representative these products are with regard to demand, production volume, setup and cycle times within their respective classes. Furthermore, all the products selected for the illustration are approximated using normally distribution demand. No products approximated by compound Poisson demand were chosen for the illustration, because the calculations are significantly more complex and therefore less ideal to illustrate findings. Table 5 provides an overview of the ten selected products and their main inventory management characteristics.

Table 5: Overview of products selected to illustrate the analysis (values in units)

Profile Line							
Group	Product	Annual Demand	Transactions	Q_{LICS}	R_{LICS}	Safety Stock	Lead time
A	150-100 SVRT	9 186	557	300	216	146	11 days
A	100-75 SVRT	5 845	413	450	418	251	11 days
B	150-100 BRUN	7 579	148	360	723	489	11 days
B	150-87 ALUZ	2 860	31	180	445	357	11 days
C	150-100 GALV	344	29	90	48	38	12 days
Ventilation Line							
Group	Product	Annual Demand	Transactions	Q_{LICS}	R_{LICS}	Safety Stock	Lead time
A	BU 125-45	370 097	6 603	3 150	18 219	9 838	6 days
A	BU 125-30	107 418	2 912	1 680	5 570	3 153	6 days
B	B 150-90	72 995	385	1 120	4 192	2 470	6 days
B	BKMU 160-90	28 774	1 180	810	1 587	898	6 days
C	B 150-30	2 467	71	150	183	124	6 days

5.1.1 Order quantities, Reorder points and Safety Stock

The analysis of reorder points as well as safety stock levels in the chosen production lines lead to notable findings, which are illustrated by the selected products in Table 5.

Generally, the profile line follows an (R,Q)-policy. However, there is a tendency to overshooting the reorder points in LICS, meaning starting production at higher inventory positions than what is prescribed by LICS is common practice for many products. A closer analysis shows a different approach to inventory management within each group. The products in group A from the profile line are all produced above the reorder point, in some cases even above R_{LICS} + Q_{LICS}. Moreover, the order quantity is generally about 20% above Q_{LICS}. Consequently, the inventory levels of these products very rarely drop close to the safety stock level or even below the reorder point. For products in group B, the reorder point is followed in most cases. Similarly, the order quantities of these products are closer to Q_{LICS} and only a few products experience a slightly higher order quantity. Hence, the (R,Q)-policy in LICS is followed much more closely. Within group C, products develop in a number of different ways with regard to the inventory level. A relatively large number of products constantly remains above the reorder point and production occurs at higher levels than necessary. Additionally, the order quantities of most products in this group are larger than Q_{LICS}.

In contrast to this, the products manufactured in the ventilation line generally do not follow the (R,Q)-policy in LICS, and the reorder points of products appear to be random. The analysis of the individual products in the groups shows that, products in group A are produced at inventory positions below the system generated safety stock, and in some cases even close to half of the safety stock level. Similarly, products in group B and C are also produced at low inventory positions. Furthermore, the order quantities in all product groups are significantly lower than Q_{LICS}. Therefore, the ventilation line experiences significantly lower stock levels than what is predicted by LICS and Axapta.

These differences between parameters that the information systems (LICS and Axapta) prescribe, how the production lines are managed, can be explained by how parameters, such as lead times, service levels and ordering costs, are determined. This will be further analyzed in the following sections.

5.1.2 Lead times

Lead times play a key role in inventory management and the levels of reorder points and safety stocks greatly depend on it. As illustrated in Figure 13, the total lead time at Lindab can be divided into raw material lead time (L_{raw}) and production lead time (L_{prod}) (Figure 13). Moreover, the production lead time can be divided into planning time, production time and time for delivery to the finished goods warehouse.

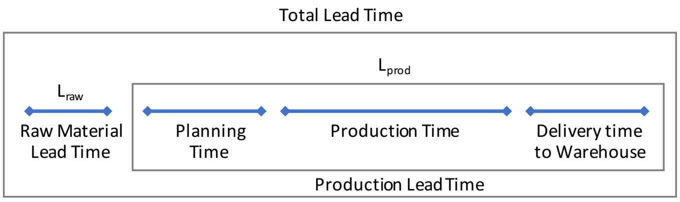

Figure 13: Elements included in the total lead time at Lindab

Generally, the production lead time for both lines is very short and most products can be produced in less than a working day. However, planning or waiting times can increase the lead time, especially in the profile line. Also, time to transport to and store products in the finished goods warehouse takes up to one day and is included in the production lead time.

The total lead time for the profile line in LICS is set between 10 and 12 days. This time consists of raw material lead time from Lindab Steel of around five days and five to six days production lead time. Interestingly, the lead time for raw materials can almost be ignored, because nearly all coils are kept on stock or are available within a very short time period. The remaining five to six days are required for production, which can likely be split into a very short period of actual production and a larger period of waiting time due to planning. Most likely the actual production lead times are in the region of five to seven days for most products. Because of the way production is planned in the profile factory (every second week and usually not at or near full capacity) it is difficult to deduce the precise production lead times from observing the stock level data. However, the available stock level data allowed for lead times estimations. These estimations were validated by discussing them with several production planners confirming their appropriateness. The estimated total lead times were obtained by measuring the time between stock levels fell below R_{LICS} and the next production run for the product. Observing the production history for 2016 showed that the estimated lead times for the selected products are very close to the production lead time for most products. However, there are some exceptions, which could be explained by unavailable coils or other disruptions. Generally, due to the lower number of production runs in the profile factory, long production lead times have a larger effect on the average lead time of these products. The following total lead time values have been estimated for the selected products in the profile line (Table 6).

Table 6: Overview of lead time values for the profile line

Product	Total lead time in LICS	Estimated total lead time
150-100 SVRT	11 days	9 days
100-75 SVRT	11 days	5,5 days
150-87 ALUZ	11 days	7 days
150-100 BRUN	11 days	6,5 days
150-100 GALV	12 days	5 days

In the ventilation line production is scheduled every day. Products usually experience a high demand and in turn more frequent production runs. While some operators see the lead time as close to zero or just a few hours, LICS provides total lead times of around six days. Generally, Lindab assumes in LIPS that the production line can manufacture four products per day and that no disruptions occur. Based on this assumption a waiting time of around three to five days per product is assumed. By adding a day for warehouse operations, the total lead time of four to six days is obtained.

Observing the inventory levels throughout 2016, it could be seen that the actual total lead time is smaller than what is assumed in LICS. Based on these observations, the actual production lead time for fast movers (group A) seems to be around one day, possibly because they are prioritized in production. For group B and C products, the production lead time appear to be larger than one day but lower than what is defined in LICS. Because of frequent production runs and limited waiting time, which is due to the daily scheduling, is was possible to calculate the actual lead time of the selected products using of the following formulas, which assumes a normal distribution.

$$E(IL^{+}) = R + \frac{Q}{2} - \mu' + \frac{\sigma'^{2}}{Q} * (H\left(\frac{R-\mu'}{\sigma'}\right) - H\left(\frac{R+Q-\mu'}{\sigma'}\right)) \quad (17)$$

$$\mu' = L_{total} * \mu = \left(L_{raw} + L_{prod}\right) * \mu \quad (18)$$

$$\sigma' = \sigma * \sqrt{L_{total}} = \sigma * \sqrt{L_{raw} + L_{prod}} \quad (19)$$

As can be seen in (18) and (19), the average demand during the lead time (μ’) and standard deviation of demand during the lead time (σ’) is based on the total lead time L_{total}. However, since the raw material lead time L_{raw} can be neglected because of existing raw material buffers, the calculation is essentially based on the production lead time L_{prod}. Furthermore, the production data only include information on the day a product was produced, but not planning time or time for transports to the finished goods warehouse. Here, the waiting time is assumed to be zero, because inventory management and production scheduling operate on a daily basis and no further differentiation is made. The time for transporting finished goods to the warehouse is considered separately and is estimated to be up to one day by operators. Hence, the production time can be calculated by inserting formulas (18) and (19) into (17). Based on the determined average inventory on hand $E(IL^+)$ from data, the reorder point R and order quantity Q as well as average daily demand μ and standard deviation of daily demand σ allowed the determination of approximate production lead time by solving (17) for L_{prod}.

The average production quantity and average stock level estimated from data in LICS and Axapta when an order is produced are assumed to represent Q_{Avg} and R_{Avg} respectively. This is done, because the ventilation line is not utilizing the designed (R,Q)-policy and these values represent the operator-based reorder point and order quantity. Based on calculated average stock on hand data $E(IL^+)$ from LICS and Axapta, the production lead times were calculated by solving (17) with (18) and (19) for L_{prod}. This lead to the results shown in Table 7. In this table, next to the calculated total lead times, estimated lead times are shown. These estimated lead times are based on stock level data from LICS and Axapta. They are determined as the time difference between the estimated reorder point R_{Avg} and the next production run for the product.

Table 7: Comparison of lead time values for the ventilation line

Product	Lead time in LICS	Estimated total lead times	Calculated total lead times
BU 125-45 GALV	6 days	1 day production + 1 day warehouse	1 day production + 1 day warehouse
BU 125-30 GALV	6 days	1 day production + 1 day warehouse	1 day production + 1 day warehouse
B 150-90 GALV	6 days	3 days production + 1 day warehouse	1 day production + 1 day warehouse
BKMU 160-90 GALV	6 days	2,5 days production + 1 day warehouse	1,5 days production + 1 day warehouse
B 160-15 GALV	6 days	-	1,5 days production + 1 day warehouse

It can be concluded that the (likely) actual lead times in both production lines are lower than previously assumed in LICS. Especially for fast moving products, group A and some of group B, the calculated lead times are 50% of what is used in LICS. As a result, LICS calculates higher than necessary reorder point and safety stock levels, which lead to higher than required service levels. In particular within the ventilation line, it can be observed that the production is capable of maintaining lower inventory levels without harming their service level.

In order to verify the research approach and to validate the obtained results, the approach and lead time assumptions for both lines were presented and discussed in meetings with production planners and logistics managers of the ventilation line. The estimates for the profile line were also discussed with production planners of the profile factory and confirmed to be realistic. Furthermore, for the ventilation line, the calculated lead times were discussed with the operators, who confirmed that the calculated values appear to be very close to reality. The estimated lead times for the ventilation were disregarded, since not sufficient data was available for all products. Therefore, it was concluded that the calculated lead times for both production lines are reliable and align well with reality.

5.1.3 Service Levels

As discussed above the current parameters and values in LICS don't reflect the actual capabilities of the production lines accurately. As a result, it is not likely the target service levels are accurately met. The analysis of the service levels focuses on the fill rates and was conducted using classical service level calculations, seen in (9). Firstly, an analysis of the current reorder points, lead times and order quantities was conducted to confirm the values in LICS. Here, formula (9) was solved for the reorder point R based on Q_{LICS}, average daily customer demand μ, standard deviation of daily customer demand σ and the lead time in LICS. The obtained reorder points and resulting safety stock levels SS in comparison with the values in LICS can be seen in Table 8 for the profile line and in Table 9 for the ventilation line.

Table 8: Comparison between R and SS in LICS and calculated levels for the profile line

	150-100 SVRT		100-75 SVRT		150-100 BRUN		150-87 ALUZ		150-100 GALV	
	LICS	Calc. Levels	LICS	Calc. Levels	LICS	Calc. Levels	LICS	Calc. Levels	LICS	Calc. Levels
Target Fill rate	98,00%		99,00%		98,00%		96,00%		96,00%	
Q_{LICS}	360		450		360		180		12	
Lead time	11 days		11 days		11 days		11 days		12 days	
Reorder point	687	593	418	427	723	722	445	298	48	34
Safety Stock	413	196	251	173	489	392	357	174	38	17

Table 9: Comparison between R and SS in LICS and calculated levels for the ventilation line

	BU 125-45		BU 125-30		B 150-90		BKMU 160-90		B 150-30	
	LICS	Calc. Levels	LICS	Calc. Levels	LICS	Calc. Levels	LICS	Calc. Levels	LICS	Calc. Levels
Target Fill rate	99,90%		99,50%		99,00%		99.50%		94,00%	
Q_{LICS}	3 150		1 680		1 120		810		150	
Lead time	6 days		6 days		6 days		6 days		6 days	
Reorder point	18 219	13 479	5 570	3 722	4 192	3 133	1 587	1 046	183	172
Safety Stock	9 838	4 707	3 153	1 172	2 470	1 399	898	363	124	83

As shown in the tables above, the reorder points and safety stock levels in LICS are (much) higher than those calculated through the theoretical approach. Resulting from this, utilizing the values from LICS (which are not realized in practice) would lead to higher service levels than targeted. For instance, if the LICS values were realized, the product BU 125-30 GALV seen in Table 9, with a target fill rate of 99,5%, would have a reorder point of 5 570 units and a safety stock level of 3 153 units. However, using these values and calculating the resulting service level through the theoretical formula, results in an abundance of stock and a fill rate of 100%. Using this information, the results shown in the columns Calc. Levels in Table 8 and Table 9 are obtained. For product BU 125-30, these calculated values are roughly 2 000 units lower than those given by LICS.

Since the actual production lead times are significantly smaller than assumed in LICS, a further analysis was conducted. For this analysis four different approaches or scenarios were created and compared against each other, namely LICS, Calc. Levels, Actual Prod. and Meet S_2. The first scenario is called *LICS* and is based on the values found in LICS. Here, no additional calculations were required apart from the achieved fill rate, which relies on the standard fill rate formula, see (9), as well as (6) and (7). The second scenario, *Calc. Levels*, has already been partially introduced. In this approach, the corresponding reorder points and safety stock levels were determined by using (9) in combination with (6) and (7) by solving for R. The lead times and production quantities in this scenario were left at the values found in LICS. The third scenario, *Actual Prod.*, focuses on the actual production estimated from stock level data (from LICS and Axapta). Here, the values for reorder points, safety stock levels, production lead times (based on the earlier analysis in Section 5.1.2) and order quantities are extracted from LICS data and interviews with operators. The reorder points, are set to the average inventory level at which production occurred, and average actual order quantities are based on production and customer demand data from 2016. The safety stock levels SS are calculated with the help of the following expression.

$$SS = R - \mu' \tag{20}$$

Furthermore, the achieved fill rate was calculated according to (9). The *Meet* S_2 scenario represents an extension of the Actual Prod. approach, by determining the reorder points and safety stock levels corresponding to the calculated production lead times (based on the earlier analysis in Section 5.1.2) and average calculated production quantities. In the Meet S_2 scenario the reorder points and safety stock levels are determined to meet the given target fill rate. For this approach, the actual production lead times and production quantities are used and (9) in combination with (6), (7) and (20) solved for the corresponding reorder point and safety stock levels. The normal distribution is used for all ten selected products. The approach for compound Poisson distributions would be very similar but require more complex calculations.

For the production line in the profile factory the results of these calculations can be seen in Table 10.

Table 10: Comparison between different inventory management scenarios for the profile line

	150-100 SVRT				100-75 SVRT				150-100 BRUN				150-87 ALUZ				150-100 GALV			
Target Fill rate	98,0%				99,0%				98,0%				96,0%				96,0%			
	LICS	Calc. Levels	Actual Prod.	Meet S2	LICS	Calc. Levels	Actual Prod.	Meet S2	LICS	Calc. Levels	Actual Prod.	Meet S2	LICS	Calc. Levels	Actual Prod.	Meet S2	LICS	Calc. Levels	Actual Prod.	Meet S2
Achieved S2	99,6%	98,0%	100,0%	98,0%	98,8%	99,0%	100,0%	99,0%	98,0%	98,0%	100,0%	98,0%	99,7%	96,0%	100,0%	96,0%	98,6%	96,0%	100,0%	96,0%
Reorder point	687	593	617	97	418	427	663	212	723	722	986	403	445	298	366	180	48	34	45	7
Safety Stock	413	196	542	21	251	173	536	85	489	392	792	208	357	174	287	101	38	17	38	0
Lead time (days)	11	11	9	9	11	11	5,5	5,5	11	11	6,5	6,5	11	11	7	7	12	12	5	5
Q_{LICS}	360	360	-	-	450	450	-	-	360	360	-	-	180	180	-	-	90	90	-	-
Avg. Q	-	-	438	438	-	-	757	757	-	-	335	335	-	-	284	284	-	-	161	161

Calculated Value LICS/ Axapta Value Observed/ Estimated Value

By comparing the results for the selected products of the profile line, production currently overachieves with regard to the service targets, see Actual Prod. in Table 10. In most cases this can be attributed to the tendency to place orders well before the reorder point R_{LICS} has been reached. Additionally, this overshooting is further intensified by shorter than assumed lead times. Assuming the actual lead times and order quantities in production are correct, even lower reorder points and safety stock levels can be achieved, see Meet S_2 in Table 10. This shows that it may be possible to lower the stock kept on hand significantly by aligning LICS with the values for Meet S_2. Through this, the stock days on hand could be reduced to almost a quarter of today's values.

On the other hand, the production in the ventilation factory relies on LIPS and production orders are based on the safety stock level from LICS instead of the reorder point. Theoretically this approach leads to a lower fill rate. However, the production line is known to be one of the best performing production lines with regard to service levels and average inventory levels. The analysis of the ventilation line is conducted using the same methods as above: LICS, Calc. Levels, Actual Prod. and Meet S_2. The results for the five selected products in the ventilation line are shown in Table 11.

Table 11: Comparison between different inventory management scenarios for the ventilation line

	BU 125-45 GALV				BU 125-30 GALV				B 150-90 GALV				BKMU 160-90 GALV				B 150-30 GALV			
Target Fill rate	99,90%				99,50%				99,00%				99,50%				94,00%			
	LICS	Calc. Levels	Actual Prod.	Meet S2	LICS	Calc. Levels	Actual Prod.	Meet S2	LICS	Calc. Levels	Actual Prod.	Meet S2	LICS	Calc. Levels	Actual Prod.	Meet S2	LICS	Calc. Levels	Actual Prod.	Meet S2
Achieved S2	100,0%	99,9%	100,0%	99,9%	100,0%	99,5%	99,8%	99,5%	100,0%	99,0%	99,8%	99,0%	100,0%	99,5%	91,4%	99,5%	95,3%	94,0%	91,9%	94,0%
Reorder point	18 219	13 479	6 121	5 761	5 570	3 722	2 225	1 494	4 192	3 133	1 650	1 346	1 587	1 046	315	524	183	172	50	62
Safety Stock	9 838	4 707	3 195	2 836	3 153	1 172	1 375	644	2 470	1 399	1 072	768	898	363	30	239	124	83	13	25
Lead time (days)	6	6	2	2	6	6	2	2	6	6	2	2	6	6	2,5	2,5	6	6	2,5	2,5
Q_{LICS}	3 150	3 150	-	-	1 680	1 680	-	-	1 120	1 120	-	-	810	810	-	-	150	150	-	-
Avg. Q	-	-	1 253	1 253	-	-	1 195	1 195	-	-	801	801	-	-	478	478	-	-	216	216

Calculated Value | LICS/ Axapta Value | Observed/ Estimated Value

As can be seen from Table 11, the Actual Prod. scenario surpasses the targeted fill rate in almost all cases. Only slower moving products miss the target, but this is likely compensated by producing these as soon as they appear on any customer order or shortage list. The reason why most products achieve the target or are close to it are the significantly lower lead times in the Actual Prod. scenario. The analysis has shown that the reorder points and safety stock levels between LICS, Calc. Levels, Actual Prod. and Meet S_2 differ significantly. Additionally, the theoretically achievable reorder points and safety stock levels, which meet the targeted fill rates, are even lower and can be found in the Meet S_2 columns.

To ensure the quality and accuracy of the estimated reorder points and service levels, the calculation approaches were validated by both supervisors of this study with the help of a stepwise walkthrough of the approach. Furthermore, all data used for the calculation in this section were provided by the company and are also used for calculations in the company. Lastly, the results were presented and discussed in detail with managers of the Supply Chain Center of Excellence to ensure that the steps taken are correct. Additionally, the approach taken to estimate reorder points and safety stock levels was discussed and confirmed by the logistics department from the ventilation line and production planners of the profile factory.

5.1.4 Economic Order Quantity and Ordering/ Setup Cost

Next to target service levels and lead times, the order quantity plays a key role in satisfying customer orders and economies of scale. In this context, the economic order quantity allows a company to balance several cost aspects with the expected demand. As described in Section 3.2 and Section 4.4, Lindab utilizes the EOQ formula to determine order quantities for each product. Within the context of this thesis, the ordering cost represents an area of interest, which is directly influenced by setup procedures and can be responsible for large variations in the calculated quantity.

An initial analysis of the ordering cost for each product revealed that ordering costs are set for each production line and individual products are not distinguished. This means that all products associated with a production line have the same setup cost. Based on the information gathered from interviews and discussions, setup costs of each production line were estimated and in some cases a lower value was put into the system to challenge the production to achieve smaller average inventory levels. For the analysis of the ordering costs and to verify these estimates the following expression was used.

$$Setup\ cost = Setup\ time * Cost\ per\ hour \qquad (21)$$

The cost per hour includes the personnel costs for operators, set by Lindab to 300 SEK per hour, and minimal costs for transferring the order through the system. The setup time was expressed in hours and was determined by creating a weighted average over all possible individual setup times for a product. Through this approach, the setup times were weighted according to number of production runs during the year 2016.

By doing this, it became obvious that the current values for the ordering cost do not reflect the current situation in the production lines accurately. In general, the setup times and therefore ordering costs can be divided into two groups. The first group represent products which have a relatively short setup time, for example 100-75 SVRT in the profile line or BU 125-45 GALV in the ventilation line. The second group consists of products that have a significantly longer setup time than all other products in these production lines. Among those products are the so-called naked metals in the profile line, e.g. GALV or ZM, or the short bends in the ventilation line, e.g. BKMU. Furthermore, the setup times within the individual groups for each production line are reasonably similar. As a result, the ordering costs for the profile line were estimated to be around 300 SEK for products within the first group and roughly 850 SEK for products in the second group. Similarly, the ordering cost for products in the first group of the ventilation line was estimated to be approximately 100 SEK, while the second group most likely has ordering costs of up to 610 SEK.

It is important to note that the exact values for the ordering cost can only be estimated, since setup times are largely dependent on the operator's performance and the sequence of the production schedule. Therefore, the actual ordering cost may be higher or lower than the estimate. Additionally, some products make use of a very similar setup so that are portion of the individual setup can be neglected. This is especially true for the ventilation line, where products with an additional barcode or a different packaging size don't require large change overs. The newly estimated ordering costs show that the current Q_{LICS} values are not necessarily the most economical value that can be achieved, and the actual values will likely be significantly higher for some products. Furthermore, an analysis of order quantities and resulting total costs showed that deviations from the economically optimal value can quickly result in significant cost increases, especially for smaller than optimal quantities can this be observed.

For the estimation of the likely value of the economic order quantity for both lines the data used, including setup times, holding costs and hourly costs, has been taken from Lindab's IT systems or in cooperation with production line operators. Through this approach, it was ensured that all data is reliable or is backed up by as many sources as possible.

In conclusion, the current approach for determining Q_{LICS} is mostly likely not providing accurate results, which can be explained by the very rough estimation of the ordering cost. Additionally, a narrower grouping of products based on setup times could lead to more accurate estimation of ordering costs and a better approximation towards the economically optimal order quantity.

5.1.5 Summary of the Inventory Management Analysis

Both production lines operate under different policies, which are sometimes loosely based on the (R,Q)-policy determined in LICS. While the production line in the profile factory operates based on higher than calculated inventory levels, which results in frequent reorder point overshooting, the production line of the ventilation factory appears to operate on a more random policy, which utilizes the safety stock level as a guide. Based on these different approaches and possibly large deviations from the targeted fill rates, the analysis focused on investigating key parameters affecting the current inventory management.

From the data analysis, the conclusion is that the total lead time values of both production lines are higher in LICS than they are in practice. For the profile line the analysis shows that the total lead times can be half of the value in LICS. Because of this, the reorder point and safety stock levels in LICS are often higher than they should be. In a similar fashion, the ventilation line also achieves lower total lead times, in some cases a third of the LICS value, which is likely due to very low planning times. Combining this with batch quantities lower than Q_{LICS} means that the ventilation line can meet the targeted fill rate in most cases or even surpass the target. In cases where the target fill rate is not achieved, production tries to meet customer expectations by producing products as soon as potential shortages arise. Resulting from these considerations and capabilities within production, the ventilation factory can operate based on safety stock levels calculated by LICS.

Additionally, the current approach for estimating the setup cost might not accurately reflect the actual costs. It can be assumed that products each both production line, can be grouped into two groups. The first group being products with a relatively short setup time, which can be assumed to be relatively close to the current setup cost. The other group consists of products with a long setup times, which therefore have a considerably larger order cost and order quantities. Because of this potential deviation from the actual setup costs, Lindab might have increased costs due to more frequent setups than what is economically optimal.

5.2 Scheduling and Sequencing

The following section analyzes the findings presented in Section 4.5 and focuses on how scheduling and sequencing parameters are employed in the production lines. Furthermore, the effects on the setup times and inventory levels of these parameters will be investigated. As before, the two considered production lines were analyzed separately because of their differences. To better highlight the use and effects of the scheduling and sequencing parameters for each line, a fixed time period in 2016 is used to illustrate analysis results. These periods are characterized by relatively high demand and production volumes as well as a number of different products being produced so that the scheduling and sequencing effects become more pronounced.

It is important to note that the production sequence of the individual production lines could not be recreated with absolute certainty, since Axapta only stores the sequence in which production orders were created and timestamps of when production began are not available. Nonetheless, with the help of the information and the approach of production planners and operators, it was possible to recreate sequences which have likely occurred.

As concluded above, the inventory management in the profile line and therefore the scheduling process are loosely based on an (R,Q)-policy. The scheduling period of ten days is relatively long and an analysis of this period reveal several aspects. First, during a planning horizon of ten days, the certainty with which the lead time demand can be determined is limited. In several cases products have been produced without any demand during the lead time. Because of this, and overshooting reorder points, inventory levels gradually increase. Secondly, several unexpected events can occur during a long planning horizon, such as large customer orders, which are only visible shortly before they are due, or unavailable raw materials or tools. In such instances the production has to deviate from the planned schedule and include demanded products or skip products in cases of unavailability. An example of this is the production during week 43 of 2016. On the 25.10.2016 an unexpected customer order caused the insertion of the product 125-100 ALUZ into the schedule. However, the same product was already scheduled to be produced the next day and the sequence has not been adapted to this change. Because of this, unnecessary setups occurred. Table 12 shows the likely sequence for the 25.10.2016 and 26.10.2016.

Table 12: Extract of the production sequence for week 43 of 2016

Week	Day	Product
Week 43	25.10.16	**125-100 ALUZ (Shortage List)** 150-100 AVIT 150-100 KMET
	26.10.16	125-100 AVIT 125-100 MET **125-100 ALUZ**

This deviation from the schedule might have been avoidable, if the planning horizon was shorter. These unexpected customer orders don't occur too often in the profile line and generally the inventory levels are almost always more than sufficient to satisfy imminent demand. However, including additional products into the production schedule usually leads to increased total setup times that could be avoided with shorter planning horizons. The reason for this is that the profile line operates with a planning horizon that is fixed to ten days. During those ten days customer demand can occur that was not known at the beginning of production scheduling. However, shortening the planning horizon, to for example three days, leads to more frequent scheduling and allows planners to include upcoming customer demand (almost) as soon as it occurs.

Another aspect is the delayed production of some MTS products, even though they have surpassed the reorder point for several days or weeks. A deeper analysis of these products revealed that they are usually experiencing a longer than average interarrival time, some as high as 87 days between demands. Figure 14 illustrates an example for product 150-120 KMET, which has not been produced during a 30 day period, even though its inventory level was below safety stock level. An analysis of this product revealed that the average interarrival time between demands is 68 days and that the delayed reordering of this product decreased its inventory level.

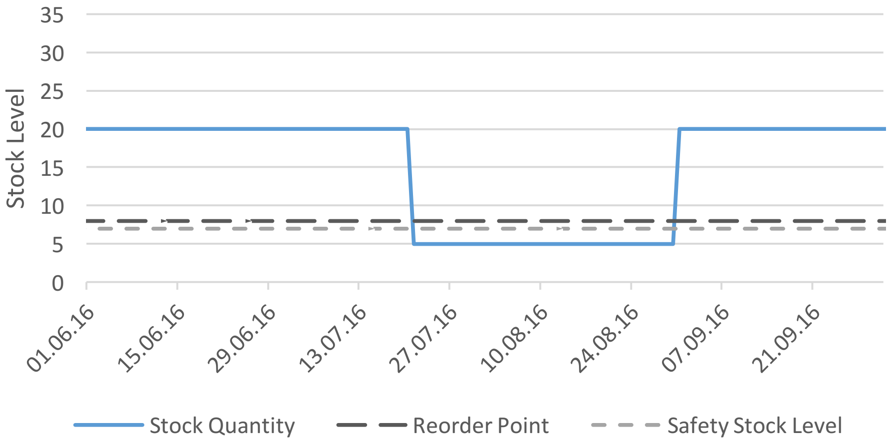

Figure 14: Stock level of product 150-120 KMET

The sequencing of the profile line shows that products with the same dimension are generally produced together. This results in shorter setup times of 15 minutes, since only the metal coil has to be changed, instead of at least an hour for set ups to produce a new dimension. An analysis of the production sequence and comparison to alternative scenarios revealed the results shown in Table 13. The scenarios chosen for the comparison to the current scenario are earliest due date first (EDD) and shortest processing time first (SPT), which represent two well-known sequencing methods that have been described in Section 3.3. For this comparison, the EDD rule assumes that products with the lowest inventory level in relation to the average daily demand should be produced first, while SPT assumes that the shortest production time for the scheduled production quantity is produced first.

Table 13: Comparison between different setup scenarios for week 35 in the profile line

		Current Sequencing Procedure	Earliest Due Date First (EDD)	Shortest Processing Time First (SPT)
Sequence		1. 100-75 ZM 2. 100-75 GALV 3. 100-87 AMET 4. 100-87 AVIT 5. 150-100 MRÖD 6. 150-100 BRUN 7. 150-100 MGRÅ	1. 150-100 BRUN 2. 150-100 MGRÅ 3. 100-75 GALV 4. 100-87 AVIT 5. 150-100 MRÖD 6. 100-75 ZM 7. 100-87 AMET	1. 100-87 AMET 2. 100-75 ZM 3. 150-100 MRÖD 4. 150-100 BRUN 5. 100-75 GALV 6. 100-87 AVIT 7. 150-100 MGRÅ
Setup time	Between Coils	15 min.		
	Between Sizes	60 min. (120 min. to raw metals & 45 min. between raw metals)		
Total Setup Time for Sequence[5]		420 min.	675 min.	675 min.

[5] It is assumed that the machine has previously not been setup for any kind of product and a setup to begin production is required.

As shown in Table 13, a comparison between the different scenarios clearly indicates that the current procedure and consideration for sequencing leads to the shortest total setup time. A reason for this can be found in one of the weaknesses of both EDD and SPT, which do not consider sequence dependent setup times. An in-depth analysis of the setup times and resulting sequences for selected week has shown that the current approach leads to one of several optimal sequences. This was also true for other randomly selected sample weeks.

The ventilation line, not only operates under a different inventory policy, the scheduling and sequencing procedures also differ from the profile factory. As described in the empirical section, operators are responsible for scheduling and sequencing. Because of the daily scheduling and sequencing of the production, operators within the ventilation line have the ability to react to upcoming customer demand or shortages. Of course, this procedure also has some drawbacks. Operators hesitate to produce Q_{LICS}, especially if it constitutes for long runs, since the perceived available time frame is limited to 24 hours. This becomes even more obvious during periods with several shortages or customer demands. During these periods the operators in the production are required to fulfill customer demands. Generally, operators are often required to schedule products on the shortage lists and regular production of MTS products is often used to complete the schedule for the day. This approach can be observed during most days of 2016 and the shortage list almost always features several products. Resulting from the frequent demand for nearly all products, the average interarrival time for the products is significantly lower than in the profile factory. Due to this, products are almost immediately produced once they reach a low enough level.

An analysis and comparison of the current sequencing procedure with EDD and SPT approaches resulted in the following table (Table 14). Because of the large number of products produced in a week and the daily scheduling at the ventilation line, only one production day, namely the 28.06.2016, is depicted in this analysis. The products BKMU 160-90 GALV, BU 125-15 GALV and BU 160-30 GALV have likely been on the shortage list of that day and are therefore first within the sequence under the current procedure.

Table 14: Comparison between different setup scenarios for the 28.06.2016 in the ventilation line

		Current Sequencing Procedure	Earliest Due Date First (EDD)	Shortest Processing Time First (SPT)
Sequence		1. BKMU 160-90 GALV 2. BU 125-15 GALV 3. BU 160-15 GALV 4. BU 160-15 EAN 5. BU 160-30 GALV 6. BU 125-45 GALV 7. B 125-45 GALV	1. BU 160-15 EAN 2. BU 160-30 GALV 3. BU 125-15 GALV 4. BU 125-45 GALV 5. BU 160-15 GALV 6. B 125-45 GALV 7. BKMU 160-90 GALV	1. BKMU 160-90 GALV 2. BU 160-15 GALV 3. B 125-45 GALV 4. BU 125-15 GALV 5. BU 125-45 GALV 6. BU 160-30 GALV 7. BU 160-15 EAN
Setup time	Between Code	10 min. (180 min. to BKMU or BMKL & 45 min. from them)		
	Between Sizes	20 min. (10 min. for angle changes)		
Total Setup Time for Sequence[6]		286 min.	280 min.	295 min.

Table 14 shows that the setup times within the ventilation line are on average not only shorter but also result in shorter overall setup times. Unlike the profile line, the current approach to sequencing does not lead to the best or an optimal sequence regarding setup times for the day illustrated in Table 14. An analysis of the current approach and the EDD heuristic shows that neither procedure results in a sequence with the lowest overall setup time. This can be achieved by moving the product BU 160-15 GALV in the EDD sequence from position five to the first or second in that sequence. By doing so all products with similar size and code are grouped together and the resulting setups in between are kept to a minimum. This change in sequence results in the best sequence for that day with an overall setup time of just 255 minutes.

Similar to the results obtained in the area of inventory management, the analysis of the production scheduling and sequencing were presented and discussed with production planners, production managers and operators of the considered production lines. Through them it could be confirmed that the generated sequences reflect the likely production sequence for the analyzed periods and that a reduction of setup times is a main goal for them. However, it was remarked that in some cases a better sequence with regard to the total setup time is disregarded in favor of raw material or tool availability.

It can be concluded that the approaches and procedures to scheduling and sequencing in the profile and ventilation line vary and lead to different results. While the schedule for the profile line is to some degree based on the classical (R,Q)-policy, where products are scheduled for production based upon their stock levels, the ventilation line relies on other parameters. Here, the schedule is based on upcoming customer demand or shortages, which can lead to several products having to be produced. Besides the different scheduling approaches, both production lines experience sequence dependent setups and changeovers, which leads to varying total setup times. The analysis has shown that the current approaches for scheduling and sequencing in the two production lines generate good results. In case of the profile line even optimal results. For the ventilation line, the current approach produces stable results which

[6] It is assumed that the machine has previously not been setup for any kind of product and a setup to begin production is required.

are usually just slightly better or worse than other, established approaches. Nonetheless it can be shown that neither the current procedure nor EDD always reliably produce the most optimal result with regard to the total setup time. Here, the analysis shows that an optimal sequence can be found by moving products to another place in the sequence.

From the one can see that setups have varying effects on the production. Comparing the two production lines and the displayed schedules for the same number of products, different total cycle time requirements exist, especially when comparing the optimal sequences. Furthermore, the differences in total setup time between the optimal sequence and the worst approach, SPT in both cases, indicates that the profile line is experiencing larger sequence dependency of setup times than the ventilation line.

5.3 Balancing of stock on hand and setup times

The different areas of analysis have shown that Lindab's inventory management and production planning is influenced by several parameters. For instance, the production line within the profile factory is heavily influenced by the production sequence and optimizing it should be a key concern. However, inventory management aspects also play a role and have to be considered. Conversely, the analyzed ventilation line mostly benefits from improvements within inventory management. Resulting from this, Lindab faces a dilemma between low stock levels and short total setup times, since high order quantities reduce the total setup time required but increase average inventory level. Therefore, each previously outlined scenario has been analyzed regarding average inventory level and setup time required throughout a year. The main KPIs chosen for this analysis are average stock on hand in days and total setup time required in hours per year. For this calculation, it is assumed that the production for a product can be setup during the predetermined average setup time, considering all setup combinations and their occurrence. The aim of this analysis is to outline the effects of those different approaches to inventory management and sequencing with regard to these two KPIs, but not necessarily to provide an optimal solution. The analysis of setups and average inventory levels for the profile line is illustrated in Figure 15.

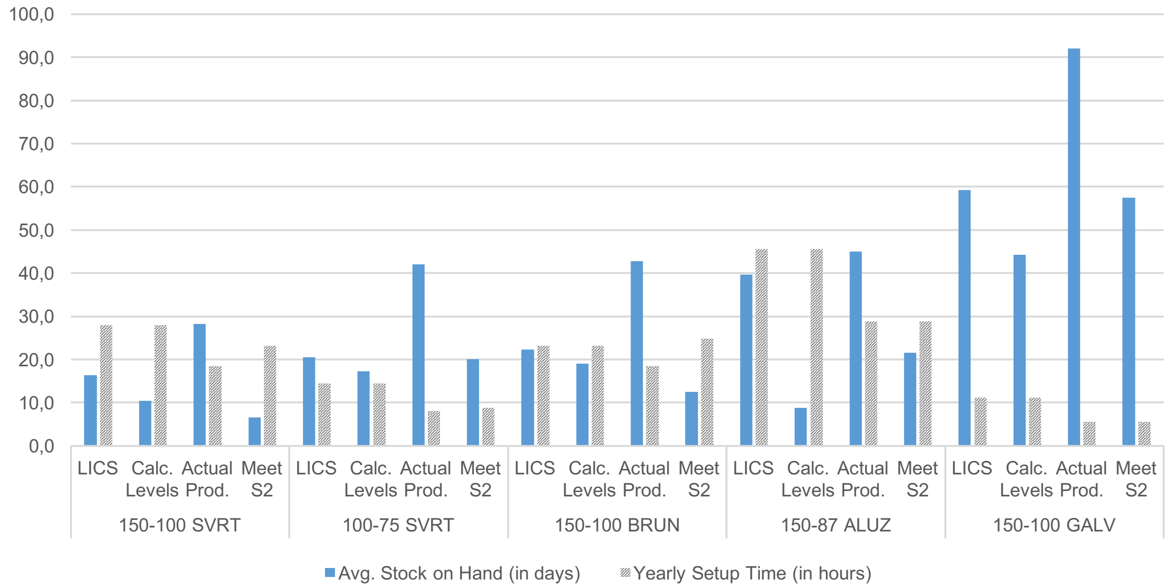

Figure 15: Comparison between setups and stock on hand for the profile line[7]

Figure 15 shows that each scenario leads to different results regarding the two chosen KPIs. In general, the scenarios based on LICS values do lead to high total setup times and relatively high stock levels. Furthermore, the current procedures in production (Actual Prod.) lead to lower total setup times but due to order quantities higher than Q_{LICS} and overshooting reorder points, the average stock level often lies considerably higher than in any other scenario. The other two more theoretical methods, Calc. Levels and Meet S_2, show somewhat higher total setup times compared to the actual approach in production, but the average stock levels are the lowest in these scenarios. Based on these findings one can conclude that the Calc. Levels and Meet S_2 seem to yield better results, considering the chosen KPIs.

The analysis of the production line from the ventilation factory was conducted in the same manner and the results can be seen in Figure 16.

[7] Deviations in the number of setups (in shifts) are due to differences in the total production quantity and the total demand during that year

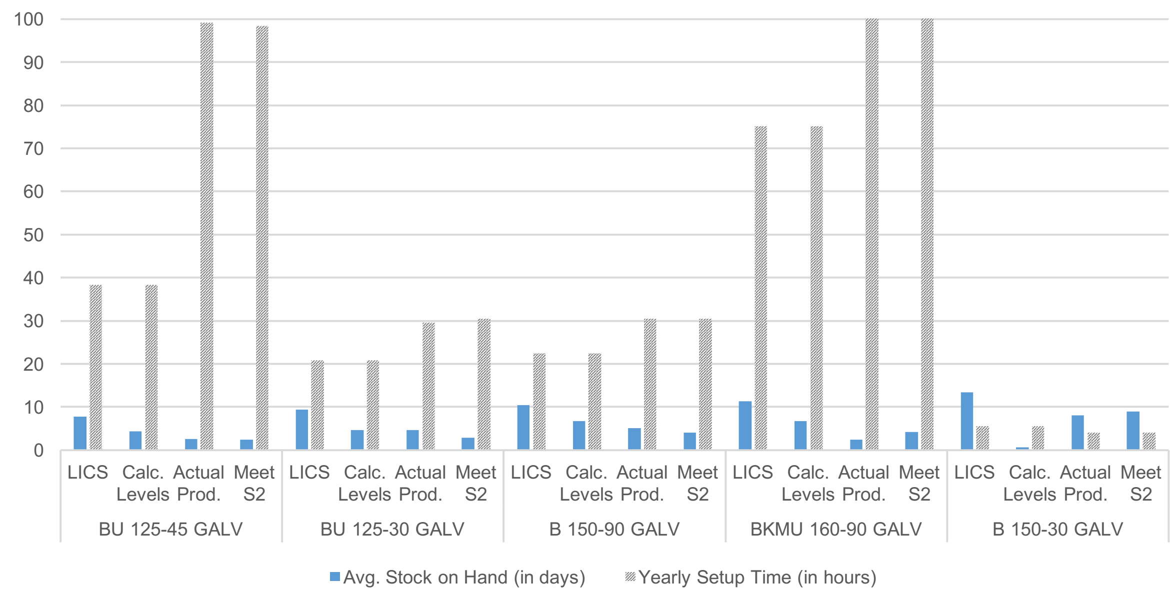

Figure 16: Comparison between setups and stock on hand for the ventilation line[8]

Figure 16 shows that following the approach suggested by LICS or the current levels from production (Actual Prod.) lead to high average stock levels or very high time requirements for setups in the ventilation line. While the differences in average stock days on hand might not seem so significant, it should be considered that each product from the ventilation line experiences substantially higher demand per day. Because of shorter setup times in this production line and the possibility to change over more frequently, the overall setup time requirement does not necessarily increase. Nonetheless, comparing the different scenarios in greater detail shows that Calc. Levels seems to lead to relatively low total setup times and among the lowest average stock levels.

In conclusion, one can see that each of the different methods leads to different results regarding total setup time and average stock days on hand. While both production lines seem to have their best levels in one of the calculated scenarios, *Calc. Levels* or *Meet* S_2, the overall decision of how the KPIs are graded lie with Lindab.

5.4 Summary of Results

In summary the analysis shows that the established processes and approaches in the two production lines lead to good results in some areas. Nonetheless, both production lines could be further improved while also maintaining some of the current approaches.

In the profile line some aspects of a (R,Q)-policy are utilized for managing inventory, for example ordering of products at (relatively) consistent levels and ordering quantities close to Q_{LICS} or multiples of it. However, the actual reorder points are often significantly above those given by LICS or calculations based on theoretically approaches. This frequently results in too high reorder points, excess inventory and in turn service levels higher than targeted. One of the reasons for this can be found in the difference between the planning horizon of two weeks

[8] Deviations in the number of setups (in shifts) are due to differences in the total production quantity and the total demand during that year

and the uncertainty of demand during that period. Furthermore, this effect is emphasized by varying lead times. Currently, LICS calculates reorder points and safety stock levels based on lead times around eleven to twelve days, but analyzing inventory levels and production schedules, the estimated total lead times about half of this. This was later confirmed by production planners for the profile line. In the area of scheduling and sequencing the profile line displays different characteristics. On the one hand, the schedules created do not always include the products that must be produced but require a similar setup, which likely is another reason for overshooting inventory levels. On the other hand, the sequencing procedures at this production line seem to create, in nearly all cases, the best sequence with regards to the setup times. The creation of a sequence as close to the optimal as possible is important at this production line, since it experiences high sequence dependency, which could lead to large increase in total setup time.

To some degree, the ventilation line represents an opposite to the profile line. Due to the implementation of LIPS, many aspects of inventory management for this production line are done by operators in production. Within LIPS the safety stock level is used as the reorder point and many operators interpret this level as the order-up-to level. This approach should lead to disastrous service levels, far off target, but an analysis reveals that the service levels for nearly all products are above or very close to their target. A close investigation of inventory levels and production schedules as well as interviews with operators showed that the estimated total lead times, similar to the profile line, are below those in LICS and Axapta. Because of this, the production line can achieve the target fill rate at significantly lower inventory levels. Additionally, the reorder point chosen by operators generally varied a lot, and the influence of some subjective parameters, e.g. preferred products or varying levels of experience, could be observed. Similar to varying reorder points, the order quantities also vary significantly and are rarely a multiple of Q_{LICS}. Usually, the produced quantities are lower than Q_{LICS} and especially products with lengthy set ups are produced in small batches. It could be shown that the production scheduling and sequencing is driven by shortages and that the manufacturing of other products often occurs so that the schedule for a day can be filled up. Causes for this are production quantities lower than Q_{LICS} in combination with increased total time spent on setups. The sequencing of a schedule at the ventilation line does not have such a large impact as it does at the profile line. This is due to relatively consistent setup times, which are mostly in a range up to 20 minutes. Furthermore, the possibilities for sequencing are limited, because products from the shortage list should be produced as early as possible so that orders can be fulfilled without risking delivery delays.

Apart from the deviations in lead times at both production lines one can conclude that the order quantities in LICS do not reflect the best values. An analysis of the setup cost demonstrated that it might be higher than assumed previously and therefore Q_{LICS} as well. Due to the influence of sequencing onto the actual setup times, this calculation can be seen as an estimation or potential upper limit of what Q_{LICS} might be. It is important to note that a finer distinction between products based on their setup time will lead to more accurate values.

Based on these findings, a re-evaluation of the different inventory levels and influencing factors seems necessary to mimic the actual production. This is especially important if not only the average stock on hand is to be kept at a minimum but also the time required for setting up production. Nonetheless, including operator experience and knowledge into the inventory management and scheduling and sequencing process seems to lead to improved performance in several areas. However, the inclusion of such knowledge should be guided so that overall economic advantages can be obtained.

Lastly, the analysis indicates that some data and information available within Lindab is not being used to its full extent. Among those are interarrival times between different demands or the use of synergies from existing setups so that average inventory levels and setup times can be lowered.

6 Model Outline

This chapter focuses on outlining a potential tool or model that could be used to support operators within production and provide feedback information about the production to other systems within Lindab.

As previously described, the model is aiming at supporting the operators and planners to make better scheduling and sequencing decisions with regard to total setup times, average stock levels and target fill rates. Also, in an attempt to utilize operator experience in the decision-making process the model relies on input from operators so that potential benefits of customized decisions are obtained. In other words, the model is designed to structure the operator's decisions and to link the decision-making processes to characteristics of each production line, in terms of demand behavior and setup times. Considering that the model is grounded in the production parameters, such as lead times and order quantities there is a need for a feedback system that the provides the update of current production parameters. This will help the model to generate more realistic solutions.

6.1 Production Planning Horizon

An important aspect of the model is the planning horizon, which is highly affected by production line characteristics and also largely affects production line performance. In general, the planning horizon describes the time period over which the model provides a tentative schedule. In this regard, sequence dependent setup times, production cycle times, order interarrival times and certainty of upcoming demand are among the important factors that affect and determine a chosen planning horizon. Generally, for both production lines the upcoming demand is known with a near 100% certainty for up to three days, meaning today and the following two days.

For the profile line, high level of sequence dependency, long cycle times, long production lead times and limited capacity, suggest a planning horizon longer than one day. As it is shown in the analysis section, setup times at the profile line vary largely depending on the sequence. Therefore, limiting the planning horizon to a single day may lower average stock levels, but reduces the possibilities to find good production sequences with low total setup times. To obtain more benefits from sequencing, the planning horizon should be extended at least to the horizon for which customer demand is known, which in this case is three days.

In contrast to this, the ventilation line experiences short and consistent setup times, therefore sequencing is not a major concern in production planning, while inventory management plays a key role. Considering the short cycle times, the short production lead times as well as the relatively short time between customer order for most products, a shorter planning horizon is attractive for this production line. By having a short planning horizon some advantages from sequencing can be obtained and production can get benefit of reducing stock levels aggressively by reacting more closely to customer orders. Therefore, a one day planning horizon is proposed for the ventilation line.

In summary, it can be said that for both production lines a (mostly) fixed planning horizon is suggested, however, with varying durations. To safeguard the production at the profile line against possible shortages, a special rule is introduced that requires operators to check daily if shortages exist and if so, include them in the current schedule. Thereby the planning horizon for the profile line can be described as semi-fixed. It is of course also possible to apply a rolling horizon with possibilities to update the schedule daily in order to be able to adapt to changing availability such as express orders or unexpected shortages in raw material or finished goods.

6.2 Model Structure

The model, outlined in greater detail below, generally consists of four main components. Each of these components fulfills a specific task, which is required to obtain a good production schedule so that average stock levels and total setup times are consistently kept as low as possible. These components are the candidate list, production list, production schedule and production sequence. The following paragraphs explain each component and its lists in detail. Afterwards, the interfaces between the individual components are described and visualized to outline the model as a whole.

Candidate list

The candidate list represents the first component required to schedule and sequence the production. The purpose of this list is to identify all products that qualify for production. Furthermore, this list compiles all data required for later process steps and decision making, for example critically of inventory levels, general availability of the product and upcoming demand for the next days. This data is used for structuring and sorting of the products on the list.

Regardless of the production line, products that qualify for the candidate list are either on the shortage list or have a low inventory level. Products that are on the shortage list do not have enough stock on hand to satisfy the upcoming customer demand. Therefore products from this list need to be manufactured quickly. Secondly, in correspondence with the already existing (R,Q)-policy, products with an inventory level below their reorder point are considered to be eligible to be manufactured. By implementing this rule, the production is forced to manufacture products (urgently) needed. Additionally, an artificial inflation of inventory levels is limited to a minimum. The data required for this candidate list can be extracted from Axapta and LICS. Figure 17 schematically illustrates how the candidate list is created.

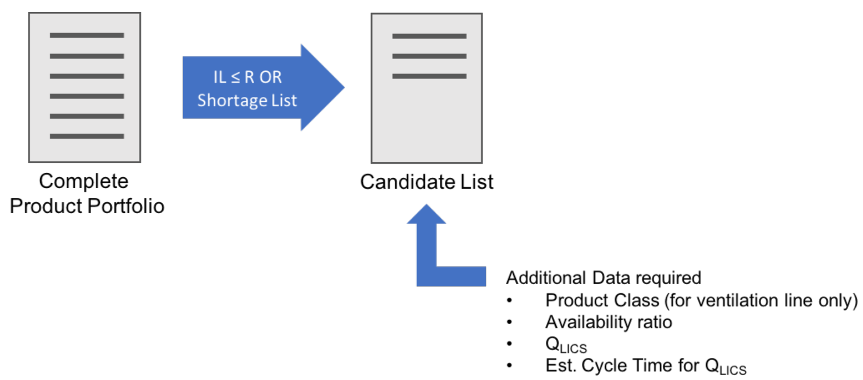

Figure 17: Creation process for the candidate list

The availability of a product, which is required for the structuring of the candidate list, is a measure that is already available and used within Lindab. Generally, Lindab defines the availability of a product by the following formula

$$\text{Current Inventory Level} \geq \max(\text{1 average transaction, 2 days demand}) = Availbility\ Criteria \quad (22)$$

For the model this measure is slightly modified to create the availability criteria, expression (22), which is the maximum of the average transaction size or demand for two days. In the next step, by using the availability criteria and upcoming demand, the availability ratio is determined. This ratio is calculated by dividing the current inventory level minus upcoming demand with the availability criteria.

$$Availability\ ratio = \frac{Inventory\ Level - Upcoming\ Demand}{Availability\ Criteria} \quad (23)$$

This ratio reflects the criticality of the product by considering the upcoming demand. The availability ratio is required, since the shortage list only includes products that will experience backorders without speedy production, but not necessarily products that will soon experience stock outages. Using the Availability ratio, it is possible to identify those products that are or soon will be unavailable. The availability ratio is one of the main decision-making parameters in the model, especially for the ventilation line and the high influence of inventory management on its performance. Furthermore, data that is added to the candidate list for the ventilation line is the demand classification, which is the same used to structure products into different groups (see Section 5.1). For the purpose of simplification, the classification is reduced to just two classes, where classes B and C are joined while class A remains. Additionally, a separate group is introduced for products with a complex and lengthy setup that is significantly different from most other products in the production line and also less regularly required. Currently, this grouping is only required for the ventilation line, where products with the codes BKML and BKMU differ largely from other products in the production line. These products are grouped together in the candidate list, since they require a similar setup and significant savings can be gained from producing them together. Lastly, the value of Q_{LICS} and likely cycle time for each product are included into the candidate list so that operators have a guideline when later selecting the actual production quantity.

Production List

The second component of the model is the production list. This list aims at providing support to operators in their decision-making process by providing them with a prioritized list of products to produce. This production list is based on the candidate list and structures it according to different criteria. The process for this varies between the different production lines, but generally it is based on similar information and steps (Figure 18).

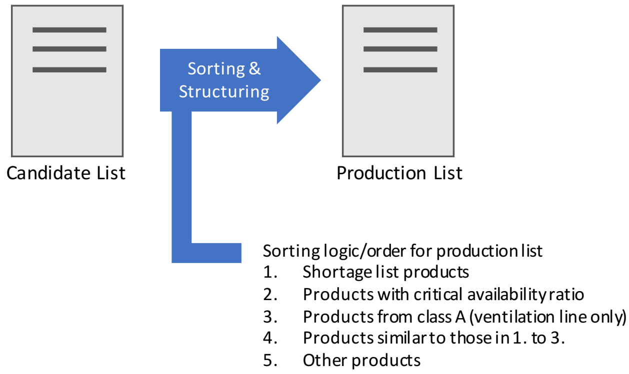

Figure 18: Process from the candidate list to the production list

For the profile line, the production list is sorted according to the following logic. The highest priority is given to products on the shortage list, which are then shown at the top of the list. Below these, products with a critical inventory level are listed. Low inventory level means that the product has an availability ratio below one. Afterwards, products with the same dimension/ size as the ones on the shortage list or with critical inventory levels are listed. If there is no product featured on the shortage list, products with the same size as the last product produced the day before are included in this section as well. Lastly, products that do not fit any above criteria are listed. The reasoning for this structuring is based on the assumption that products on the shortage list or with a critical inventory level should be produced as soon as possible, even though this might not lead to the most optimal sequence regarding total setup time. To lower this measure, products with the same dimensions as those that have to be selected are listed next, which leads to reduced setup times between products.

The process for the ventilation line has some resemblance to the profile line, but also includes additional aspects. As in the profile line, products featured on the shortage list are listed at the very top. However, after those products, the next section consists of products attributed to class A, meaning fast movers that generally are demanded daily in relatively large quantities. Below those, all products with critical inventory levels are listed. Here, an availability ratio below one is proposed. Afterwards, products with similar characteristics as those in the top sections are listed. On the one hand, products that have the same dimension but a different angle or code are included by this criterion. On the other hand, if a product from the group of complex and lengthy setups is already listed, other products from this group are included in this section as well. At the bottom of the production list for this production line, products that meet none of these criteria or characteristics are listed.

Production Schedule

The production schedule represents the interface between model and operator and serves as the point where the experience of operators can influence and improve the potential schedule. The production schedule is based on the production list and allows the operator to select the products to be produced and in what quantity. Deriving from the slightly different structure or content of the candidate lists for each production line, the process in creating the schedule differs. Generally, the process starts with the compulsory selection of products from the shortage list and other critical or highly demanded products. Afterwards, other products are selected until the schedule is full. This process is depicted in Figure 19.

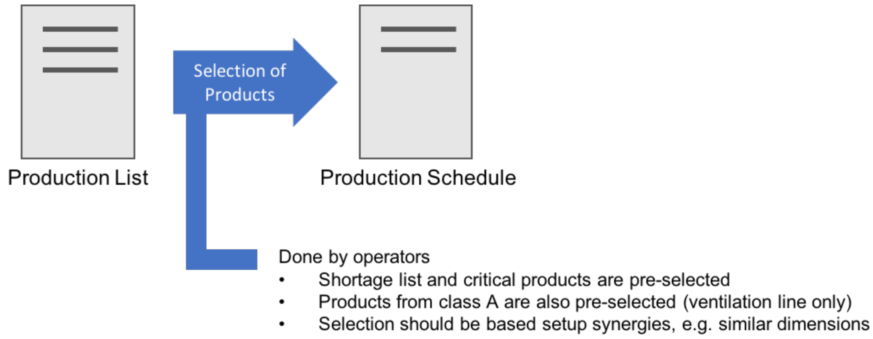

Figure 19: Creation of the production schedule from the production list

The profile line approach for selecting products for manufacturing can be described as follows. In an initial and potentially automatic step, all products from the shortage list and with critical inventory levels are fixed to the schedule. Here, the operator can only determine the order quantity, or deselect products from the schedule, if raw materials, tools or other required resources are not available. Next, operators can add more products to the schedule, if time within the schedule is still available. For each product that is added to the schedule, the order quantity has to be determined so that the model can verify that sufficient time is available. This last step should be repeated until a complete schedule is created, which means that as little time as possible within the planning horizon is left. Here, it is important to note that during this process the model has to include the potential setup times between products. This can be achieved by utilizing the average setup time for products and also introducing some buffer time into the schedule so that longer actual setup times do not lead to an infeasible schedule. Eventually the actual sequence dependent setup times can be used instead. Due to a planning horizon of three days and potential shortages arising during this period, operators have to monitor the shortage list daily and if a shortage appears during an active schedule, integrate the respective product. Within this additional step, the model is moved more towards a rolling planning horizon and allows flexibility to challenges in real time.

The procedure for the ventilation line is related but, due to some differences in its characteristics a slightly different procedure is proposed. As in the profile line, products in the top section of the production list, which experience a shortage, a critical inventory level or considered fast-movers, are pre-selected for the schedule. For these products operators have to select an order quantity before other products can be selected. If sufficient time in the planning horizon is available, other products can be selected into the schedule. These products are from the section of products which require a similar setup to those in the top section. For each product that is added to the schedule, the order quantity has to be determined so that the model can verify that sufficient time is available. Like the process for the profile line, this last step should be repeated several times until the schedule is complete. If a product from the so-called complex group is selected, other products in the production list from that group are selected as well. Through this, setup times between products can be kept at a minimum. Understandably, operators in both production lines have to be trained or should be obliged to initially select products from the group of products with the same dimension as those in the top section. By doing this it can be ensured that synergies from similar setups can be obtained and therefore the total setup time kept to a minimum.

An additional feature of the production schedule is the support in deciding the order quantity within that planning horizon. Initially, the production schedule is based on and displays Q_{LICS} for each product. In this model, it is assumed that most products are manufactured as closely to the calculated value of Q_{LICS} or multiples of it. A possible decision rule, that introduces some flexibility into this process but also maintains a cost level around the EOQ, can be described as follows. Generally, the operator is given the possibility to deviate from the value of the Q_{LICS} within a fixed range. This range can be determined by limiting the cost increase from the EOQ to a certain value. This value has to be determined by Lindab and represents a management decision much like target service levels. However, for the purpose of this thesis a maximum cost increase of 10% from the optimal is used to outline the process and its results. This range could be modified or discarded for certain products, such as products from the complex group or class A. Especially, for products such as BKML 160-90 GALV from the ventilation line this is beneficial since the generally small order quantities lead to significant increase in costs.

An exception to this rule can be given to products on the shortage list, where the demanded quantity might be larger than the calculated value of Q_{LICS}. Here, either the demanded quantity or the next multiple of Q_{LICS} above the demanded quantity can be produced.

Production Sequence

The sequencing of the production schedule represents the last component of the outlined model. This step in the model is automated and done by the model without any input from operators. Generally, the sequencing process aims at achieving the lowest possible setup time between the scheduled products. As it has been outlined in Section 3.3.5, greedy algorithms and tabu search methods can be used to determine a feasible, (near) optimal solution within a short amount of time. As in the previous components, both production lines share some process steps within the production sequencing, but not all.

Manufacturing on the profile line is highly dependent on the production sequence. Therefore, the sequencing of this production line can consider the last product being produced on the day before so that as little production time as possible is sacrificed for setups. From this information and the production schedule, the (near) optimal sequence is created. The application of tabu search means that the structure from the production schedule can be completely changed, because it might save setup time. From the analysis of the production line is can be assumed that this can be seen as the regular approach, but for products on the shortage list a different approach is required. Here, the last product from the previous day is disregarded and the production of the shortage list is placed at the beginning of the sequence. The reasoning for this is that products on this list are required as soon as possible and that regular sequencing of them might place them at the end of the sequence, which might severely complicate a timely delivery to customers. After the shortage list products, regular products are sequenced with the help of a greedy algorithm or tabu search method, considering the last product on the shortage list. Here, it should be noted that a full tabu search might be a little too advanced for this kind of sequencing problem and utilizing a greedy algorithm would be a natural first step.

As shown in the analysis, the ventilation line regularly experiences demand which cannot be met by current inventory levels, even though the limitation of order quantities close to Q_{LICS} will likely reduce the frequency of this. Furthermore, the sequence dependency of the production at this production line is limited. Therefore, the consideration of production from the previous day is rarely required or necessary.

Complete Structure

Based on these individual components, the complete structure is illustrated in Figure 20. In this model, operators are guided through the production scheduling and sequencing process, which is more consistent and potentially leads to lowered total inventory costs.

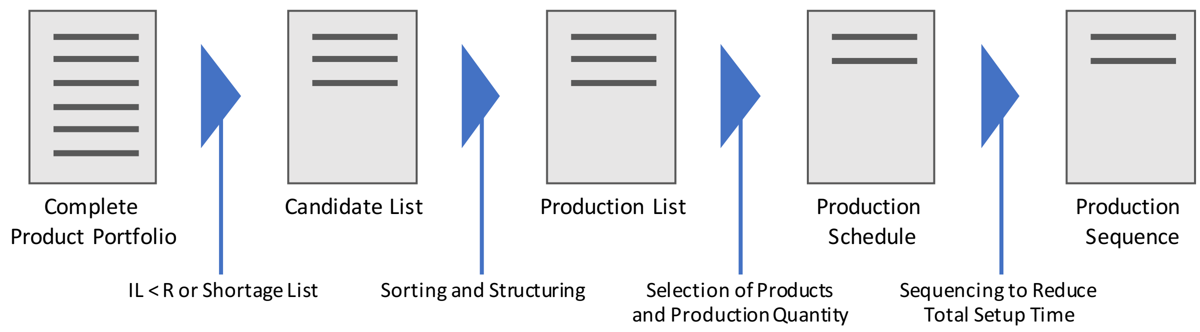

Figure 20: Complete structure of the model

It should be noted that the model is designed with operator interaction in mind, in particular during the selection of products for the production schedule. However, the interaction between operators and the model does not have to be limited to the production list. Potentially, all the different elements could be used as an entry point, with varying levels of model support, into production scheduling and sequencing. These aspects could be interesting for several reasons. Firstly, from a change management perspective, operators might feel that their responsibilities are cut back severely if the model is introduced as outlined, therefore the model could also be introduced step-wise. Secondly, the different lists could be used to grant operators more freedom based on their experience level. Consequently, less experienced or new operators could be limited to the production list while experienced operators could decide which list they choose to start the production planning from.

6.3 Example Production Scheduling and Sequencing

In the following a scheduling and sequencing example for each production line is presented so that the theoretical approach described above becomes more understandable. Therefore, one example week for each production line has been selected to exemplify the model.

For the profile line, week 37 is selected due to its relatively high demand level. Considering the suggested planning horizon of three days, the first step considers a production schedule for the 12th, 13th and 14th of September. The candidate list is created, which contains all products that qualify for production and also adds some required data. Based on the earlier described process the candidate list for this production line and week will have the following appearance (Table 15).

Table 15: Candidate list for the profile line on the 12.09.2016

Product Group	Product	Availability Ratio	Q_{LICS} Cycle Time
Shortage List	100-87 SVRT	-0,4	5,5 h
Inventory Level below reorder point	150-100 SVRT	3,7	4,9 h
	150-100 ZM	0,4	2,4 h
	150-100 MGRÅ	8,2	4,9 h
	150-87 AMET	4,7	2,4 h
	150-100 AVIT	8,9	4,9 h
	150-100 BRUN	10,0	4,9 h
	125-100 ZM	2,4	1,5 h
	125-100 BGRO	0,0	0,2 h
	150-111 AVIT	1,2	0,4 h
	150-111 SMET	1,6	1,1 h

From the candidate list in Table 15 the production list is created. This means that the candidate list is sorted so that operators can decide on next products to be produced. Since the products 100-87 SVRT, 150-100 ZM and 125-100 BGRO are the most critical or on the shortage list, the production list is structured around them. The resulting production list can be found in Table 16.

Table 16: Production list for the profile line on the 12.09.2016

Product Group	Product	Availability Ratio	Q_{LICS} Cycle Time
Shortage List	100-87 SVRT	-0,4	5,5 h
Critical Products	125-100 BGRO	0,0	0,2 h
	150-100 ZM	0,4	2,4 h
Same Dimension as Shortage List or Critical Products	125-100 ZM	2,4	1,5 h
	150-100 SVRT	3,7	4,9 h
	150-100 MGRÅ	8,2	4,9 h
	150-100 AVIT	8,9	4,9 h
	150-100 BRUN	10,0	4,9 h
Other Products	150-111 AVIT	1,2	0,4 h
	150-111 SMET	1,6	1,1 h
	150-87 AMET	4,7	2,4 h

From Table 16 one can see that several products have the same dimension as those two products that have critical availability ratios. These products are displayed beneath those that have to be produced. The next step is the selection of products to be manufactured and their respective production quantity. A challenge in creating the final production schedule is choosing the product and their respective quantity, since not all products can be manufactured in a single planning horizon. For this example, products similar to 125-100 BGRO are selected first and then products similar to 150-100 ZM. Generally, this step falls into the responsibility of operators and might include additional aspects, but commonly is should be based on low availability ratios. Furthermore, for this example, the order quantity is assumed to be the current Q_{LICS}. The resulting production schedule for the profile line is shown in Table 17.

Table 17: Production schedule for the profile line on the 12.09.2016

<table>
<tr><th>Product Group</th><th>Product</th><th>Availability Ratio</th><th>Q_{LICS} Cycle Time</th></tr>
<tr><td>Shortage List</td><td>100-87 SVRT</td><td>-0,4</td><td>5,5 h</td></tr>
<tr><td rowspan="2">Critical Products</td><td>125-100 BGRO</td><td>0,0</td><td>0,2 h</td></tr>
<tr><td>150-100 ZM</td><td>0,4</td><td>2,4 h</td></tr>
<tr><td rowspan="2">Similar Dimension as Shortage List or Critical Products</td><td>125-100 ZM</td><td>2,4</td><td>1,5 h</td></tr>
<tr><td>150-100 SVRT</td><td>3,7</td><td>4,9 h</td></tr>
</table>

The next step is to sequence the products according to the principles described earlier. This leads to the following production sequence, depicted in Table 18.

Table 18: Production sequence for the profile line on the 12.09.2016

Product	Place in Sequence	Setup Time	Cycle Time	Production Time Remaining
100-87 SVRT	1	1,25 h	5,5 h	17,25 h
125-100 BGRO	2	1,25 h	0,2 h	15,80 h
125-100 ZM	3	2 h	1,5 h	13,80 h
150-100 ZM	4	3 h	2,4 h	8,4 h
150-100 SVRT	5	0,25 h	4,9h	3,25 h

Table 18 shows that 3,25 hours of potential production time are not used. However, using an order quantity larger than Q_{LICS} could help reducing this time. Potentially, the order quantities of some products in the sequence may also be reduced to allow one more product in the schedule.

For the ventilation line, week 21 of 2016 is selected. Because of, the planning horizon of a single day, only the 23rd of May is scheduled and sequenced. As for the profile line the first step is the creation of the candidate list, which is depicted in Table 19.

Table 19: Candidate list for the ventilation line on the 23.05.2016

Product Group	Product	Availability Ratio	Q_{LICS} Cycle Time
Shortage List	BKMU 160-90 GALV	0,3	4 h
Inventory Level below reorder point	BU 125-15 GALV	1,9	6 h
	BU 125-45 GALV	2,1	16 h
	BU 125-45 EAN	3,5	9 h
	BKML 160-90 GALV	0,3	1 h
	BMU 125-45 GALV	0,8	1 h
	BU 125-15 EAN	0,0	2 h
	BU 125-30 EAN	3,6	3 h
	BU 160-15 EAN	0,0	1 h

Based on this candidate list, the products are sorted according to the logic explained in Section 6.2. First, products featured on the shortage list are listed. Then products with critical availability ratios, then fast movers and then products similar in dimension to those listed previously. Lastly, any product that does not meet any of those criteria is listed. Table 20 shows the production list for the chosen example day.

Table 20: Production list for the ventilation line on the 23.05.2016

Product Group	Product	Availability Ratio	Q_{LICS} Cycle Time
Shortage List	BKMU 160-90 GALV	0,3	4 h
Critical Products	BU 125-15 EAN	0,0	2 h
	BU 160-15 EAN	0,0	1 h
	BKML 160-90 GALV	0,3	1 h
	BMU 125-45 GALV	0,8	1 h
Similar Dimension as Shortage List or Critical Products	BU 125-15 GALV	1,9	6 h
	BU 125-45 GALV	2,1	16 h
	BU 125-45 EAN	3,5	9 h
	BU 125-30 EAN	3,6	3 h
Other Products	-		

This list is then presented to the operator, who has to select the products to be manufactured as well as their respective production quantity. As before, it is assumed that the production quantity is equal to the current Q_{LICS} value. Given the 24-hour planning horizon and production time, the operator now faces the challenge of having more options than capacity allows. An approach would be to select products based on their availability ratio until no production time is available. The production schedule under these considerations can be seen in Table 21.

Table 21: Production schedule the ventilation line on the 23.05.2016

Product Group	Product	Availability Ratio	Q_{LICS} Cycle Time
Shortage List	BKMU 160-90 GALV	0,3	4 h
Critical Products	BU 125-15 EAN	0,0	2 h
	BU 160-15 EAN	0,0	1 h
	BKML 160-90 GALV	0,3	1 h
	BMU 125-45 GALV	0,8	1 h
Similar Dimension as Shortage List or Critical Products	BU 125-15 GALV	1,9	6 h
	BU 125-30 EAN	3,6	3 h

Based upon this information, it is now possible to sequence the production for the 23rd of May. This is done by the model itself and focuses on finding a production sequence with the lowest total setup time. The likely sequence for this day and production line can be seen in Table 22.

Table 22: Production sequence the ventilation line on the 23.05.2016

Product	Place in Sequence	Setup Time	Cycle Time	Production Time Remaining
BKMU 160-90 GALV	1	3,00 h	4 h	17,00 h
BKML 160-90 GALV	2	0,16 h	1 h	15,84 h
BU 160-15 EAN	3	0,33 h	1 h	14,51 h
BMU 125-45 GALV	4	0,33 h	1 h	13,18 h
BU 125-30 EAN	5	0,16 h	3 h	10,02 h
BU 125-15 GALV	6	0,16 h	6 h	3,86 h
BU 125-15 EAN	7	0,0 h	2 h	1,86 h

As with the other production line, not all the available production time could be filled by using the Q_{LICS} value, but allowing operators to slightly deviate from it will provide sufficient flexibility to fill up the remaining time.

6.4 Feedback System

As mentioned earlier in this chapter, there is a need for feedback and updating of the production data in Axapta and LICS to continuously improve the model and production planning. This updating of data and model parameters is required so that Lindab can consistently determine correct values for its inventory control and managements systems. Among the data that should be measured and updated are production lead times and setup times. For instance, producing Q_{LICS} will affect the waiting time for other products and the production line is blocked for some additional hours. Because of this, the actual production lead times might vary over time. Therefore, follow up of the production parameters should be done regularly to evaluate the effects of changes on the current system. Furthermore, changes and improvements in setup procedures have a direct impact on setup times and will likely result in varying Q_{LICS} values, which in turn leads to changes in production lead times.

6.5 Further Development of the Model

There are many aspects of the model the can be developed to find more refined and efficient solutions, one direction is to quantify the total costs associated with the scheduling and inventory management decisions. However, this would require more accurate estimation of the holding cost and setup cost parameters. This can partly be achieved through continuous measuring of the parameters in the production. In doing so, a more accurate estimation of the economic order quantity can be obtained for each product.

A first potential aspect in the development of the model is the implementation of a more dynamic Q_{LICS}, which varies based upon the sequence of products within a schedule. Here, depending on how much setup time is required, the production quantity could automatically be adapted. Furthermore, a potential further development stage of the model is to differentiate between products with large order interarrival time and other items in the model. Postponing the production of items with a large interarrival time and prioritizing other products, can achieve flexibility in production planning and lower average inventory levels.

7 Discussion

The purpose of this study was to identify and analyze parameters affecting the total inventory and production costs for two production lines at Lindab AB and based on this outline a quantitative model that supports operators within production to make better planning decisions. In this section, the findings of the analysis as well as the outlined model are discussed with regard to the purpose of this study. Furthermore, the contribution to the research field and areas for future research are outlined.

7.1 Discussion of the analysis

Through the analysis it could be shown that the main parameters affecting Lindab's total cost are largely influenced by lead times, reorder points, setup times and order quantities. Currently, the investigated production lines rely on the parameters determined by LICS to some degree. Each line utilizes them differently or uses those parameters as they see fit. Furthermore, by analyzing these parameters, we can see that a strong reliance on a single aspect, e.g. low average inventory level, not necessarily leads to overall improvements but potentially a decline of other, e.g. total setup time. Therefore, we recommend balancing these two aspects to achieve more efficient operations.

Although slightly different results might be obtained through more accurate raw data, the general implications of the analysis should hold true. A main finding of this study is that all parameters identified are part of well-established approaches, however in order to achieve substantial improvements, the parameters should not be considered in isolation.

7.2 Discussion of the model

The presented model mainly aims at supporting operators in their decision-making process during production planning. The output of the model may not always represent the best solution. However, in many cases it should provide good and robust solutions, since it considers a product's inventory level, demand characteristics, setup characteristics as well as an operators experience. The ambition behind this approach is to utilize theoretical models and (unstructured) operator experience to its full potential and avoid unwanted result.

Understandably, fixing the planning horizon for any period of time could result in challenges once unexpected customer orders arrive, which is more likely to occur in the profile line due to its three-day planning horizon. To circumvent this issue while maintaining the benefits from a long planning horizon, the special routine introduced to daily check the shortage list was established. Through this the model should be able to generate a (nearly) optimal schedule and sequence without risking customer service.

To avoid overcomplicating the model, some limitations are introduced. This includes limitations in both lines regarding tools, operators, breakdowns or specific due dates. It is assumed that tools, lift trucks, machines and labors are always available. However, further development of the model in the future could include some of these capacity limitations and the operator can manually exclude products that are not possible to produce.

7.3 Contribution to the research field

Generally, this study focused on investigating a specific issue for two of Lindab's production lines. However, the approach and the insights from the analysis are quite general and can be used for other parts of Lindab or other similar manufacturing companies to investigate the balancing of different inventory management KPIs. Furthermore, if similar disparities between KPIs are identified, the introduction of the outlined model might be helpful in achieve better overall results.

The model presented in this study represents a relatively simple approach to balancing two KPIs, namely average inventory levels and total setup times, with the goal of lowering them. It is built on well-established models and utilizes parameters that are present in any inventory or production environment. Therefore, adapting the model for different production lines or companies should be relatively easy. In summary, the outlined model presents a simple and easily implementable attempt to balance two KPIs to achieve better overall results for a single production line.

7.4 Areas for future research

A key area that requires further investigation is the quality of the raw data, both received and observed. Throughout the data collection period, it became evident that different entities within the supply chain base their work on varying definitions and values of parameters. Because of this and very rough estimations of some parameter's values, it is likely that the results obtained are a conservative estimate of what might be achieved by Lindab through the implementation of the recommendations. A further area for future research is the investigation of the actual costs associated with the different parameters of inventory management. Through a detailed analysis and determination of these parameters it might be possible to more closely compare the total cost for the system and optimize the decisions to minimize it.

8 Summary and Conclusion

Lindab's current approach to inventory management and production planning, also referred to as their internal VMI system, already operates at a high level and presents the company with several advantages. Firstly, the combination of theoretically founded calculations with the vast experience of operators helps Lindab to improve their operations. Under the current settings in the ventilation line, operators play an important role in production planning where they are seen as suppliers. They have access to a wide range of data, including real time stock on hand, upcoming orders, and are given a large degree of freedom in scheduling and sequencing their line. This approach differs from the standard inventory and planning system which is based on the average expected demand. Allowing the operators to customize planning based on upcoming customer orders, current stock levels and production capacity as well as other important aspects, such as availability of raw materials and tools has many advantages. Acting based on the real data on current situation gives the production the ability to adjust its planning and sequencing to reduce the stock level and setup times. Besides, engaging the operators in decision-makings can increase motivation in the shop floor and have positive effects on the quality of work and possibly productivity.

However, the company has focused mostly on its production and only recently focused more on supply chain management. As part of this effort inventory management has increased in its importance and lowering costs associated to it is a primary objective. Nonetheless, this single-sided focus does not necessarily lead to the desired savings and presents Lindab with potential areas of improvement. Also, a drawback of the current setting is that, production planning and sequencing is subjective, unstructured and do not leverage important parameters, such as fill rate, and economic order quantity to its full potential.

Through the analysis it could be shown that the current inventory system, LICS, which is based on a (R,Q)-policy, has differing results from those practiced in the production. These contradictory approaches or results, have a number of causes, namely too long lead times, reorder points and safety stock levels as well as inaccurate estimated ordering costs. Based on these findings, it is concluded that Lindab should modify their current approaches and calculations to better align different stages within their supply chains.

To facilitate Lindab's efforts in further lowering their total inventory and production costs, a model was outlined. The model aims at providing operators a guideline in their planning by suggesting the products that should be scheduled and subsequently sequenced. The model itself operates based on four sequential lists that gradually reduce the number products that should be considered by an operator. Here, products are also sorted according to their importance to Lindab and its customers, based on a product's availability and upcoming demand. Furthermore, operators are supported in their decision-making process for the order quantities so that both resource utilization and costs are balanced. Here, some flexibility is given around the economic order quantity and operators can freely choose a production quantity within a range.

The model is customized based on the characteristics of two production lines and could easily be modified to fit any production line with the similar characteristics regarding customer demand behavior and products and production characteristics. In general, the model for the ventilation line can be applied to lines with relatively large levels of flexibility in changeovers/setups, small number of products with large and frequent customer orders, and low average cycle times. On the other hand, the model for the profile line is suitable for production lines with highly sequence dependent setup times and therefore lower flexibility in changeovers, relatively large number of products with small and infrequent customer orders, larger average cycle times and production lead time. It is important to note that both lines are experiencing relatively stable lead times since almost all products have small batch sizes that can be produced in one or two working shifts, and therefore not blocking the line for a long period, which could lead to a fluctuation in production lead times.

In conclusion, through this study it could be shown that Lindab's approach to inventory management and production planning is adequate. However, several parameters influencing the production planning and inventory management have been identified and more optimal approaches or values have been presented. Furthermore, the designed model presents Lindab with an outline of how the production scheduling and sequencing could be structured so that the average inventory and total setup time are potentially lower or at least more balanced.

9 Recommendations

Based on the analysis results and the outlined model, Lindab is recommended to pursue the following aspects.

Firstly, both main inventory IT systems, LICS and LIPS, should be aligned with each other. This means that both IT systems utilize the (R,Q)-policy and do so in the same way. This would result in LIPS having to change and display the reorder point instead of the safety stock level. Lindab might still want to display the safety stock level within LIPS, which could be achieved through a number of ways, e.g. changing the color of the bar once safety stock levels are reached. By aligning LICS and LIPS it is now possible to more closely monitor and manage the different products of a production line and identify potential areas for improvement more easily. In parallel with the alignment of LICS and LIPS, Lindab should re-evaluate the reorder points and safety stock levels of the products. As illustrated in the analysis a re-calculation could lead to significantly lower average inventory levels, especially when considering estimated actual lead times. Furthermore, a close investigation of the actual setup times could help Lindab to determine a more accurate ordering cost, which in turn leads to more accurate economic order quantity. An alternative to this detailed and possibly lengthy investigation is the differentiation of products into two separate ordering costs groups. Through this more accurate economic order quantities are obtained, especially for products with longer setup times.

Secondly, in the area of production scheduling and sequencing, it is recommended to provide a more structured process to the operators so that more consistent results are obtained. As described in the model outline, the model should distinguish between different types of production lines, one similar to the ventilation line and the other like the profile line. Through this, it is possible to obtain the best results for these or any other similar production lines. Therefore, the profile line should be based on a semi-fixed planning horizon of three days, while the ventilation line should operate on a daily planning horizon. With regards to sequencing of the production, both production lines can benefit from optimized production sequences and therefore it is recommended to structure or potentially automate this process step.

Lastly, it is recommended to establish a continuous feedback and updating routine so that accurate production data, such as achieved setup times or production lead times, is available in the IT systems. Through this, the actual values from the production floor can be used by

LICS and Axapta to more accurately determine reorder points, safety stock levels, order quantities or production sequences.

In conclusion, this study recommends Lindab to re-evaluate some aspects of its inventory management and production scheduling and sequencing. The focus should be obtaining benefits from rigid inventory management systems and (unstructured) operator experience so that as many parameters as possible are considered and costs are kept at a minimum.

10 References

Allahverdi, A., Ng, C.T., Cheng, T.C.E., Kovalyov, M.Y., 2008. A survey of scheduling problems with setup times or costs. European Journal of Operational Research 187, 985–1032.

Agustin, R.O. & Santiago, F., 1996. Single-minute exchange of die. In IEEE/SEMI 1996 Advanced Semiconductor Manufacturing Conference and Workshop. Theme-Innovative Approaches to Growth in the Semiconductor Industry. ASMC 96 Proceedings.

Axsäter, S., 2006. Inventory control, 2. ed., International series in operations research & management science. Springer, New York, NY.

Barnes, J.W. & Laguna, M., 1993. A tabu search experience in production scheduling. Annals of Operations Research, 41(3), pp.139–156.

Berling, Peter. 2005. "On Determination of Inventory Cost Parameters." Lund University Department of Industrial Engineering Division of Production Management.

Berling, P., Rosling, K., 2005. The Effects of Financial Risks on Inventory policy. Management Science 51, 1804–1815.

Bozarth, C.C. & Handfield, R.B., 2008. Introduction to Operations and Supply Chain Management, Prentice Hall.

Bryman, A., Bell, E., 2011. Business research methods, 3rd ed. ed. Oxford University Press, Cambridge ; New York, NY.

Çetinkaya, S, & Lee, C 2000, 'Stock replenishment and shipment scheduling for vendor-managed inventory systems', Management Science, 46, 2, p. 217-232.

Chopra, S., Meindl, P., 2007. Supply chain management: strategy, planning, and operation, 3. ed., Pearson internat. ed. Pearson Prentice Hall, Upper Saddle River, NJ.

Cormen, T.H., 2009. Introduction to Algorithms, MIT Press.

Disney, S. M., and D. R. Towill. 2003. "The Effect of Vendor Managed Inventory (VMI) Dynamics on the Bullwhip Effect in Supply Chains." International Journal of Production Economics 85 (2): 199–215.

Dong, Yan, Kefeng Xu. 2002/4. "A Supply Chain Model of Vendor Managed Inventory." Transportation Research Part E: Logistics and Transportation Review 38 (2): 75–95.

Glover, F., 1990. Tabu Search: A Tutorial. Interfaces, 20(4), pp.74–94.

Harris, F.W. 1913, "How many parts to make at once", Factory, The Magazine of Management 10(2), vol. 152, pp. 135-136.

Hill, A., Hill, T., 2009. Manufacturing operations strategy, Palgrave Macmillan.

Hillier, F.S., Lieberman, G.J., 2010. Introduction to operations research, 9th ed. ed. McGraw-Hill Higher Education, New York.

Hopp, W.J., Spearman, M.L., 2001. Factory physics: foundations of manufacturing management, 2nd ed. ed. Irwin/McGraw-Hill, Boston.

Karabati, S., Akkan, C., 2006. Minimizing sum of completion times on a single machine with sequence-dependent family setup times. Journal of the Operational Research Society 57, 271–280.

Kotzab, H., Westhaus, M. (Eds.), 2005. Research methodologies in supply chain management. Physica-Verlag, Heidelberg ; New York.

Laguna, M. & Marklund, J., 2013. Business Process Modeling, Simulation and Design, Second Edition, CRC Press.

Lee, Hau L., V. Padmanabhan, and Seungjin Whang. 1997. “Information Distortion in a Supply Chain: The Bullwhip Effect.” Management Science 43 (4): 546–58.

Lowson, R.H., 2003. Strategic Operations Management: The New Competitive Advantage, Routledge.

McIntosh, R.I. et al., 2000. A critical evaluation of Shingo’s “SMED” (Single Minute Exchange of Die) methodology. International Journal of Production Research, 38(11), pp.2377–2395.

Pinedo, M.L., 2016. Scheduling: Theory, Algorithms and Systems. Springer International Publishing, Cham.

Pinedo, M.L., 2009. Planning and Scheduling in Manufacturing and Services. Springer New York, New York, NY.

Shingo, S., 1985. A Revolution in Manufacturing: The SMED System, Productivity Press.

Silver, E.A., Silver, E.A., Pyke, D.F., Peterson, R., 1998. Inventory management and production planning and scheduling, 3rd ed. ed. Wiley, New York.

Simchi-Livi, D., P. Kaminsky, and E. Simchi-Livi. 2000. “Designing and Managing the SC-Concepts.” Strategies. McGraw-Hill, Singapore. Tomado de: Tyan Y Wee.

Sourd, F., 2005. Earliness–tardiness scheduling with setup considerations. Computers and Operations Research 32, 1849–1865.

Tyan, Jonah, and Hui-Ming Wee. 2003/1. “Vendor Managed Inventory: A Survey of the Taiwanese Grocery Industry.” Journal of Purchasing and Supply Management 9 (1): 11–18.

Yin, Robert K. 2009. Case Study Research: Design and Methods. SAGE.

11 Appendix

11.1 Setup Time Matrix for the Profile Line

Dimension	Length	100/75	100/87	125/100	150/100	150/111	150/120	150/87
100	75		60	60	60	60	60	60
100	87	60		60	60	60	60	60
125	100	60	60		60	60	60	60
150	100	60	60	60		60	60	60
150	111	60	60	60	60		60	60
150	120	60	60	60	60	60		60
150	87	60	60	60	60	60	60	

Color	387	ALUZ	AMET	AVIT	BRUN	GALV	MGRÅ	MRÖD	SMED	SVRT	TRÖD	ZM
387		120	15	15	15	120	15	15	15	15	15	120
ALUZ	15		15	15	15	45	15	15	15	15	15	45
AMET	15	120		15	15	120	15	15	15	15	15	120
AVIT	15	120	15		15	120	15	15	15	15	15	120
BRUN	15	120	15	15		120	15	15	15	15	15	120
GALV	15	45	15	15	15		15	15	15	15	15	45
MGRÅ	15	120	15	15	15	120		15	15	15	15	120
MRÖD	15	120	15	15	15	120	15		15	15	15	120
SMED	15	120	15	15	15	120	15	15		15	15	120
SVRT	15	120	15	15	15	120	15	15	15		15	120
TRÖD	15	120	15	15	15	120	15	15	15	15		120
ZM	15	45	15	15	15	45	15	15	15	15	15	

Setup times between different sizes or coils in minutes

Explanation

The setup times between different products on the profile line are a combination between the values in the two table. For example, a setup from 100-75 BRUN to 100-75 MRÖD requires 15 minutes, because only the coil color changes. On the other hand, a change from 100-75 BRUN to 150-120 SMED firstly requires 60 minutes for the tool changes and then, secondly, 15 minutes for the change to another coil. As a result, the setup time for this change over is 75 minutes.

11.2 Setup Time Matrix for the Ventilation Line

Code	B	BU	BMU	BKLM	BKMU	BEJ
B		10	10	180	180	1
BU	10		10	180	180	1
BMU	10	10		180	180	1
BKLM	45	45	45		10	45
BKMU	45	45	45	10		45
BEJ	10	10	10	180	180	

Dimension	Angle	125/15	125/30	125/45	150/30	150/45	150/90	160/15	160/30	160/90
125	15		10	10	20	20	20	20	20	20
125	30	10		10	20	20	20	20	20	20
125	45	10	10		20	20	20	20	20	20
150	30	20	20	20		10	10	20	20	20
150	45	20	20	20	10		10	20	20	20
150	90	20	20	20	10	10		20	20	20
160	15	20	20	20	20	20	20		10	10
160	30	20	20	20	20	20	20	10		10
160	90	20	20	20	20	20	20	10	10	

Setup times between different codes or sizes in minutes

Explanation

The setup times between different products on the ventilation line are the maximum of the corresponding values from both tables. For example, for a change from B 125-30 to BU 150-45, setup times of 10 minutes and 20 minutes can be found in the two tables. Because of have operators conduct the setup, the setup time for this change lies at 20 minutes.