TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

TUOMO PELTOLA

REDUCING DISRUPTIONS IN PRODUCTION PROCESS BY SOLVING INVENTORY RELATED ISSUES

Master of Science Thesis

Examiner: prof. Jussi Heikkilä
Examiner and topic approved on
3 January 2018

ABSTRACT

TUOMO PELTOLA: Reducing Disruptions in Production Process by Solving Inventory Related Issues
Tampere University of Technology
Master of Science Thesis, 63 pages, 16 Appendix pages
January 2018
Master's Degree Programme in Industrial Engineering and Management
Major: Industrial and Business Economics
Examiner: professor Jussi Heikkilä

Keywords: Inventory record inaccuracy, work-in-progress inventory, lean thinking, theory of constraints, production disruptions

This study examines two inventory related issues pointed out by the case factory. The record inaccuracies in the raw material store and the capacity of the work-in-progress (WIP) inventory were seen as causing disruptions in the production process of the case factory. The objective of this study is to find the causes behind the issues and their effects on the production process, and thereafter to give suggestions on how to improve operations.

A data based analysis is performed on the given problems. The main data used in the study is historical production data from a period of 12 months gathered from the case factory's information systems. Observing processes and interviewing operators are also utilized in data gathering. Suggestions for improvement are given based on the gathered and analyzed data with guidance from chosen literature principles. The reviewed literature includes inventory management, lean thinking and the theory of constraints (TOC).

Six different sources of inventory record inaccuracy were identified. Both system error and human error are present in the identified sources of inaccuracy. The best solution for eliminating inaccuracies is to update the raw material store management system because the current system does not offer the required functionalities for better management of records. The inaccuracies can be controlled to some extent by the means of changing the ways of working and implementing a form of cycle counting. Increasing the inventory record accuracy results in raw material cost savings and less disruptions and waste in the process due to less usage of substitute materials.

The capacity of the WIP storage can be seen as disrupting Feeder's production, but is not the root cause. The root causes are the reasons for the performance difference between the converting process and the Feeder, which cause WIP products to build up in the storage. The converting process is the constraining resource of the production system and should be elevated. Focus should be in eliminating non-value adding disruptions and examining the possibility of increasing the capacity of the converting process. Reducing disruptions leads to better production scheduling which leads to better control of the WIP storage area. The primary objective of scheduling should be maximizing the uptime of the converting machines.

TIIVISTELMÄ

TUOMO PELTOLA: Häiriöiden vähentäminen tuotantoprosessissa ratkaisemalla varastojen hallintaan liittyviä ongelmia
Tampereen teknillinen yliopisto
Diplomityö, 63 sivua, 16 liitesivua
Tammikuu 2018
Tuotantotalouden diplomi-insinöörin tutkinto-ohjelma
Pääaine: Talouden ja liiketoiminnan hallinta
Tarkastaja: professori Jussi Heikkilä

Avainsanat: Varaston saldovirheet, keskeneräisten tuotteiden varasto, lean-ajattelu, kapeikkoajattelu, tuotantohäiriöt

Tämä tutkimus käsittelee kahta varastoihin liittyvää ongelmaa, jotka annettiin tutkimuksen kohteena olevalta tehtaalta. Saldovirheet raakamateriaalivarastossa ja keskeneräisten tuotteiden varasto aiheuttavat häiriöitä tehtaan tuotantoprosessissa. Tämän tutkimuksen päämääränä on löytää syyt kyseisten ongelmien taustalla ja niiden vaikutus tuotantoprosessiin, minkä jälkeen antaa kehitysehdotuksia ongelmiin liittyen.

Mainittuja ongelmia tutkitaan dataan perustuvan analyysin keinoin. Tutkimuksessa käytetty pääasiallinen data on tehtaan tietojärjestelmistä kerätty tuotantodata 12 kuukauden ajalta. Prosessien havainnointia ja työntekijöiden haastattelua on myös hyödynnetty datan keräämisessä. Kehitysehdotuksia annetaan perustuen kerättyyn ja analysoituun dataan sekä valittuun kirjallisuuteen. Kirjallisuuskatsauksessa läpikäydyt aiheet ovat varastonhallinta, lean-ajattelu sekä kapeikkoajattelu.

Kuusi eri saldovirheiden lähdettä tunnistettiin rullavarastossa. Sekä järjestelmävirhe että inhimillinen virhe ovat läsnä tunnistettujen syiden joukossa. Paras ratkaisu virhelähteiden eliminoimiseen on päivittää varastonhallintajärjestelmä, koska nykyinen järjestelmä ei sisällä vaadittuja toiminnallisuuksia varastosaldojen parempaan hallintaan. Saldovirheitä pystytään kontrolloimaan tiettyyn pisteeseen asti muuttamalla toimintatapoja ja ottamalla käyttöön inventointijärjestelmä. Parantamalla varastosaldojen tarkkuutta saavutetaan kustannussäästöjä raaka-aineiden käytössä ja vähennetään häiriöitä tuotannossa korvaavien materiaalien käytön vähenemisen myötä.

Keskeneräisten tuotteiden varaston kapasiteetin voidaan tulkita rajoittavan syöttäjän tuotantoa, mutta sen ei nähdä olevan juurisyy häiriöihin tuotannossa. Syyt suorituskykyerojen taustalla jalostusprosessin ja syöttäjän välillä ovat juurisyy ongelmille aiheuttaen keskeneräisten tuotteiden kasautumisen välivarastoon. Jalostusprosessi on tuotantoa rajoittava resurssi, jonka suorituskykyä tulisi parantaa. Keskittymisen tulisi olla arvoa tuottamattomien tuotantohäiriöiden eliminoinnissa. Mahdollisuutta jalostuskapasiteetin nostolle tulisi myös tutkia. Häiriöiden vähentäminen johtaa parempaan tuotannonsuunnitteluun, joka johtaa parempaan keskeneräisten tuotteiden varaston hallintaan. Tuotanto tulisi suunnitella ensisijaisesti jalostuskoneiden käyntiajan maksimoinnin kannalta.

PREFACE

I want to thank the case factory for giving me an interesting topic for my master's thesis to end my studies with. I also want to thank professor Jussi Heikkilä for comments and guidance during the study.

The process of writing this study was very varying. There were times when everything flowed smoothly forward and times when it felt like I hit a wall hard. However, the correct direction was always found and the goal was reached. The seven and a half years of studies are soon over and it's time to head towards new challenges.

Tampere, 19 January 2018

Tuomo Peltola

CONTENTS

LIST OF ABBREVIATIONS

DBR	Drum-buffer-rope scheduling
JIT	Just-in-time production philosophy
MRP	Material requirements planning
RFID	Radio frequency identification technology
SAP	Enterprise resource planning software
SKU	Stock keeping unit
TOC	Theory of constraints
WIP	Work-in-process
WMS	Warehouse management system

1. INTRODUCTION

This master's thesis examines two problems in the production process of the case factory pointed out by the production management. The problems concern two separate and different types of inventories which are seen as causing disruptions in the production process. The first problem concerns the raw material storage, which contains the main materials used in the manufacturing process. The second problem concerns the work-in-progress (WIP) product storage where the material produced by the Feeder is stored before the converting process.

1.1 Problem descriptions and research questions

The problem with the raw material store is that there are many and frequent inventory record inaccuracies between what the system shows and what physically is in the warehouse. For example, an item might show 10 000 kg in stock, but if checked physically, the actual quantity might be 8 000 or 13 000 kg. This causes problems especially to production planning and scheduling, but also to manufacturing operators. Planning production and managing inventory is frustrating because of the lack of exact record information – what really is available in the raw material store.

The problem with the WIP storage is that in certain situations the inventory might act as a constraint in the production process. The WIP storage is not actually an operation in the production process but it has a limited capacity. The material produced by the Feeder is stored there before the converting process. As the fill rate of the inventory increases to a high level, the probability of problematic situations is high. There can be situations where the Feeder has to stop production because the WIP storage is full and at the same time, one of the converting machines is waiting for material.

Both of these problems can cause disruptions in the production process. The problems are investigated in this study in order to find the root causes for the issues. Therefore, the objective of the thesis is to reduce disruptions caused by these problems on the output of the production process. The main research question of the thesis is the following:

- What are the effects of the identified inventory related problems on the total output of the factory?

The following research sub-questions are used to find the answer to the main question:

  - How is the raw material store currently managed?

- Which factors cause the item record inaccuracies in the raw material store?
- How is the WIP storage currently managed?
- What are the main reasons for WIP storage related disruptions in the production process?
- How can the operations be developed to avoid the detected problems?

1.2 Research methodology

This section presents the research methodology, which explains how the research in this study is done. Saunders et al. (2009, pp. 136-137) argues that there have to be valid reasons for all research design decisions, and the justification should always be based on the research questions and objectives. Focus should be on how the research questions are answered. Clear objectives and sources of data collection should be specified.

The essence of the study is in problem solving. Two problems were given by the case factory and solutions to these problems are generated in this study. The research strategy is a case study, which Robson (2002, p. 178) defines as a strategy for doing research involving an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence. The case study has considerable ability to generate answers to questions ‘why?’, ‘what?’, and ‘how?’ (Saunders et al. 2009, p. 146). The case study was chosen as the research strategy because it was seen to fit best with the objectives of this study in doing a comprehensive analysis on the underlying problems to find root causes behind them.

The idea is to get a good understanding of the topics through a literature review and thereafter, to perform a data based analysis on the problems at the case factory. More specifically, descriptions about the current state of the raw material and WIP inventory processes are provided and after that, data is collected and analyzed to determine what causes the underlying problems, and, what are the effects in the production process. Finally, after the effects are analyzed, suggestions to solve these problems are given based on the analyzed data and the obtained theoretical understanding of the topics. This approach to research is partly constructive meeting the first three steps of a constructive research (Kasanen et al. 1993, p. 246). However, the solutions are not tested during the study.

The primary sources of data are the case company’s information systems. The collected data include production data from a period of one year and selected warehouse transaction data. Some of the collected data is in the form of physical files and has to be gathered manually. Additionally, data is gathered through observing the production processes and interviewing operators. Therefore, both primary and secondary data are used in the research, secondary being the main material.

The data in the company's information systems was chosen to be the primary source of data because it was identified as the best way of analyzing what happens in the production process and how different tasks are related. This is because every operation on every machine is logged and quite easy to access historically. Qualitative data is gathered through interviews to support the historical data from the information systems. The research choice is therefore mixed-method, as both quantitative and qualitative data are used (Saunders et al. 2009, pp. 151-155).

1.3 The structure of the thesis

This thesis is structured as follows. In chapter two, the theoretical background of the research is provided. It consists of inventory management literature and low-inventory production philosophies. These include lean thinking and the theory of constraints (TOC). The factory has implemented lean tools earlier and therefore, lean is a part of the management practices. Literature considering the industry where the case factory operates is also briefly reviewed to find characteristics of top performing plants that have implemented lean tools. The literature regarding inventory counting systems and record inaccuracies is given more focus. Additionally, literature regarding WIP buffers is discussed from the perspective of the previously mentioned manufacturing philosophies.

Chapter three provides the description about the current state of the processes around the given problems. Chapter four presents the data that is gathered regarding the two problems along with the analysis of the data. The chapter is divided roughly in two sections concerning the two problems. At the end of the chapter effects of the problems on the production process are discussed. Chapter five discusses how the problems and the results of the data analysis relate with the literature. Suggestions for improvement are then formulated based on this discussion. Conclusions are drawn in chapter six which includes limitations of the study and suggestions for further research.

The case factory does not want the company name or industry to be published in this study, nor any production figures. Therefore, quite a lot of data used in the analysis phase is removed from this version of the thesis. Additionally, the production process is not described in high detail and the names of the machines are changed for anonymity reasons.

2. LITERATURE REVIEW

2.1 The role of inventories in manufacturing

Inventory refers to stocks of goods and materials that are maintained for many purposes, most commonly to satisfy normal demand patterns (Murphy & Wood 2008, p. 216). Stevenson (2014, p. 557) recognizes six different types of inventories. These are raw materials and purchased parts, WIP inventory, finished goods inventories or merchandise, tools and supplies, maintenance and repairs inventory and pipeline inventory. Pipeline inventory includes goods-in-transit to warehouses, distributors, or customers. However, according to Ballard (1996, p. 12) inventory is generally considered to comprise of raw materials and components, WIP and finished goods. Raw materials are the goods purchased by the organization. WIP comprises all the items that have been partly manufactured and have had value added. Finished goods are the completed products awaiting shipment to customers. (Ballard 1996, p. 12)

A way of minimizing inventory and purchasing costs is to buy quantities that exceed immediate requirements. This necessitates storing some or all of the purchased amounts for later use. Inventory is also sometimes used for hedging against price increases. This means that a firm might suspect that a price increase might occur and purchase larger amounts than normally to beat the increase. Another function of inventory is to permit operations. Production operations take certain amount of time meaning that there will generally be some amount of WIP inventory. (Stevenson 2014, p. 558) However, Koumanakos (2008, p. 356) says that too much inventory consumes physical space, creates a financial burden, and increases the possibility of damage, spoilage and loss.

An investment in inventory enables an organization to decouple successive operations or anticipate changes in demand. It also enables an organization to produce goods at some distance from the actual customer. (Vollmann et al. 2005, p. 134) Inventories held to satisfy expected demand are referred to as anticipation stock. Anticipation stock is needed for products with seasonal demand. They are built up in advance and depleted during the peak demand periods. Manufacturing firms have historically used inventories as buffers between successive operations to maintain continuity of production that would otherwise be disrupted by events such as breakdowns of equipment. While the problem is resolved, buffers permit other operations to continue temporarily. Safety stocks are held to reduce the risk of shortages. They ensure that customer demand can be satisfied immediately. (Stevenson 2014, p. 558; Vollmann et al. 2005, pp. 135-136)

Historically, the justification of WIP has been that it provided buffers between operations preventing shutdown of a machine due to lack of work. Another factor has been that it maximizes the utilization of equipment capacity. The rationale behind this thinking was that the cost of having idle capacity was greater than the cost of carrying the inventory. The trade-off between these two costs became under close scrutiny with the advent of Just-in-Time (JIT) philosophy. (Crandall & Burwell 1993, p. 6) JIT is both a philosophy and a set of techniques, which go beyond the traditional manufacturing planning and control system techniques. Toyota was the early adopter of JIT techniques. (Vollmann et al. 1997, p. 68)

Norris et al. (1994, pp. 63-66) studied the success level of JIT implementations in auto, electronic, and machinery fields. Improvements were measured in terms of inventory turnover, WIP, total manufacturing costs, information flow, human factors and quality control. The results were clearly on the positive side in each of the categories. (Norris et al. 1994, pp. 63-66) Fullerton and McWatters (2001, p. 93) also found that managers adopting JIT practices have experienced considerable benefits in all of the measured areas: quality improvements, time-based responses, employee flexibility, accounting simplification, firm profitability, and inventory reductions. They also found that high adopters reaped the highest rewards.

Callen et al. (2000, p. 295) analysed the relative performance of JIT and non-JIT plants operating in the auto-parts and electronic components manufacturing industries. They found significant differences between JIT and non-JIT firms in WIP levels, finished goods inventories and profitability. Overall their results showed that JIT manufacturing is associated with greater plant productivity in inventory usage, improved quality of processes, lower total and variable costs, and higher profits. (Callen et al. 2000, p. 295) Fullerton et al. (2003, p. 400) studied whether JIT practices make a positive contribution to firm profitability. They found a positive relationship between firm profitability and the degree to which waste-reducing production practices are implemented.

2.2 Low inventory manufacturing philosophies

Smith (2000, p. vii) introduces that companies that excel in increasing sales and market share, reducing cycle time or lead time, increasing quality, reducing inventory and reducing costs have the ability to compete based on these features rather than on price alone. Programs such as JIT, lean manufacturing and TOC's drum-buffer-rope (DBR) are all aimed at inventory and lead time reductions. These concepts are reviewed next to present the thinking and objectives behind low inventory manufacturing.

2.2.1 Lean

The development of lean has led to confusion about what constitutes lean, and what does not. Lean does exist at a strategic level and at an operational level, as demonstrated in Figure 1. The strategic customer centred thinking applies everywhere, whereas the shop-floor tools do not. This has often confused practitioners or caused misunderstanding as to where to apply lean. Lean production is encouraged to be used for shop-floor tools and lean thinking for the strategic value chain dimension. (Hines et al. 2004, pp. 1005-1006)

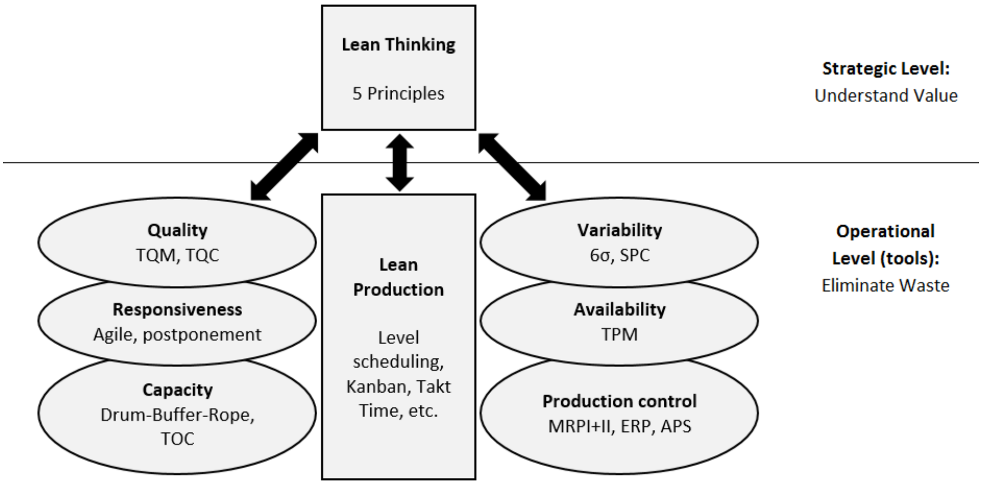

Figure 1. *A lean framework (Hines et al. 2004, p. 1007)*

Lean is a philosophy and a methodology focusing on eliminating waste – activities that do not add value to the process. Another focus of lean is to streamline operations by closely coordinating all activities. (Stevenson 2014, p. 619) Lean thinking originates from the shop-floors of Japanese manufacturers, particularly Toyota Motor Corporation. The lean operations management design approach represented an alternative model to the capital-intense mass production with large batch sizes, dedicated assets and hidden wastes. (Hines et al. 2004, p. 994) The concept of lean production was pioneered after World War II by Eiji Toyoda and Taiichi Ohno (Womack 1991, p. 11).

Lean production is typically conceptualized as a multi-dimensional construct composed of multiple lean practices such as total quality control, total productive maintenance, JIT, etc. These practices are widely implemented and they usually result in improved operational performance in terms of inventory management, process control, information flows, human factors, delivery, flexibility and quality. The financial performance of companies implementing these practices has been found to be positively affected. (Eroglu & Hofer 2011, p. 357)

Lean has evolved over time on the basis of its five principles: 1) the identification of customer value, 2) the management of the value stream, 3) developing the capability to flow production, 4) pull mechanisms to support flow of materials at constrains and 5) the pursuit of perfection. (Hines et al. 2004, p. 995) It has long gone beyond a mere factory shop-floor application. Organizations that miss the value creation and understanding customer value, and assume that quality, cost and delivery equal customer value only address the cost dimension of customer value. (Hines et al. 2004, pp. 1005-1006)

Vollmann et al. (2005, p. 628) describe lean's improvement objectives as to make significant reductions in inventory levels, throughput times, and responses to customer demand – all with less people and resources. Womack and Jones (2003, p. 15) describe lean thinking as being lean because it provides a way to do more and more with less and less. This mean less human effort, less equipment, less time, and less space, while at the same time coming closer and closer to providing customers with exactly what they want. (Womack & Jones 2003, p. 15)

Focus on value is the critical starting point of lean thinking. (Womack & Jones 2003, p. 16; Hines et al. 2004, p. 995) Value creation is often seen as equal to cost reduction which is a critical shortcoming of the understanding of lean. (Hines et al. 2004, p. 995) The identification of value and the definition of value propositions for specific customers is the starting point. You cannot move forwards without a robust understanding of what the customer values. (Melton 2005, p. 665) Value is defined by the ultimate customer and is created by the producer. Value is only meaningful when expressed in terms of a specific product which meets the customer needs at a specific price at a specific time. What's really important to understand in defining value is to determine where value is created. Lean thinking must start with a conscious attempt to precisely define value through a dialogue with customers. (Womack & Jones 2003, p. 16-19)

The value stream is the second principle of lean thinking and defined by Womack and Jones (2003, p. 19) as the set of all the specific actions required to bring a specific product through the three critical management tasks of any business. These are the problem-solving task from concept through detailed design and engineering to launch, the information management task from order-taking through scheduling to delivery and the physical transformation task from raw materials to a finished product in the hands of a customer. This step almost always exposes enormous amounts of waste. Value stream analysis almost always shows actions in the value stream that can be classified into three types: value creating steps, necessary steps that do not add value and lastly, additional steps that create no value and that are immediately avoidable. (Womack & Jones 2003, pp. 19-20)

The third step is to make the value-creating steps flow. (Womack & Jones 2003, p. 21) Liker (2004, p. 87) sees flow as the heart of the lean message of shortening the elapsed time from raw materials to finished goods will lead to best quality, lowest cost and shortest delivery time. Flow tends to also force the implementation of a lot of the other lean tools and philosophies. Creating flow exposes inefficiencies and forces to find immediate solutions. (Liker 2004, pp. 87-88) Melton (2005, p. 665) describes flow as probably the hardest lean concept to understand. The lack of flow in manufacturing processes accounts for huge warehouses which consume the working capital of the business. (Melton 2005, p. 665) Womack and Jones (2003, p. 21) warn that making steps flow requires a complete rearrangement of one's mental furniture. We are born into a commonsense conviction that activities ought to be grouped by type so they can be performed more efficiently and managed more easily. Activities are also performed in batches because through common sense it seems more efficient to do so. (Womack & Jones 2003, p. 21)

However, batches always mean long waiting times. The product sits patiently awaiting the department's changeover to the type of activity the product needs next. The approach keeps the members of the department busy and equipment running hard, so it seems efficient – but is not. As batch thinking is the intuitive approach, it is also the most basic problem of flow thinking, because it is obviously counterintuitive. As departments and equipment for making batches at high speed are put in place, it is hard to switch over to flow. This is because both the career aspirations of employees and the calculations of the corporate accountants – who want to keep expensive assets fully utilized – work powerfully against switching over to flow. (Womack & Jones 2003, pp. 20-23)

The first visible effect of converting to flow is that the time required to go from concept to launch, sale to delivery, and raw material to the customer falls dramatically. Flow results in an ability to design, schedule, and make exactly what the customer wants just when they want it. A customer can pull the product from you as needed rather than pushing often unwanted products to the customer. (Womack & Jones 2003, p. 24) Pull is the fourth principle in lean thinking. In a pull system, each workstation pulls the output from the preceding station as it is needed. Output of the final operation is pulled by customer demand or the master schedule. (Stevenson 2014, p. 635) In simplest terms, pull means that no one upstream should produce a good or service until the customer downstream asks for it. However, this rule is a bit more complicated in practice. (Womack & Jones 2003, p. 67)

In a pull system the accumulation of excessive inventories is avoided between operations. There can be small buffers of work between stations. The size of the buffer supply depends on the cycle time of the preceding workstation. Short cycle time means little or no buffer, whereas long cycle time means a considerable amount of buffer. However, pull systems are not necessarily appropriate for all manufacturing operations because they require a fairly steady flow of repetitive work. (Stevenson 2014, pp. 635-636) Disruptions upset the flow of products through the system. Poor quality, equipment breakdowns, changes to the schedule and late deliveries are some examples of disruptions, which should be eliminated. (Stevenson 2014, pp. 622-623) At Toyota there is a standard formula that machines should be available for production about 90 percent of the time and down for changeovers about 10 percent of the time. (Womack & Jones 2003, p. 69)

The fifth and final principle of lean thinking is perfection. Womack and Jones (2003, p. 25) see perfection as a result of the preceding four principles. They describe that when the four principles are in action, suddenly there is no end to the process of reducing effort, time, space, cost, and mistakes while offering a product which is ever more nearly what the customer actually wants. This is because the principles interact with each other. By getting value to flow faster, hidden wastes are exposed in the value stream. Pulling harder reveals more and more impediments to flow. Dedicated product teams always find ways to define value more accurately in dialogue with the customer. And thereafter, perfection does not seem like a crazy idea. (Womack & Jones 2003, p. 25)

2.2.2 The seven wastes of lean

Hiroyuki Hirano defined waste as being everything that is not absolutely essential. He also defined work as any task that adds value to the product. The original seven wastes defined by Shigeo Shingo that are common to factories are:

1) Overproduction
2) Inventory
3) Transportation
4) Product defects
5) Processing waste
6) Inefficient operations
7) Inactivities or waiting time (Santos et al. 2006, pp. 7-8; Stevenson 2014, p. 623)

Liker (2004, pp. 28-29) adds an eighth waste to the above core list of seven wastes:

8) Unused employee creativity

Inventory is seen as waste beyond minimal quantities, because it is an idle resource that takes up floor space and adds to cost (Stevenson 2014, p. 623). It is also considered to have the greatest impact. It is a sign of an ill factory, hiding the problems instead of resolving them. (Santos et al. 2006, p. 8) For example, when a machine breaks down, the system is not that disrupted if there is inventory to feed the next workstation. However, a better way would be to focus on investigating the causes of machine breakdowns and eliminate them. Carrying extra inventory creates a tremendous burden in cost and space allowing problems to go unresolved. The lean approach is to pare down inventories to uncover problems. Low inventories are the result of a process of successful problem solving. (Stevenson 2014, pp. 628-629)

Overproduction involves excessive use of manufacturing resources. Waiting time requires space and adds no value. Unnecessary transporting increases handling and increases the WIP inventory. Processing waste is an unnecessary production step. Inefficient work methods reduce productivity, increase scrap, and increase WIP inventory.

Product defects require rework costs and might cause possible loss of sales due to customer dissatisfaction. (Stevenson 2014, p. 623) Liker (2004, p. 29) sees that time, ideas, skills, improvements and learning opportunities are lost by not engaging or listening to employees, which comprises the eighth waste.

A central theme of a true lean approach is working towards continual improvement of the system. This includes for example reducing inventories, setup cost and time, improving quality, increasing the output rate and generally cutting waste and inefficiency. A culture of problem solving must be assimilated into the thinking of management and workers. In a lean system, managers are expected to be leaders and facilitators, not order givers. The communication between workers and managers is encouraged to be two-way. (Stevenson 2014, pp. 632-633)

2.2.3 Lean production in the industry in question

Pinnington (2005, pp. 305-318) studied the case factory's industry in an attempt to find some of the best performing plants. The finding of plants that fit the set criteria turned out successful in Japan, Australia and USA. The objective was to identify the reasons for their impressive results, particularly in relation to the principles of lean management and lean production. (Pinnington 2005, p. 305) The first half of the study was presenting and comparing different production measures from these plants, and after that, analysing the possible effect of lean management on these measures.

According to Pinnington (2005, pp. 314-135) there are 5 key areas to cover in a plant in terms of lean production: raw material store, Feeder, material flow optimisation, quality management, and motivation. A high volume is required utilizing JIT and the quality of work is high with least costs possible. The plant data analysed in the study shows that there are several ways to obtain high productivity. The best practice in terms of economic success cannot be answered, because it is dependent on the individual price composition of a structure. (Pinnington 2005, p. 315)

In a country with good infrastructure, meaning short delivery distances, a sufficient amount of raw materials stock is to cover 1 to 1.5 weeks of output. In addition, a computerised management system for the raw material store is recommended. (Pinnington 2005, pp. 315-316) Laakso and Rintamäki (2001, p. 115) argue that material handling efficiency is a factor that critically affects production efficiency on this type of a factory. In addition to the nature of production, this is also because of the significant amount of waste handled. (Laakso & Rintamäki 2001, p. 115)

A ready supply of raw material is required to be maintained to ensure uninterrupted operation. This is primarily due to long delivery times for raw materials. The raw materials are stored in a cold or moderate warm roof covered warehouse. The material is stored in several layers on top of each other. The material is handled with a forklift with great attention and precision to avoid damaging the material. Damaging the material is easy, and if damaged, causes difficulties in production and at worst is useless. (Laakso & Rintamäki 2001, p. 115)

Pinnington (2005, p. 310) gives general guidelines for the capacity of the WIP storage. The WIP storage is largely determined by the characteristics of the Feeder as well as the range of products. If the Feeder is able to produce one type of material at a time, WIP capacity should be 0.5 - 1 shift production. In case of two types of materials, the capacity should be 1 - 2 shifts. If the Feeder is able to produce three types of materials at the same time, the capacity should be 2 - 2.5 shifts. The minimum values in these three cases are for a higher proportion of unconverted material. (Pinnington 2005, p. 310)

A semi- or fully automated WIP buffer is recommended for ideal material flow and easy recording of the number of orders. It is of great advantage particularly in plants in which the Feeder is able to produce two to three different materials at the same time and require the marshalling of part orders which are often not converted immediately. Older plants often have limited space for the WIP inventory. In these cases a two-tier storage is recommended if more space is needed. The converting area should be principally sized according to the pull principle of lean. The entire converting section should have at least a 10 to 15 % higher capacity than the Feeder. If the WIP area is overloaded, it can be compensated by an increase in converting capacity. (Pinnington 2005, p. 316)

2.2.4 Theory of constraints

TOC is broadly seen as an approach to scheduling which was developed by Eliyahu Goldratt in the 1980s. Since then, an increasing number of firms have been implementing a scheduling system using TOC concepts. (Vollmann et al. 2005, p. 379; Stevenson 2014, p. 722) However, Smith (2000, p. 33) identifies TOC as a broad-based management strategy tool that has been successfully applied also to for example distribution, project management and marketing. TOC has also been considered a tool in the lean production philosophy as seen in Figure 1 by Hines et al. (2004, p. 1007).

TOC is based on three measures in manufacturing, which are throughput, inventory and operating expenses. Throughput is the rate at which an organization generates money through sales: sales revenue – variable cost. Inventory is all the money that the system invests in purchasing things it intends to sell. Operating expenses are all the money the system spends in order to turn inventory into throughput. (Chaudhari & Mukhopadhyay 2003, p. 800)

The fundamental principle of TOC is that only those resources that are bottlenecks are of critical concern in scheduling. This is because the bottleneck resources limit the overall output of a plant. The objective of TOC scheduling is to maximize throughput of a production system. Therefore, as the bottlenecks or constraints limit the throughput of the system, all efforts are devoted to maximizing the capacity of these resources. The goal is always to break a constraint condition and thereafter identify the next constraint. (Vollmann et al. 2005, p. 379; Stevenson 2014, p. 722)

The rate of the whole system's output determines the rate at which the goal of the organization is accomplished (Gupta & Boyd 2008, p. 993). Goldratt (1990, p. 4) describes a system's constraint as anything that limits a system from achieving higher performance versus its goal. When viewed from the operations perspective, a list of constraints can be quite long. However, not all constraints can be the weakest link in the chain. (Gupta & Boyd 2008, p. 993) As Goldratt (1990, p. 4) puts it: any system has very few constraints, and conversely, any system must have at least one constraint. The five step process of improving the performance of the constraint is:

1) Identify the system's constraints
2) Decide how to exploit the system's constraints
3) Subordinate everything else to the above decision
4) Elevate the system's constraints
5) If in the previous steps a constraint has been broken, go back to step one, but do not allow inertia to cause a system constraint.

Rahman (1998, pp. 337-338) presents this same process as a continuous improvement circle, illustrated in Figure 2.

It is rare for a company to have a real market constraint. Additionally, a true bottleneck is very rarely found on the shop floor. Usually, production policies are constraining the system (Goldratt 1990, pp. 4-7) causing a specific resource to not be utilized properly, or operations functions do not have enough of a specific resource. (Gupta & Boyd 2008, p. 995) Smith (2000, p. 15) defines a policy constraint as a practice or policy regarding how to manage a resource, not the actual physical capacity of the resource. Vendor constraints are very rare, but purchasing policy constraints are quite common (Goldratt 1990, p. 7). Gupta and Boyd (2008, p. 995) determine that management must make a conscious decision concerning what resource or capability should be the organization's most limiting factor.

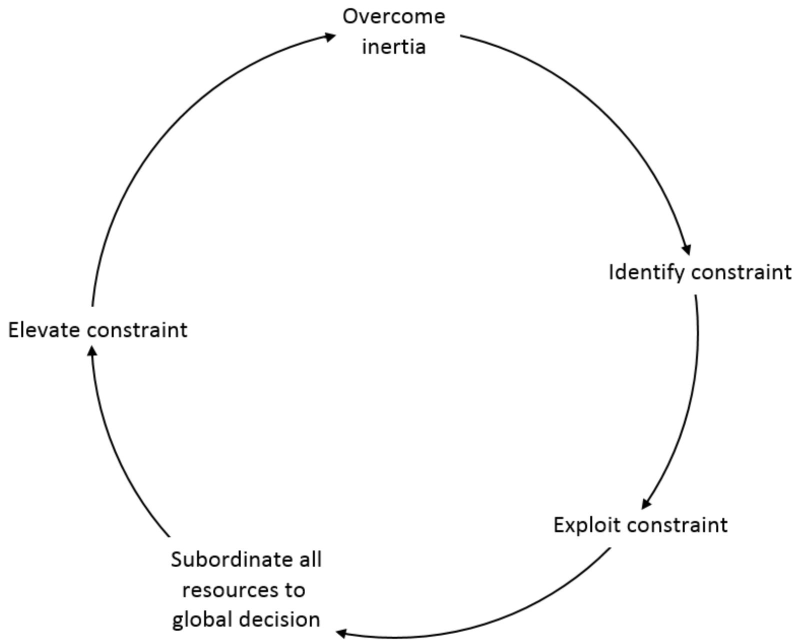

Figure 2. *The TOC process of on-going improvement (Rahman 1998, p. 338)*

Chaudhari and Mukhopadhyay (2003, pp. 799-800) mention that identifying the non-physical/intangible constraints is very important. This is because most of the physical constraints are the result of non-physical constraints. The overcoming of intangible constraints may not involve major financial investments. Constraints can be removed by just changing relevant policies or performance measures. (Chaudhari & Mukhopadhyay 2003, pp. 799-800)

Nanfang et al. (2008, p. 1) argue that rigorous academic testing has validated the early findings that manufacturing systems employing TOC techniques exceed the performance of those using material requirements planning (MRP), lean manufacturing, agile manufacturing, and JIT. The results indicate that TOC systems produce greater levels of output while reducing inventory, manufacturing lead time, and the standard inaccuracy of cycle time. However, mainstream acceptance of TOC has proven elusive as less than 5 % of U.S. manufacturing facilities drive process improvement efforts with TOC. (Nanfang et al. 2008, p. 1)

The approach used in TOC scheduling uses a DBR concept to manage the system. In the DBR concept the constraining resources are called drums which set the pace of production. (Vollmann et al. 2005, p. 379; Stevenson 2014, p. 722) DBR is a finite-capacity scheduling method, MRP, which assumes infinite capacity. MRP must be coupled with some kind of capacity check to ensure that the resulting schedule is capacity-feasible. (Gupta & Boyd 2008, p. 1001)

The drum resource is used to control the workflow of the plant. Any resource with a higher capacity than the drum is called a non-drum. (Vollmann et al. 2005, p. 379) The constraint resource is scheduled first and material release is then back-scheduled from the constraint by the setup and processing times of upstream resources. Non-constraint resources are assumed to have excess capacity so that queue times at these resources will be minimal. (Gupta & Boyd 2008, p. 1001) The goal is to schedule to make maximum use of bottleneck resources.

The rope refers to pull scheduling at the non-constraint work stations. The purpose is to tie the production at each resource to the drum. (Vollmann et al. 2005, p. 379; Stevenson 2014, p. 722) The constraint resource needs to be protected against random disruptions and non-instant availability of a resource (Smith 2000, p. 65). Resource-related disturbances include disturbances caused by machine capacity, operator capacity, and tool capacity. These often cause real problems regarding the performance of production units. Job-related disturbances include the unavailability of raw materials and order-specific drawings, inaccuracy from the planned sequence, rush orders and extra work that has to be scheduled due to scrap. (Stoop & Wiers 1996, p. 41)

A non-instant availability means that a resource is idle because it must wait for other resources to finish before it can begin. Protecting against disruptions is done by the placement of strategic buffers (Smith 2000, p. 65). Rahman (1998, p. 339) describes buffer as strategically placed inventory to protect the system's output from the variations that occur in the system. Buffer management uses time-buffers as an information system to effectively manage and improve throughput. There are three types of time-buffers: constraint buffers, assembly buffers and shipping buffers. (Rahman 1998, pp. 339-340)

The constraint buffer is located in front of the constraint resource, assembly buffer before the assembly, which is fed by constraint and non-constraint resources. The shipping buffer is located at the end of the process. (Rahman 1998, p. 340) Basically, the concept in TOC scheduling is to move material as quickly as possible through the non-constraint resources until they reach the constraining resource. The work at the constraining resource is scheduled for maximum efficiency. After the constraining resource, work continues at maximum speed to the finished goods inventory and the shipping dock. (Vollmann et al. 2005, p. 380)

According to the TOC way of thinking, there are six interdependent and necessary conditions which result in having the least amount of inventory in the system (Smith 2000, p. 17):

1. Producing to order
2. Releasing material at the rate of the constraint or critical process
3. Reasonably buffering the constraint to ensure it is not starved
4. Maximizing the uptime of the constraint process
5. Purchasing to ensure a buffer of raw materials so the beginning process can start in time to maintain the constraint's buffer

6. Ensuring the reliability of all processes to support reasonable buffer levels in front of the critical processes

The key is to understand the interdependency of these conditions. Conflicts arise if one or two of the conditions become the focus for driving improvement methodology. It can be a problem if a condition is translated in to a "key performance indicator" and becomes the end objective of the improvement process. (Smith 2000, p. 17)

2.3 Inventory counting and monitoring

A system to keep track of the inventory on hand and on order is a must have for management to effectively manage the inventory. An inventory counting system can be either periodic or perpetual. In a periodic system, items are physically counted in an inventory at for example weekly or monthly. Based on this information, decisions are made on how much to order of each item. A perpetual inventory system keeps track of removals from the inventory on a continual basis. The information on the current level of inventory for each item can be provided whenever needed. Despite the continuous monitoring system, a physical count of inventories must still be performed periodically. The reason for this is that there can be errors, pilferage, spoilage, and other factors that may distort the records. (Stevenson 2014, p. 559-560)

Ballard (1996, p. 11) argues that if monitoring and measuring of stocks in the warehouse is overlooked or given little consideration, the feedback information is unreliable and gives no indication as to the quality of the inventory management. The purpose of inventory monitoring and measurement should be to provide management with the information to improve operations and reduce errors. Warehouse management systems and inventory control systems should not be confused. Inventory management is concerned with the control of stocks throughout the supply chain and inventory monitoring and measurement takes place at each point in the supply chain. (Ballard 1996, pp. 11-12)

Warehousing is primarily about the physical control of goods and materials. A fundamental principle of materials management is that material flow and information flow must go hand in hand. It is essential to know where an item of stock is and everything about that item. Monitoring and measuring inventory is about knowing everything that needs to be known about the stock at all times. Best systems monitor the process rather than just the stock, which means that monitoring and measurement take place after each action. This highlights errors immediately. (Ballard 1996, pp. 12-13)

Manufacturing industry benefits from the simplified production and inventory control that for example bar coding provides. Bar codes can be attached to parts, subassemblies, and finished goods. This greatly facilitates counting and monitoring activities. Bar coding can also be used in automatic routing, scheduling, sorting and packaging. (Stevenson 2014, p. 561) Raw material suppliers can mark items with bar codes. In the storage inventory, bar codes are then used to constantly update the item records. (Laakso & Rintamäki 2001, p. 115)

Ballard (1996, p. 13) splits the stock information that needs to be monitored and measured into three categories: fixed information, variable information and derived information. Fixed information includes for example product code, description, size and weight. Variable information includes for example location of each unit, movement of each picked item and load status. Derived information is determined by analysis of fixed and variable information. For example movement rate, stock discrepancies and space utilization. (Ballard 1996, p. 13)

With effective systems monitoring and managing the warehouse process, formal periodic stock counting is not necessary. Cycle counting and residual balance counting are options to replace a formal periodic count. In cycle counting a selected number of items are counted every day. The count can be performed by stock keeping unit (SKU) or by location. (Ballard 1996, p. 14) Stevenson (2014, p. 565) points out cycle counting can also be based on the ABC classification approach. The approach means that the items are classified in three categories, namely very important (A), moderately important (B), and least important (C). (Stevenson 2014, p. 563). The key questions concerning cycle counting for management are:

1) How much accuracy is needed?
2) When should cycle counting be performed?
3) Who should do it?

Items in an inventory are usually not of equal importance. Therefore, it is reasonable to allocate control efforts according to the relative importance of various items in inventory. (Stevenson 2014, p. 563) A commonly used rule of thumb is that 80 percent of a company's sales come from 20 percent of products. And conversely, 20 percent of company's sales come from 80 percent of products. Therefore, the primary focus should be on the 20 percent of products that generate the 80 percent of sales. (Murphy & Wood 2008, p. 227)

Residual balance counting is performed simultaneously with picks and put-aways of items. A "real-time" warehouse management system needs to be in use. Every time an operator visits a location he or she reports on the number of items remaining in that location. The reported number is then compared with the master stock record and if discrepancies are found, action can be taken immediately. A record is maintained of the locations visited and locations that are not visited during day-to-day operations are counted according to another system. Reporting can be done if stock is zero, when stock falls to a threshold level or only reporting after a set number of visits to the location. (Ballard 1996, p. 14)

Researchers and practitioners have begun speculating about widespread adoption of radio frequency identification (RFID) technology in supply chains. The technology provides an opportunity to improve inventory management. It offers potential to increase accuracy in inventory records. (Hellström & Wiberg 2010, p. 345) A case study was done by Hellström and Wiberg (2010) on implementing RFID technology in the automotive industry. They found that the technology improves inventory accuracy in production and assembly processes.

Wang et al. (2010, p. 2539) also did a case study of implementing RFID technology in warehouse management. They found that the operating performance improved in visualized management of inventory, automatic storage/retrieval assignment, forklift automated guiding and loading time reduction. The detailed information of inventory was accurately shown on a map in real time. Mistakes made by management on manual memory were significantly reduced. The delivered products were transported in the form of digital pallets when loading, which meant that there was no need for operators to scan the barcode of products. All they needed to do was to pass a scanner with the digital pallet and the barcode data was automatically read. With the RFID technology inventory accuracy increased from 80 % to 99 %. (Wang et al. 2010, pp. 2539-2541)

2.4 Inventory record inaccuracy

Managing the inventories effectively is important for successful operation of most businesses and supply chains. Poor inventory management hampers operations, diminishes customer satisfaction, and increases operating cost. (Stevenson 2014, p. 555) Inventory record inaccuracy is defined as the inaccuracy between the inventory record level and the physical inventory. It has been identified as one of the main causes of supply chain uncertainty and performance deterioration (Bruccoleri et al. 2014, p. 798). Inventory inaccuracy has a significant negative impact on the performance of raw materials replenishment and production control. Inaccuracy of inventory records exists at all stages of a supply chain including raw materials replenishment, production control and final goods distribution. (Li & Wang 2017, pp. 137-138)

Van der Vorst and Beulens (2002, p. 426) found a lot of uncertainty in different case studies related to a lack of correct, accurate and up-to-date stock level information. Poorly managed and out dated stock level and stock availability information results in a larger order forecast horizon. The authors experienced lack of accuracy in recording inventory levels in all cases they observed. For example, the computer could show 100 items in stock, and actually the number was 60 items. (van der Vorst and Beulens 2002, p. 426) Kang and Gershwin (2005, p. 846) argue that perfect inventory records are difficult to maintain. However, their analysis concerns retail stores that can have thousands of different items in stock. Common causes of discrepancies are stock loss, transaction error, inaccessible inventory, and incorrect product identification. (Kang & Gershwin 2005, p. 846)

Inventory record inaccuracy is actually a widespread phenomenon both in the context of manufacturing and retailing. An analysis of 37 retail stores shows that more than 65 percent of 370 000 inventory records are inaccurate. Even low discrepancy between physical inventory and recorded inventory produces suboptimal system performance in terms of service level delivered to customers, stockouts, and inventory costs. Inventory record inaccuracy also creates critical distortions in order placement, as almost every order policy uses information on current inventory levels. Therefore, it damages supply chain performance. (Bruccoleri et al. 2014, p. 803)

Cannella et al. (2015, p. 127) argue that especially in highly collaborative supply chains, the benefits provided by sharing information between supply chain members are strongly compromised by inventory record inaccuracies. There is an intense deterioration on the performance of the companies in upstream stages of the supply chain. Therefore, investments in any connective technologies can be undermined by inventory inaccuracies. The upstream supply chain partners experience extra costs due to demand amplification, but are also subject to the risk of paying penalties to their direct customers for a problem generated by the customers themselves. (Cannella et al. 2015, p. 127)

An associated shortcoming related to inventory record inaccuracies is found by DeHoratius and Raman (2000) who studied inventory records in the retail sector. Inaccurate inventory records compromise the value of automated decision support tools like demand forecasting, planning product assortments, and replenishing store shelves. This is because all of these tools use recorded inventory quantities as inputs. Commonly cited sources of inaccuracies include selling and restocking errors, replenishment errors, database errors, poor or incomplete data synchronization and counting errors. (DeHoratius & and Raman 2000, p. 627)

Inaccuracies in records can occur because of mis-scanning or improper processing of items. Replenishment errors can also cause inventory record inaccuracy. In the retail sector it is possible that each item delivered is not scanned. Instead, employees verify whether the expected number of pallets or cases has been received and assume that they include the correct amount of items. Database errors and poor data synchronization can also be a cause of inventory record inaccuracy. For example, an item's information might be incorrect, meaning that it actually has more or less content than what the system says. Data lags are also a problem. There can be delay between the flow of materials and information which can cause inaccuracy. Manual errors, for example, during inventory counts can occur. (DeHoratius & Raman 2000, p. 628)

Delaunay et al. (2007, p. 2) and Bruccoleri et al. (2014, p. 803) classify errors happening in a supply chain to four types: shrinkage, misplacement, random yield of the supplier, and transaction type. Shrinkage could be applied to obsolescence problems as well as broken products. Misplacement type is a temporary shrinkage in the physical stock. It can be replaced after every counting or every period. Random yield of the supplier means a permanent loss or surplus in the physical due to an error of the supplier. A transaction type of error affects the information system, contrary to the previous errors which modify the physical inventory. (Delaunay et al. 2007, p. 2)

It is normal to control what comes from the supplier, but nothing prevents making mistakes during the checking. It is possible that some products are counted several times or forgotten in the counting. These are transaction type of errors. The physical inventory remains unchanged, but the information system inventory is made different. Misplacement of items is another inventory problem. It poses the problem of obsolescence. (Delaunay et al. 2007, p. 2)

Bruccoleri et al. (2014, p. 811) argue that the damages on supply chain performance generated by inventory record inaccuracy are highly influenced by behavioral aspects of workers. High levels of inventory and a high volume of transactions increase the environmental pressure of employees who work in a crowded space and can't detect stock-out and thus inaccuracies in data (Bruccoleri et al. 2014, p. 802). This leads to the fact that order and inventory management policies that are traditionally used for dampening the bullwhip effect are not effective if a certain level of inaccuracy is generated due to workers' behavioral aspects. (Bruccoleri et al. 2014, p. 811)

The inventory record inaccuracy due to workload pressure depends on the psychological stability of the workers in dealing with a given range of throughput values. The psychological sensitivity of the worker to his/her level of arousal and his/her psychological stability to deal with a given range of operational conditions have a combined and multiplying effect over the amplification of order and inventory variance generated by his/her errors. The deteriorating effect of psychological sensitivity with respect to the bullwhip effect is strongly influenced by the psychological stability of the worker with respect to the changing operational conditions. (Bruccoleri et al. 2014, p. 811)

The change in inbound throughput level has two types of effects on workers: they may be sensitive to a decrease in throughput or to an increase of it. When throughput decreases, their level of arousal decreases too much and errors occur. On the other hand, when throughput increases, their level of stress increases too much and errors occur. Nevertheless, worker psychological stability and her/his sensitivity can have a multiplying effect on inventory record accuracy. This results in a deterioration of the global performance of the supply chain in terms of order and inventory variance amplification. This calls for a greater managerial attention to employee well-being to maximize their performance potential and for a greater attention of logistics mangers to the minimization of the variance of inventory incoming item flow. The concentration should not just be on avoiding increases or decreases of workers' workload but also on minimizing the variance of the workload itself. (Bruccoleri et al. 2014, p. 812)

Li and Wang (2017, p. 138) find that inventory record inaccuracy can be dealt with either by prevention/correction or developing robust policies that perform well even if records are not accurate. Heese (2007, pp. 550-552) finds that the RFID technology can solve the inventory inaccuracy problems. The technology promises full transparency. However, adopting the technology is still expensive. Kang and Gershwin (2005, p. 859) argue that even without sophisticated identification technologies, the inventory inaccuracy problem can be effectively controlled.

If no corrective action is taken on inventory inaccuracies, even a small rate of stock loss can disrupt the replenishment process and create severe out-of-stocks. The lost sales due to stock loss can be substantially higher than the stock loss itself. What's more, the effect of stock loss is greater in lean environments that are characterized by short lead times and small order quantities. (Kang & Gershwin 2005, p. 859)

2.5 The relationship between WIP and throughput

JIT programs have the reduction of WIP inventories as one of the major objectives. The result of reduced inventory is the expected reduction in lead times and greater flexibility in responding to customer demands. A possible negative consequence from reducing inventory is reduced throughput. If this is the case, then the problem is evaluating trade-offs between the costs of reduced throughput and the benefits of reduced lead times. The ideal situation is the combination of reduced WIP, reduced lead times, and increased throughput. (Crandall & Burwell 1993, p. 6)

Excessive inventory may compensate for sloppy and inefficient management, poor forecasting, haphazard scheduling, and inadequate attention to process and procedures. (Koumanakos 2008, p. 356) Gupta and Boyd (2008, pp. 1000-1001) argue, that too much inventory is only possible to acquire by having resources produce more than they should. What's more, when they are producing more than they should, they are not available to produce when they need to in order to support the throughput of the whole system. Too much inventory also causes lead times to be high, which also results in a loss of throughput to customers who need lower lead times. (Gupta & Boyd 2008, pp. 1000-1001)

Too low inventory, on the other hand, often disrupts manufacturing operations, and increases the likelihood of poor customer service. (Koumanakos 2008, p. 356) It can threaten the throughput of the whole system, because the constraint resource may starve for material to work on. Another reason might be that the shipping schedule may not be met. TOC recommends using buffers, primarily in front of the constraint and at shipping to deal with these problems. (Gupta & Boyd 2008, pp. 1000-1001)

Inventories should be considered as productive. The main purpose of productive inventory is to protect the throughput of the system. Too much inventory can reduce throughput by making it physically difficult to move things around. Also, it can be difficult to keep track of things, which causes disruptions in production while material is searched. (Gupta & Boyd 2008, pp. 1000-1001) In the lean philosophy, on the other hand, inventory is an idle resource, which takes up space and adds cost to the system. Inventories should be minimized as much as possible. (Stevenson 2014, pp. 622-623)

By modeling and simulating a simple production process Crandall and Burwell (1993, p. 8) found that throughput decreases as product/process variation increases. Also, throughput decreases as the process complexity increases. Furthermore, if there is large product or process variability, some WIP is required to prevent a reduction in throughput. Therefore, if product/process variability can be reduced, it should be possible to benefit from reduced WIP inventory and reduced lead times while maintaining current levels of throughput. (Crandall & Burwell 1993, p. 10)

Owen and Huang (2007, p. 2363) found that locally improving a production system may result in decreased overall performance. They see it noteworthy because it is directly counter to general intuition regarding production system performance. The two surprising results regarding system throughput are, that (i) increasing station speed may decrease system throughput, and (ii) adding buffering capacity may decrease system throughput. These results are consequences of competition for shared resources in complex systems. It is impossible to predict when the results of the study will hold for general systems, but the authors see value in reminding practitioners to be cautious on extrapolating results from simple systems to more complex ones without appropriate understanding.

Gunn and Nahavandi (2000, p. 305) describe that the increasing customer requirements and expectations require in-full and on-time delivery of quality products and services, at the best possible price. Therefore, companies with sizeable manufacturing facilities must increase the flexibility and responsiveness of their manufacturing operations. An enabler of rapid response to new orders is reduced lead time. The key dilemma that arises from these conditions is the trade-off between manufacturing throughput and production lead times. It is thought that high level of WIP is necessary to avoid starvation of machines in order to obtain and maintain high throughput. However, this has unacceptable consequences, namely poor production coordination and long manufacturing lead times. (Gunn and Nahavandi 2000, p. 305)

Throughput can be maintained with high levels of WIP and long manufacturing lead times, or with minimal lead times and low levels of WIP. So the problem is how to best maintain throughput, while reducing and minimizing manufacturing lead times. The question is finding the optimum level of WIP where the desired throughput can still be maintained. As buffer levels are maintained minimum into the critical resources, the WIP through the plant will be kept at a minimum and therefore lead times through the plant are maintained near a minimum. (Gunn & Nahavandi 2000, pp. 305-306)

Vollmann et al. (2005, p. 376) say lead time and WIP are directly related. The longer the lead time is perceived to be, the longer the time between order launching date and due date. The longer this time is, more orders are in the shop. More orders in the shop means more queue time, which means more WIP. Controlling the amount of WIP in a production system can yield lower carrying costs and increased flexibility. (Stevenson 2014, p. 638) Minimizing lead times provides greater flexibility to the factory which allows releasing appropriate work orders, and more rapid response to changing conditions both internal and external to the manufacturing facility. However, variations in machine failure rates, product mix and demand place large strain on the manufacturing operation. Therefore, finding the optimum WIP level in practice is difficult. (Gunn & Nahavandi 2000, p. 306)

2.6 Usage of the theoretical concepts in the empirical work

The introduced theoretical concepts did not include any specific tools to be included in the data gathering and analysis section. However, these introduced theoretical concepts were used to guide the thinking behind analyzing the gathered data and identifying areas for improvement. Additionally, the concepts were utilized to construct suggestions for improvement.

The inventory record inaccuracy literature was used to guide the identification of the sources for record inaccuracies in the raw material store. The available literature introduced different types of causes for inaccuracies. Choosing the areas in the raw material store that were investigated were partly based on the literature. The literature on inventory counting and monitoring systems was mainly used to explore different ways of reducing inaccuracies.

The thinking of TOC was used in analyzing the production process and identifying the constraining resource of the system. The literature regarding top performing lean plants in the industry was used to examine if there is some area in the production process that is off compared to the top performers. The main concepts utilized from the lean philosophy were the thinking behind why higher inventories are not recommended, and other wastes in production.

3. CURRENT-STATE DESCRIPTION

3.1 Description of the manufacturing process of the case factory

The manufacturing process of the case factory is a continuous process. Basically all machines are operated on a continuous basis. The factory works two eight hour shifts a day, on weekdays. First shift begins at 6.00 in the morning and ends at 14.00. The second shift begins at 14.00 and ends in the evening at 22.00. The process begins in the raw material store, which is described in more detail in the next section. In short, warehouse operators send raw material to the Feeder according to the production plan that the production planners have formed. The Feeder operators then produce the desired amounts of products planned by production planners. After that, the produced material is moved to the WIP storage by the conveyor system. A simple illustration of the production process is presented in Figure 3.

The material flows presented in Figure 3 are percentages of the overall output of the Feeder. The output figures are averages calculated from production data from a period of 12 months starting November 2016 and ending October 2017. The Converter 1 output is 18.1 %, which is input from the Feeder divided into the three different destinations. Waste values are not considered in these figures. It is presumed in this example that all the material that comes from the Feeder goes through the converting machines. So Figure 3 is to give an idea on how the material produced by the Feeder is distributed between the converting machines and the bypass track. It can clearly be seen that the converting process creates most of the output of the factory – 82.4 %.

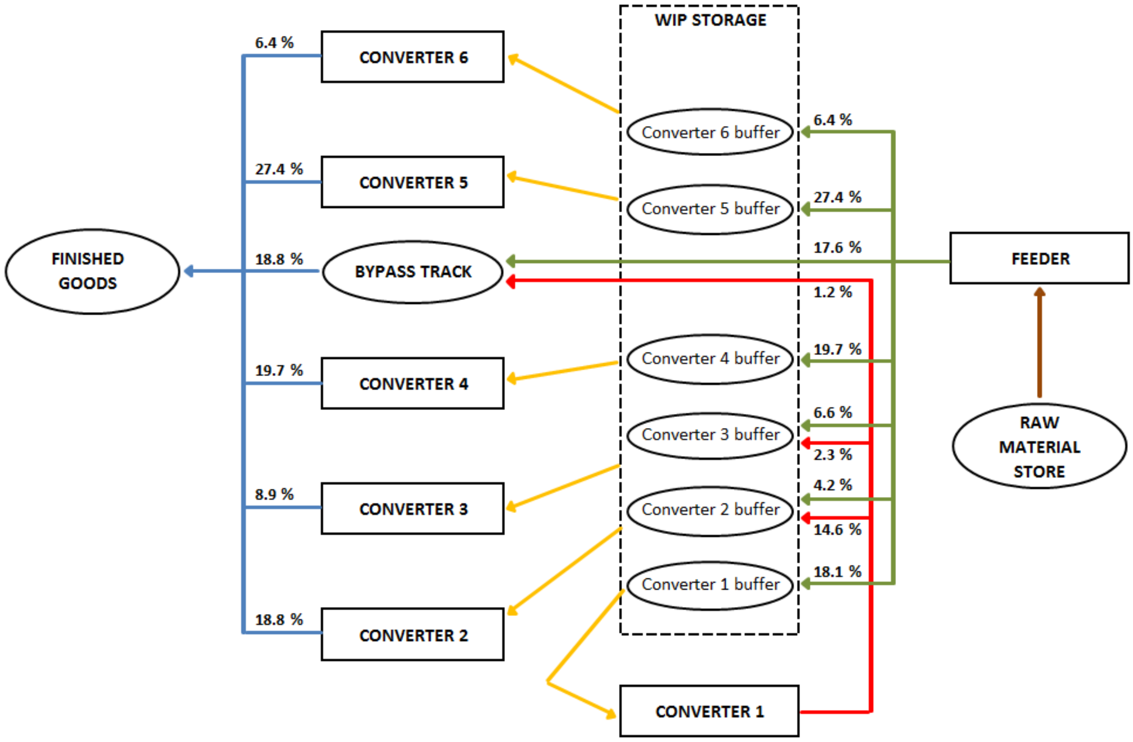

Figure 3. *The production process material flows of the case factory*

The WIP storage will be discussed in more detail later. After the WIP storage, material is processed in some of the converting machines, or sent through the bypass track to another factory for converting. There are six different converting machines which allow for a large range of different products to be produced.

The basic principle in production planning is to keep a minimum of 4 hours of production plans locked for the Feeder and the converting machines. Having also 4 - 6 hours of material ready for each of the converting machines is considered a good minimum amount. This means that Feeder production needs to be planned based on the converting machines' need of material. But there is no upper limit on how much material has to be ready, waiting for converting. After the material has been converted according to customer specifications, it is sent to packaging. There are two packing lines, which lead to the finished goods store. The products wait there for the transport partner company to pick them up and deliver them to customers. The goods leave the finished goods storage quite quickly. In most cases the same day they are produced.

3.2 Description of the raw material store process

There are three systems involved in the raw material store process: SAP, warehouse management system (WMS) and the Feeder operating system. The WMS was tailored for the case factory in the beginning of the century at the same time as the factory wide conveyor system was acquired. The WMS is unique. No other factory in the world has the same system.

There are some manual tasks that the operators do, and automated system tasks. Involved in the process are warehouse operators, Feeder operators, the conveyor system, automated trucks, production planners and the three above mentioned information systems. The tasks of the warehouse operators are roughly divided in two. The other is the one who monitors the raw material request list and controls which items are sent to the Feeder – to which unit and in which order. The other operator is the forklift driver who unloads shipments and collects requested material from the warehouse according to what the other operator asks.

The layout of the warehouse including material conveying routes to the Feeder is illustrated in Appendix A. The process begins with an arriving shipment of material from a supplier. The truck driver of the transport company enters the warehouse and hands over the delivery notes to the warehouse operator. The warehouse operator in the forklift driver task unloads the shipment and enters the amount of material received in kg to SAP according to the delivery note. This is a manual operation by the warehouse operators. There is no optical reading of material bar codes in this phase of the process. The raw material inventory is managed in kilograms which leaves the unit amount of items in the inventory unknown.

Different raw material qualities have their designated places in the warehouse, but they are not documented in any way. Basically, all of the items of certain material are stored next to each other. However, there is a limited space reserved for each quality, so it is possible that the space is full and some of the material needs to be stored elsewhere. There is a small space reserved in the warehouse for these types of situations where more material is received than fit the designated space. It is called a surplus space. All the material that does not fit the designated space is stored there. The places of qualities are changed every time a notable difference occurs in consumption of materials.

The usage of raw material is planned by a production planner. There are two production planners – one for each shift. Warehouse operators get a raw material request list according to what the production planner has scheduled for the Feeder. They collect and send the required amount of raw material according to this request list to the Feeder. The warehouse is divided in two sections, unused items and partly used items. When the operators choose to use unused items, they read the bar code of the item with an optical reader. This creates the item to the WMS.

If the operator decides to use a partly used item instead of an unused item, bar code reading is not required. This is because the information of the partly used item is stored in the WMS. There are two automated trucks that manage the partly used items. If the operators want to send an item from the partly used item's inventory to the Feeder, they choose the item they want in the WMS and call an automated truck to pick the item up. The automated truck brings the item to the end of a conveyor line and it is sent to the Feeder.

The size of the item in consumption is updated in real time in the WMS according to what the Feeder operating system communicates. When an item is returned from the Feeder back to the warehouse, a Feeder operator removes the remains of the item from Feeder and moves the item to a return conveyor line. The operator then prints a label to the item which includes the information of the item. The item is then conveyed to the warehouse by the automated conveyor system. The bar code of the label is read by an automatic optical reader as it comes to the warehouse to verify which item and material is returned. The reader is located over the item's path, so the label has to be placed to the right spot on top of the item.

The returned amount of material is deposited to SAP when the remains of the material has reached the end of the return conveyor line and picked up. At this moment the icon in the WMS disappears. The item is typically picked up by an automated truck in order to move it to the partly used item's store. Items that have been consumed partially, but are rarely used in production are not stored in the partly used item's store. They are lifted to the warehouse floor to the company of unused material of the same quality. This is because the operators do not want them taking space from the partly used item's store. When this is the case, the operator removes the automated truck order of moving the item to the partly used item's store, and lifts the item to the floor with the forklift.

4. DATA GATHERING AND ANALYSIS

4.1 Raw material store

Some efforts have been made in the past at solving the cause of the item record inaccuracies in the warehouse. The previous larger study of the warehouse was done in 2008. Five items' logs were studied and compared regarding the WMS and SAP systems from a period of one month. Inaccuracies were found and production planners made corrections to the item records, but the cause remained unknown. It was then suspected that the cause might somehow involve the partly used item's store.

After that, no significant studies have been conducted regarding the warehouse. Single items' records and logs have been monitored remotely, and the use of substitute material has been monitored briefly, but unfortunately these tracking efforts have not delivered any significant results. Therefore, the only reasonable approach to attempt to find the cause of the item record inaccuracies was to monitor the traffic in and out of the warehouse manually. The gathered data would then be compared to the data exported from SAP from the same time period.

The analysis done in this section is mainly done using the weights of the items. But, because of confidentiality reasons, any figures that could expose produced amounts during a given time period are left out.

4.1.1 Analysis of manually gathered item traffic data

The raw material store was eventually monitored for six full shifts, which is a total of 48 hours. The time was divided equally between the two shifts. In Table 1 below, are listed the number of transactions and errors during the observation period. 481 transactions including withdrawals and deposits were manually recorded in the raw material store. These transactions included items taken to consumption at the Feeder, and items that are returned back to the warehouse from the Feeder. Out of these 481 transactions one withdrawal was completely inexplicable.

Table 1. *Summary of the warehouse observation*

DAY	SHIFT	TIME	TRANSACTIONS	CORRECT	ERRORS
Monday 25.09.2017	A	6.00 - 14.00	63	41	26
Tuesday 26.09.2017	A	6.00 - 14.00	100	78	24
Wednesday 27.09.2017	A	6.00 - 14.00	86	77	11
Monday 02.10.2017	B	6.00 - 14.00	97	91	6
Tuesday 03.10.2017	B	6.00 - 14.00	76	69	7
Wednesday 04.10.2017	B	6.00 - 14.00	59	50	9
		48 hours	**481**	**406**	**83**

Out of the total 481 transactions 406 were logged correctly and without a delay in SAP. A total of 83 errors were found in 75 transactions. This means that some of the transactions had more than one error. What's interesting is that there is clearly more transaction errors in shift A than shift B on this time period. However, it is not convenient to draw conclusions from these numbers. The errors need to be analyzed in more detail. A summary and classification of the 83 different errors is presented in Table 2 below.

Table 2. *Summary of different types of errors in SAP transactions*

TYPE OF ERROR	25/09	26/09	27/09	02/10	03/10	04/10	TOTALS
Difference in kg	7	4	3	0	1	6	21
Logging delayed (<1h)	16	10	3	0	1	0	30
Fixed by production planner	3	9	2	6	5	3	28
Transaction missing	0	1	3	0	0	0	4
	26	**24**	**11**	**6**	**7**	**9**	**83**

The types of transaction errors can be classified into four groups: differences in kg, delayed logging, transactions fixed by a production planner and missing transactions. There is a difference in the kg amount of the transaction with every Russian item that is logged. This is because the bar code labels only include one bar code which only includes the item ID. All other suppliers have a second bar code in the item label that is used for reading the item information to the WMS. Therefore, as the Russian items' information cannot be read, it has to be entered manually. However, the item weight cannot be entered to the system. The system calculates the weight from the other manually entered data. The calculated amount rarely equals the real item weight presented in the item label and therefore transactions do not match.

There were a lot more Russian items in production during the time of observing shift A than shift B. Out of the total of 21 differences in kilograms, Russian items account for 19. The inaccuracy that occurs with every item can be anything between 0-100 kg between the label and the calculated weight. Therefore, the WMS withdraws an incorrect amount of weight from SAP. The weight inaccuracy can be either more or less than the real weight of the item. The 19 Russian items accounted for a total of -240 kg inaccuracy during the observation period. This means that the SAP record ended up -240 kg below the actual item record.

The inaccuracy of the Russian items in weight during the observation period was -0.79 %. This does not sound like a huge amount, but if we think about a five and a half month period for example, the inaccuracy becomes notable. The inaccuracy percentage equals to about 3 items which can cause significant problems for scheduling production.

The delayed loggings mean that when a transaction is done physically in the warehouse, the transaction happens with a delay in the system. The transaction was defined delayed if the SAP logging happened more than one hour later than it was physically done. This is the category that differs the most between the two shifts. However, this is also a category where the operators have no control. It is unclear why the transaction takes hours to log into SAP at times. But it causes a possibility of inaccuracy in the item records. If a logging of a transaction takes five hours for example, and a production planner physically checks the amount of an item in the warehouse during this time, it is possible that the planner fixes the record according to the physical count and then the delayed transaction goes through after – and an inaccuracy occurs.

The category of transactions that are fixed by a production planner includes transactions where an iDoc error occurs. iDoc is the message transferred from WMS to SAP. The error means that the message does not transfer correctly between WMS and SAP. It goes through to SAP but is not logged. It remains in the iDoc error log of SAP. Production planner is the one that corrects the message and then the transaction is logged in SAP. This happens multiple times daily. During this observation of the warehouse, it averaged 4.67 times per shift, which means 9.33 times a day in average. It is possible to make manual mistakes in the correction task, which happened once during the observation. An iDoc error happened with a transaction of an item weighing 3 250 kg. It was manually corrected, but one digit was left off the corrected weight, making the transaction to be 250 kg, which resulted in a 3 000 kg inaccuracy in records.

The last category includes transactions that are missing in SAP. There were four cases in this category during the observation period. One of the transactions was completely inexplicable. There was no explanation to it. It was an unused item and everything was done correctly in the warehouse. The item information was read from the item label and the item was created in the WMS. Then it was normally conveyed to the Feeder. However, the item was not consumed fully, so the remains were returned to the warehouse, and this transaction was logged correctly in SAP. This means that the item information was correct in the WMS and something happened between WMS and SAP communication during the withdrawal.

The remaining three cases turned out to be a mismatch between the data transfer principles of the system and the way of working. One of these three cases was a test made to confirm the finding. The two example cases were the following. First, an unused item was taken from the warehouse and sent to the wrong unit at the Feeder. Therefore, the item had to be taken back to the warehouse. When the item reached the end of the return conveyor line, it was manually picked up with a truck, moved to the feed conveyor line, turned around and sent to the correct Feeder unit. The item icon in the WMS was manually moved from the return conveyor line to the feed conveyor line. During this event, SAP showed two withdrawals of the item, as it should have showed a withdrawal, a deposit, and then a withdrawal. This resulted in a -3 468 kg inaccuracy in the records of the material.

The second case was the following. An item was taken from the warehouse, stripped, and sent to the Feeder for consumption. About two thirds of the item was consumed and the 725 kg remains were sent back to the warehouse. The warehouse operator saw an opportunity to use the remains in another unit at the Feeder in the next run. So as the item reached the end of the return conveyor line at the warehouse, the operator manually moved the item to the feed conveyor line. He moved the item icon in the WMS to the correct place, and conveyed the item back to the Feeder for consumption. During this event, SAP showed the withdrawal of the full item and the withdrawal of the remains of the item, as it should have showed the withdrawal of the full item, the deposit of the remains, and then the withdrawal of the remains again. This resulted in a -725 kg inaccuracy in the item record.

4.1.2 Delivery note analysis from a period of five and a half months

All archived delivery notes of received material were reviewed from a period of May 1st to October 13th. This time period was chosen because a precise physical count of the item records was performed on May 1st and a rough physical count on October 13th. It is convenient to study data between two known dates when the item records are known. The information presented in the delivery notes was entered to an excel file and compared to SAP data from the same period. The delivery notes are made and printed out by the suppliers and they differ significantly between firms. The most important thing from the warehouse point of view is that the amount of different items is presented simply and clearly. Unfortunately there is a lot of variation in the delivery notes which causes headaches to the warehouse operators.

The best case scenario from the warehouse point of view is that the delivered items are presented in the delivery note on a single page, one item below the other. However, more often than not, the items are presented on different pages. What's more, there can be several pages of the same item. The above situation makes entering the received amount to the system challenging. The warehouse operators have to manually find all of the rows/pages where amounts of the same item are and manually add these together. Then, when they have added them together they manually enter the received amount to SAP using the SAP order number.

As receiving goods in the system is a completely manual task, high precision is needed in entering the correct amounts to the correct items and purchase orders in the system. It is completely up to the operator to enter the correct amounts. Comparing the delivery notes data and SAP data, it was found that errors have occurred over the five and a half month period. The amount of errors or the magnitude of single errors is not significant in per cents, but still cause inaccuracies in inventory records, and problems in production scheduling.

A summary of the findings regarding the reception of goods is presented in Table 3. A positive difference means that there is more material in the warehouse than the system shows and vice versa.

Table 3. *Summary of inaccuracies between delivery notes and SAP*

ERROR	**NO. OF ROWS**	**DELIVERY NOTES**	**SAP**	**DIFFERENCE**
Reception done to a wrong item in SAP	7	38 474 kg	38 474 kg	0 kg
Amount difference between SAP/delivery note	26	236 703 kg	247 703 kg	-11 000 kg
Reception missing in SAP	7	27 893 kg	0 kg	27 893 kg
Reception done to a wrong purchase order	4	21 299 kg	21 299 kg	0 kg
Reception done with a delay in the system	19	188 065 kg	188 065 kg	0 kg
	63	**512 434 kg**	**495 541 kg**	**16 893 kg**

The errors are classified to five different categories in Table 3: reception done to a wrong item in SAP, amount difference between SAP and delivery note, reception missing in SAP, reception done to a wrong purchase order and reception done with a delay in the system. All individual inaccuracies total in 0.09 % of the received amount during the time period in kg. Using absolute values of the transactions, the total record inaccuracies caused by transaction errors in receiving goods is 0.29 % of the total amount of goods received in kg. All of the reception errors on different items are summarized in Table 4.

Table 4. *Summary of all reception inaccuracies on different items during the time period*

ITEM	NUMBER OF ERRORS AND INACCURACIES DURING THE PERIOD		ERROR CATEGORY
1001-100-2350	1 error	**-5 704 kg**	Amount difference
1001-125-2050	1 error	**24 kg**	Amount difference
1001-125-2200	1 error	**72 kg**	Amount difference
1001-150-2050	1 error	**30 kg**	Amount difference
1001-150-2200	1 error	**-200 kg**	Amount difference
1001-150-2500	2 errors	**3 353 kg**	Reception missing in SAP
1001-186-2050	1 error	**40 kg**	Amount difference
1001-186-2500	1 error	**180 kg**	Amount difference
2200-135-2050	1 error	**-1 kg**	Amount difference
2200-175-2500	1 error	**-6 284 kg**	Reception done to a wrong item
2300-130-2200	1 error	**-3 kg**	Amount difference
2300-175-2050	1 error	**45 kg**	Amount difference
2300-175-2500	2 errors	**6 281 kg**	Reception done to a wrong item
3300-100-2200	1 error	**2 950 kg**	Reception done to a wrong item
4081-140-2500	1 error	**-2 820 kg**	Amount difference
5000-127-2045	1 error	**6 kg**	Amount difference
5000-127-2495	1 error	**5 kg**	Amount difference
5000-175-2195	2 errors	**12 160 kg**	Reception missing in SAP
5000-175-2495	1 error	**9 769 kg**	Reception missing in SAP
6000-090-2045	1 error	**2 kg**	Amount difference
6000-090-2195	2 errors	**-3 030 kg**	Reception done to a wrong item
7004-130-1950	1 error	**890 kg**	Reception done to a wrong item
7050-157-1800	1 error	**-890 kg**	Reception done to a wrong item
8001-125-2200	1 error	**18 kg**	Amount difference
24 ITEMS	**SUM**	**16 893 kg**	

The reception of goods is monitored from the Netherlands by a supply chain administrator. This is done about once a month. If the supply chain administrator detects deliveries that seem to not be received in the system, production planners or purchasing manager are asked about the matter. It is very difficult to get a hold of a missing receipt of goods from up to a month ago, since the material is most likely used already. Because any item numbers are not saved in SAP, it is almost impossible to know whether the items have been missing from the delivery or if the reception is missing in the system. If the items have been used already, the only way to get some sort of sense of the situation is to compare the item weights to the material usage history list in SAP.

What's more, if an item transaction is found that is the same weight as the one that is searched for, there is no way to know whether this is the exact item. Therefore, the only situation when an item can be matched to a delivery is when the item has not been used and is still in the warehouse. In that situation it is easy to check if the item label information matches the delivery notes – particularly the item ID number. The lack of historical tracking is a critical shortcoming in this matter.

4.1.3 Detected inaccuracies in item records

A list of manual corrections to the warehouse item records was used to gather the detected inaccuracies from a period of five and a half months, starting May 1st 2017 and ending October 13th 2017. The list was run from SAP and a presumption was made that every time an inaccuracy is detected, it is corrected in the system. The reason behind choosing this time period is the same as before. To include the inaccuracies on October 13th, the results of the rough count performed that day was used. Small detected inaccuracies in the rough count were not included as they might have happened due to average weight estimation.

Production planners are the ones who make corrections to the item records if they detect any inaccuracies. The SAP list included two types of manual corrections. The majority were correcting failed communication between WMS and SAP – iDoc message errors, which were introduced earlier. The other manual corrections are item record fixes to match reality. In addition to the physical counts described earlier, production planners tend to check the balances of items physically if they feel that they might not be true in the system. This checking occurs practically daily. The detected item record inaccuracies from that time period are presented below in Figure 4.

The figure sums all items and is presented on a weekly basis. The detected inaccuracies are summed together for each week whether they are positive or negative. Therefore, a negative column can include also positive inaccuracies, but the sum of the inaccuracies is negative. Interestingly, the first half of the time period consists mainly of negative inaccuracies, and during the second half, mainly positive inaccuracies are detected. However, no reasonable explanation was found for this. Most of the detected inaccuracies are dated on the 13th October when the physical count was performed. The cumulated record inaccuracies that were detected ended up slightly on the negative side over the time period. Measured in percentages, the amount of record inaccuracy is 0.07 % of the total amount of material received during the time period.

There were a total of 37 negative item record corrections, and 31 positive item record inaccuracies detected. Negative inaccuracies mean that there is less material physically in the warehouse than in the system. On the contrary, positive inaccuracies mean that there is more material in the warehouse than in the system. Again, measured in percentages negative inaccuracies totaled in -0.6 %, and positive inaccuracies in 0.5 %. The absolute sum of the detected inaccuracies accounted for 1.2 % of total material received during the time period. This means that the warehouse records are 98.8 % accurate with the current systems and policies.

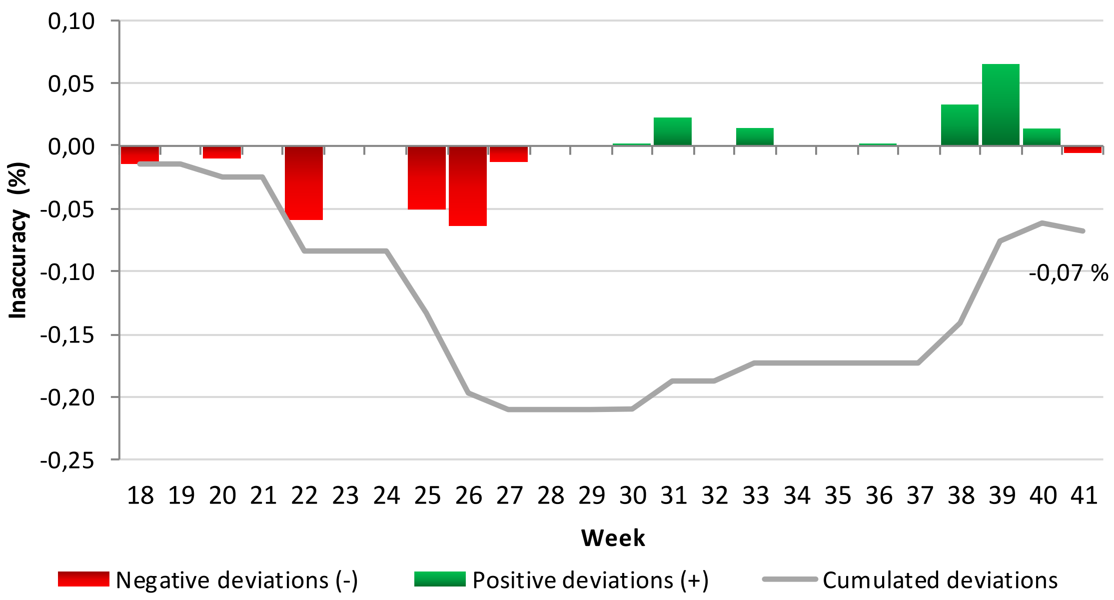

Figure 4. *Sum of detected item record inaccuracies between 01.05.2017 – 13.10.2017*

During the time period, inaccuracies were detected on 56 items' records. Overall the inaccuracies in item records can be interpreted as completely random. However, there are two interesting cases especially. In the first case a negative correction of -3 882 kg is made on week 19, and a positive correction of +3 720 kg is made on week 41. Then, in the second case a negative correction of -3 027 kg is made on week 26, and a positive correction of +2 950 kg on week 41.

These corrections are so close to each other that it raises a question if there has been an item that has not been detected during a physical count and the records have been wrongly corrected. It is possible that an item has been in a wrong pile and has not been noticed. Or, this might have happened because of a delayed transaction during which a production planner has counted the balances of the items and corrected them manually. However, this is impossible to know because historical tracking of items is not available.

4.1.4 Misconceptions and working errors in the warehouse

During the observation of the raw material store process, it was found that data did not transfer between WMS and SAP when assumed. The conception of the data transfer between WMS and SAP amongst the warehouse operators was that an item's weight is withdrawn from SAP when it leaves the end of the conveyor feed track and heads to the Feeder hall. In reality, the amount is already withdrawn when the item is at the end of the conveyor track. It seems that the amount is withdrawn when the item leaves the turntable. There was also a misconception regarding the deposition of a returned item to SAP amongst the operators. The conception was that the amount is deposited back to

SAP as the returned item reaches the end of the return conveyor line. The conception of the IT department was that the amount is deposited when a truck picks up the item. Actually, neither of these was the case.

The two cases described earlier show that the data transfer principles of the system do not correspond to the way of working. When this was discovered, a question arised whether partly used items that have been lifted to the warehouse floor have been registered to SAP. The warehouse floor was searched for partly used items and the SAP system was checked to see if those amounts had been deposited there. The amounts of 23 out of 24 partly used items were found as deposits in SAP. As 96 % of the items were found, it can be interpreted that this operation works well between the systems. The one missing item can be waste that has been transferred to the warehouse by tricking the system intentionally.

The fact that the partly used items were found in SAP repeals the assumption that the deposit is made to SAP when a truck picks up the item. When an item is lifted to the warehouse floor, the automated truck is first cancelled from picking up the item. Then the item is picked up with a forklift and the item icon automatically disappears from the WMS. Therefore, it seems that the deposit is done at the moment when the item icon disappears from the WMS. A test was made regarding this event to verify if moving the icon is the reason for the transaction not going through to SAP. A returned item was pushed from the end of the return track to the feed track. At that moment the item icon disappeared from WMS. Then the item was created to the WMS again by reading the item label and conveyed to the Feeder hall, and straight back to the warehouse through the return line. This resulted in a successful transaction between WMS and SAP, and so it was verified that the disappearing of the item icon at the end of the return conveyor line is the moment when the deposit transaction happens.

The placement of items in the warehouse can sometimes cause problems regarding physical counting. A rough physical count of the whole warehouse was done on October 13th. This is typically done by one of the two production planners. As this was timely right now during this research, I also took part in the count. The practice is that precisely counting every item in every physical count is perceived to be too time consuming, because of the fact that item labels can be facing the wrong way and are not readable. Additionally, because items are piled up to several layers means that the information of the top item can be up to 5 - 6 meters high and hard to see. Therefore, the rough physical count was done by counting the number of items of the same material. Then, the material records are calculated by approximating the average weight of those items clearly visible and multiplying it with the number of items. A precise physical count is performed once a year, at the end of the fiscal year.

The item placement in the warehouse is entirely dependent on the memory of the operators. It is not documented in any way. The placement or layout is thought together with the production planners. They also need to know the placement of different qualities when they physically count the balance of a specific item. As the warehouse layout or the correct storing places of different qualities are not documented in any way, it is possible to misplace items. As I was walking around the warehouse attempting to make sense of the places of different qualities, I noticed a couple of items in a wrong pile.

According to the operators this can happen from time to time. Especially if there is a substitute worker unloading deliveries due to an absence of a regular warehouse worker. What's more, warehouse operators are reluctant at correcting mistakes they have not done themselves. Therefore, the misplacement of item(s) can exist for quite a while. What makes this situation tricky is if a production planner physically comes to the warehouse to see how much of Material A, for example, there is in the warehouse. Due to the misplacement of items, they get an incorrect observation. And, according to this observation they adjust the records in SAP which creates an inaccuracy.

As we were performing the physical count of the warehouse together with the production planner, I remembered the items in the wrong pile. I went and checked if they were still in the wrong pile and I found one of them. The other seemed to have been consumed already. The material had been moved from the other end of the warehouse to the other and still the item had not been spotted in the wrong pile. If I had not remembered this error, we would have miscounted the balance of these two materials in question.

4.1.5 The magnitude of detected sources of error

The detected sources of error that can cause inaccuracies in the raw material item records can be classified into system error, human error, or a combination of these two. The human error in receiving goods and inaccuracies caused by Russian items are the only categories whose magnitude can be calculated. This is because it is impossible to know exactly how often inexplicable system errors occur or how often a partly used returned item is re-used right away and worked around the system. Let alone finding out how often transactions are delayed, how often items are placed in wrong piles, and, during the misplacement, counted physically. However, the magnitude of the remaining error types can be estimated by interviewing interested parties, mainly production planners and warehouse operators.

Estimating the magnitude of the different types of sources of error began by classifying the sources of error to either positive, negative, or both. Incorrect way of working with partly used returned items, Russian item kg inaccuracy, placing items in wrong piles and human errors in receiving material were identified as causing positive inaccuracies. Inexplicable missing transactions, Russian item kg inaccuracy, delayed logging and iDoc errors, placing items in wrong piles and human errors in receiving material were identified as causing negative inaccuracies.

The positive inaccuracies were estimated first. After calculating the human errors in receiving materials and Russian item kg inaccuracies 62.3 % of the positive inaccuracies were left to be allocated between placing items in wrong piles and the incorrect way of working with partly used items. It was estimated that the incorrect way of working with partly used items happens 10 times a month, which totals 55 times during the time period and results in about 55.1 % of the total positive inaccuracies. Then, 7.2 % was left for placing items in wrong piles. The positive sources of error are summarized in Table 5. The red rows are estimations and black rows are calculated.

Table 5. *Positive inaccuracies estimated.*

POSITIVE	100 %
Incorrect way of working with partly used items	55,1 %
Human errors in receiving material	35,9 %
Placing items in wrong piles	7,2 %
Continuous kg inaccuracy in Russian items	1,7 %

Estimating the negative inaccuracies began in the same categories as the positive. After calculating human errors in receiving materials and Russian item kg inaccuracies, placing items in wrong piles was estimated the same magnitude as in the positive side. This is because if one item is taken from one pile and added to another, the inaccuracy is the same magnitude, but the opposite number. After this, 69.4 % of negative inaccuracies were left to be divided between inexplicable missing transactions and delayed logging. It was estimated that the majority of this amount are inexplicable missing transactions. However, the delayed loggings were also considered to be a big problem. Therefore, the percentage was estimated to be quite significant, and resulted in 25 %. Then, the rest was allocated to inexplicable missing transactions, 46.4 %. This is summarized in Table 6. Red rows are estimations and black rows are calculations.

Table 6. *Negative inaccuracies estimated*

NEGATIVE	100 %
Inexplicable missing transactions	46,4 %
Delayed logging and iDoc errors	25,0 %
Human errors in receiving material	16,7 %
Placing items in wrong piles	6,4 %
Continuous kg inaccuracy in Russian items	5,5 %

The overall inaccuracy estimation of sources of error is summarized in Table 7 below. Here, the absolute values from the estimated positive and negative inaccuracies were summarized and the proportions calculated. The human errors in receiving goods and the inaccuracies caused by Russian items account for about 30 % of the total detected item record inaccuracies. That means that about one third of the total detected inaccuracies over the time period can be quite accurately calculated. However, about 70 % of the inaccuracies are estimated between the remaining four sources of error. These are estimations by the author based on discussions mainly with production planners and also warehouse operators. It has to be reminded that the truth can be different.

Table 7. *Estimations of sources of error summarized*

SOURCES OF ERROR IN THE RAW MATERIAL STORE	CLASSIFICATION	% OF TOTAL ABSOLUTE INACCURACIES DETECTED	EFFECT
Way of working with partly used items	System and human error	25,8 %	Positive
Human errors in entering received amounts of material to SAP	Human error	25,7 %	Both
Inexplicable missing transactions	System error	24,7 %	Negative
Delayed logging	System and human error	13,3 %	Negative
Placing items in wrong piles	Human error	6,8 %	Both
Continuous kg inaccuracy in Russian items	System error	3,7 %	Both

The amount of inexplicable missing transactions seems huge, but it means about 4 items a month. During six shifts 500 transactions were made, which equals three days of working. This means that over a one month period about 3 500 transactions are done. Measured in percentages, four missing transactions account for about 0.1 % of all transactions. Incorrect way of working with partly used items and human errors in receiving materials are also in the same size class. So, small errors in the transactions account for big problems in production planning. How the sources of inaccuracies relate to the information flows from the raw material store to the production planner is visualized in Figure 5. About 63.8 % of all inaccuracies are estimated to happen between the WMS and SAP.

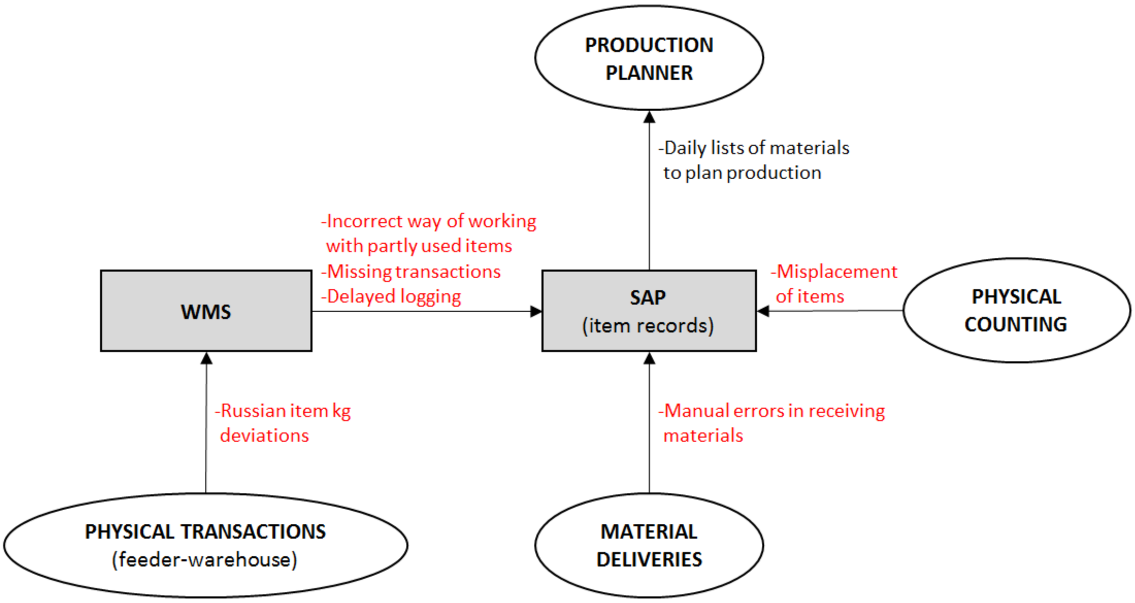

Figure 5. *The item records information flows from the warehouse to the production planners*

Whatever the percentages are, the bottom line is that to eliminate the record inaccuracies, all of these sources of error need to be eliminated. System error is present in four detected sources of error. The incorrect way of working with partly used items is quite easily eliminated, if the warehouse workers learn and remember to work as the system requires. Re-using a returned item needs to be done so, that the item icon disappears from the WMS as the item is moved from the return conveyor line to the feed conveyor line. Then the item needs to be re-read to the WMS. Continuous kg inaccuracy in Russian items can also be eliminated if the supplier can provide another bar code where the item information can be read optically to the system. However, this leaves two categories where system error is present in communication between WMS and SAP.

4.2 The WIP storage

WIP storage is unavoidable in the manufacturing process of the case factory because there is only one machine feeding six machines. The Feeder cannot produce material to all machines at the same time, so to keep the converting machines running there has to be a certain amount of buffer for each machine, at all times. The WIP storage consists of 32 conveyor tracks where the material is stored before converting, and one waste return line.

4.2.1 Operating the WIP storage

The WIP storage is managed electronically using a tailored software. In both shifts there is one operator who manages the contents of the WIP storage. The basic principle is to keep the material in correct order for the converting machines. The operator monitors mainly the running schedule of the Feeder, but has to also monitor the schedules of the converting machines. The operator manually reserves conveyor tracks from the WIP storage to different jobs according to the running schedule of the Feeder. Then, when material arrives from the Feeder towards the WIP storage, the system knows where to convey the material. The idea is to gather all material of the same job to the same track in the WIP storage as long as possible. If there is a situation where several jobs have to be gathered on the same track, they have to be arranged according to the running schedule of the particular converting machine.

The general understanding is that the system should be able to work automatically but according to the operators, it does not work well. The system works okay on automatic when the fill rate is between 0 - 40 %. However, even then some problems can occur. The basic problem in the system, when operated on automatic, is that it does not gather the material of the same job together. It might store some of the material here and some there completely messing up the entire storage. For example, if both of the conveyor cars are digging certain jobs from different tracks in the middle of the storage on automatic, they might mess up each other's work. The other might move material to the track which the other is working on and vice versa – a never ending loop is created.

The guideline regarding the fill rate of the storage according to the supplier is that 75 % fill rate should not be crossed. According to the operators, the storage is quite easy to control when the fill rate is around 50 - 60 %. They always aim at leaving at least one or two tracks open in the storage, and if operated on automatic the system might use all the tracks already at a 40 % fill rate. Leaving tracks open in the WIP storage is a precaution for cases like material defects in jobs that have already reached the converting machines or other disruptions at converting machines. These require material to be returned back to the WIP storage from the converting machine. If there are no free tracks, they have to be created by moving material around and the operation takes a lot longer. This of course leaves the machine in starvation for a longer period of time. In addition, tracks are also left open for planned unconverted orders.

Sudden changes in converting machine running schedules can also cause problems in the WIP storage and the magnitude of this problem is greater when the fill rate of the storage increases. If the running schedule is changed, arranging these jobs in the correct order so that starvation does not occur on the machine can be challenging. If at this point the fill rate is so high that there are no free tracks available, the task of digging the job from the middle of the storage is very challenging and time consuming.

Unprocessed orders are gathered to the WIP storage before moving them forward to packaging all at once. There are several reasons for this. To begin with, the orders need to be in whole in the finished goods store so that it is easy for the forklift drivers to load trucks and that the whole order leaves at once. Everything goes well in the WIP storage regarding job arrangement and managing if the situation is monitored closely. If an error happens, it usually leads to a couple of more errors, and these couple of more errors can cause even more errors. One of the operator of the WIP system described the WIP storage monitoring as playing Tetris. We all know how difficult Tetris can be when the screen keeps filling up and the amount of free space keeps decreasing.

4.2.2 Theoretical calculations of the WIP storage capacity

It is important to know the capacity of the WIP storage to be able to analyze WIP related events. The general understanding at the factory is, that the capacity of the WIP storage is about one shift's production. However, the capacity of the WIP storage is dependent on several characteristics of the produced material. The WIP storage is monitored by the fill rate measure, which indicates how full the inventory is in percentages. The fill rate is determined by how much of the length of the conveyor tracks is used. If two different jobs' material is the same length but different width, they still consume the same amount of the WIP capacity.

There is no historical logging in the system of the contents of the WIP storage. So it cannot be accurately back-tracked precisely which orders or amounts have been in the WIP storage at any given point in time. However, a report of the contents of the WIP storage is exported at the end of each month to be included in a monthly report. This information is presented in Table 8 below from a period of 12 months. From this data it can easily be seen that more than one shift's budget production fit the storage. The biggest amount of material in the storage among these points in time has been 1.76 shift's production.

Table 8. *Contents of the WIP storage at the end of each month during a 12 month period*

11/2016	12/2016	01/2017	02/2017	03/2017	04/2017
1.3 shifts	1.29 shifts	1.34 shifts	0.91 shifts	0.78 shifts	0.81 shifts
05/2017	**06/2017**	**07/2017**	**08/2017**	**09/2017**	**10/2017**
1.51 shifts	1.48 shifts	0.91 shifts	1.27 shifts	1.27 shifts	1.76 shifts

In calculating the capacity of the WIP storage average values for the variables regarding Feeder production were calculated from production data. In other words, the WIP storage capacity was calculated if average material was produced. Out of the information the capacity of the WIP storage was calculated to be about 2.35 shifts of average production. The situation is visualized in Appendix C and all of the information used in the calculations is also gathered there.

Of course, production is never average. Therefore, a situation where the contents of the WIP store would near 2.35 shifts, will probably never happen. As mentioned earlier, a principle in production planning is to have a minimum of about 4 - 6 hours of material ready for each converting machine at all times. To estimate the capacity of the WIP storage in production hours, average production figures of all converting machines need to be used. These are presented in Table 9. During the production of a job there are two phases that are necessary: setup time and run time. Average job times including setup time and run time are calculated in the bottom row of the table. In reality there are also different types of disruptions in production. These calculations assume that the production of a job goes perfectly without any other events despite the necessary setup and running.

Table 9. *Average job sizes, setup times, run times and job times*

Data removed for confidentiality reasons.

From this data the amount of WIP products can be calculated for the 4 - 6 hours that is the production planning principle and more. These calculations are presented in Table 10. These calculations show that 4 - 6 hours of WIP products correspond to roughly 25 - 40 % of WIP fill rate. The bottom row of 12 hours of WIP products corresponds to roughly 80 % of WIP fill rate.

Table 10. *Production hours converted to amounts of WIP products*

Data removed for confidentiality reasons.

As the principle in production is to stop the Feeder when the fill rate of the WIP storage reaches about 80 %, this means that at this point there should be about 12 hours of material available for every machine. This depends of course on several factors, which includes for example the order mix of the week. There has to be a suitable amount of orders available to planning to be able to produce material evenly between converting machines.

4.2.3 Disruptions in production and their relation to the WIP storage

Historical production data was reviewed from a twelve month period of 01.11.2016 - 31.10.2017. The gathered data included the overall daily output of the factory with outputs of the Feeder and all of the converting machines. Additionally, information regarding Feeder stops due to lack of space in the WIP storage was gathered along with converting machine stops due to starvation. This information is visualized in Appendixes D and E. Using the gathered information regarding outputs and the WIP storage data in Table 8, a daily estimation of the WIP storage contents was made for the same period. This estimation is also included in the monthly data in Appendix E.

It seems impossible to count exact amounts of products in the WIP storage because the needed information does not seem to be available in the production system. The data in Table 8 gave 12 days on which the actual amounts of materials in the WIP storage are known. Then, the daily increases/decreases in the WIP storage were calculated by adding the Feeder production to the amount of the day before, leaving the amount of unconverted orders out because they do not spend a long time in the storage, and reducing the converting output from the value. The daily amount of material was calculated by reducing the amount of converting output from the daily packed production. This calculation does not include any waste figures. Therefore, a daily factor had to be estimated which would be reduced from the calculated daily values of WIP storage products to be able to match the twelve known points with the estimation.

As this is more of an estimation than a precise calculation, the level of products in the WIP store was divided into five classes: very high, high, average, low and very low. The purpose of the WIP level estimation is to give an idea of the state of production on each day of the year, even though exact amounts are not available. According to the estimation, amount of products in the WIP storage has been very low 3 days, low 49 days, average 187 days, high 104 days and very high 22 days. It can be seen in Appendix E that the level of products in the WIP storage fluctuates quite a lot.

The total amounts of Feeder stops due to lack of space in WIP storage and converting machine starvation are presented monthly in Table 11. The number of stops in converting due to starvation is a bit distorted, because a period of material waiting can consist of several shorter periods in reporting. Also, converting material waiting figures include not only lack of material but also tool waiting times. There is no way to divide these figures in the historical data between those reasons for waiting. This is simply because all material waiting is reported using the same code.

All of the situations when the Feeder has stopped, and at the same time some of the converting machines have been in starvation were searched from the production data. They are marked with red circles in the production data presented in Appendix E. The situations were checked from the reported work events for every time a Feeder lack of space in WIP store was close to converting starvation. Starvation was recognized to be connected to Feeder stopping if the converting starvation occurred during, or after the Feeder stop, and the material production (that the converting machine was waiting for) had been delayed because of the stoppage.

Table 11. *Monthly Feeder stops due to lack of space in WIP store and converting starvation*

FEEDER			CONVERTING		
Month	Stops due to lack of space in WIP		Month	Stops due to starvation	
11/2016	8	13:37	**11/2016**	127	80:07
12/2016	5	10:46	**12/2016**	92	50:53
01/2017	7	17:05	**01/2017**	57	35:13
02/2017	4	4:13	**02/2017**	70	46:21
03/2017	3	9:11	**03/2017**	115	99:21
04/2017	3	5:28	**04/2017**	60	42:03
05/2017	13	30:44	**05/2017**	79	46:20
06/2017	6	10:39	**06/2017**	89	64:16
07/2017	8	16:39	**07/2017**	82	83:05
08/2017	4	9:13	**08/2017**	74	50:12
09/2017	8	19:39	**09/2017**	70	45:03
10/2017	0	0:00	**10/2017**	75	49:22
	69	**147:14**		**990**	**692:16**
	9 d,	**3:14**		**40 d,**	**9:43**

In a surprisingly large amount of cases the material was produced a day or more before the starvation on the converting machines, and could not therefore be connected to Feeder stopping. However, from the total amounts over the year, 45:59 (31.2 %) of Feeder stops were identified as causing starvation in converting. On the other hand, 35:00 (5.1 %) of starvation were identified to be directly caused by Feeder lack of space in WIP. The percentage of starvation is a bit larger in reality, because the lack of material figures contain other waiting times in addition to material waiting as described earlier. It is also possible that a full WIP storage has caused more starvation in converting because of the difficulties in moving material when the storage is full. How the 35:00 of starvation was divided between the converting machines is presented in Table 12.

Table 12. *Starvation caused by Feeder stopping due to lack of space divided between converting machines*

	TOTAL	COUNT
Converter 1	20:27	14
Converter 3	6:45	4
Converter 5	2:52	4
Converter 6	2:31	1
Converter 2	1:43	2
Converter 4	0:42	1
	35:00	**26**

It was earlier discovered that when the WIP storage is at 80 %, and considered full, there should be about 12 hours of material available for each converting machine. These 35 hours of starvation on converting machines because of Feeder stopping seem unbelievable considering the previous fact. This simply means that material has not been produced evenly between the converting machines. The reason why this has happened is unknown. It might be because of bad judgement in production scheduling or simply because of the available order mix. There are many random disruptions in production because of which production scheduling is very difficult.

4.2.4 Reasons for WIP storage filling up

Feeder stopping due to lack of space in WIP directly caused starvation in converting on a total of 17 occasions over the period of 12 months. The production data on these days is gathered to Table 18 in Appendix F. The output of each machine is presented relative to the average output over 12 months. This data shows that on fourteen of these occasions one or more converting machines have performed under their average performance over 12 months while Feeder has performed better, which explains why the WIP storage has reached its limits.

However, on three occasions the converting total has been over the average, which does not explain the lack of space in WIP. On two of these occasions, however, Feeder has produced way over its average on the time period despite stopping due to lack of space. This explains the WIP storage filling despite good performance in converting.

The rest of the cases when the Feeder has stopped due to lack of space in WIP storage were also analyzed and the result is that on most of the days, again, one or more converting machines have performed poorly, or the Feeder has performed way better than converting, which has caused the WIP storage to fill up. This data is presented in Table 19 in Appendix F. Overall it can be said that Feeder lack of space occurs because the Feeder performs better than converting and the difference is stored in the WIP storage. This can be either because converting machines perform poorly or Feeder performs very well and lack of synchronization exists between the operations.

Filling up the WIP storage does not happen all of a sudden. It is a process of many different events. All of the events include the fact that the Feeder has produced more material than converting machines have been able to process. However, if all converting machines performed perfectly, meaning that every day consisted only of setups and running, they would have no problem processing the material that the Feeder is feeding them at the budget pace. This calculation is done with average setup times, average running paces and average job sizes on the converting machines with the Feeder running at a steady budget pace. This situation is visualized in Figure 23 in Appendix G in a form of a simple production simulation.

The time period in the case is 48 hours. The converting machines have a 30 min stop every 16 hours which corresponds the daily cleaning at the end of the day. Then at the start of every 16 hours the converting machines do a setup. In this example the amount of WIP products starts from 0.59 shift's production and a slight decrease in the level can be seen during the time period. If looked closely, three of the converting machines experience a small amount of starvation towards the end of the period. Converter 4, Converter 3 and Converter 6 do not experience starvation. Waste figures are not taken into account in these simulations and the amount of unconverted material of Feeder output is always 17.6 %, which is the average amount.

Figure 24 in Appendix G shows a situation where the Feeder runs at budget pace and average daily unplanned stoppages have been included in the converting machine production. The simulation shows the rate at which the level of WIP products increases if the Feeder produces that much more compared to converting. Figure 25 in Appendix G visualizes the pace at which the Feeder can run if average daily unplanned stoppages are included in the converting process figures. This simulation shows that the Feeder must run at 14.5 % under budget on average to not overproduce compared to the converting process. The average daily unplanned stoppages on the converting machines include start of the day and job changing, machine repairing (under 4 hours), material defects, tool fixing, clearing disruptions, lack of space at converting machines and automatic breaks.

Using this simulation where the Feeder runs at 85.5 % of budget pace and converting at average figures and average daily unplanned stoppages, the starting level of WIP products was varied to find the WIP level at which converting machines do not experience any starvation. This is visualized in Figure 6. Starvation is experienced at average job sizes and above mentioned conditions when the amount of WIP products is under 0.59 shift's production. Provided also, the amount of WIP products is divided equally between the converting machines at the beginning. Using the calculations done in chapter 4.2.2 this corresponds to about 25 % of WIP fill rate. Therefore, the WIP level of the rest of the simulations in Appendix G were chosen to be 0.59 shift's production and are discussed next.

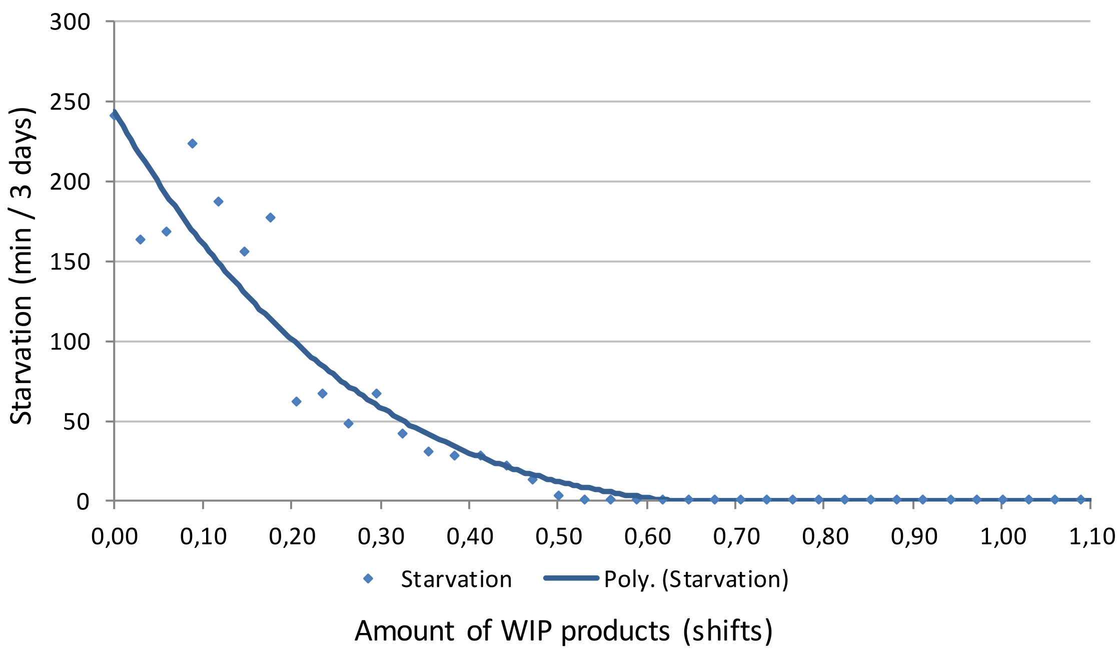

Figure 6. *The amount of starvation in converting as a function of amount of WIP products over a period of 48 hours*

Figure 26 and Figure 27 in Appendix G show situations where preventive maintenance has been scheduled on converting machines. If Converter 2 and Converter 1 have preventive maintenance during the time period, the contents of the WIP storage deviate upwards about 0.15 shift's production. If Converter 4 and Converter 5 have five hour stoppages due to preventive maintenance, the contents of the WIP storage deviate upwards about 0.29 shift's production. On these cases Feeder produces at 85.5 % budget pace, 17.6 % unconverted orders per day. The preventive maintenance of Converter 3 and Converter 6 is not simulated because their effect is least notable on the WIP storage due to their capacities.

Figure 28 in Appendix G shows bad performance on Converter 1, Converter 4 and Converter 5, and their effect on the WIP storage level. First, Converter 1 performs poorly during the first day of the time period and the Converter 4 performs badly during the second day, and Converter 5 performs poorly on the third day of the time period. This results in the WIP storage going slightly over 1 shift's production, meaning an upward inaccuracy of about 0.41 shift's production compared to the first case. Figure 29 shows one full shift breakdowns on Converter 3 and Converter 2. During these events the WIP level increases to around 1 shift's production meaning an increase of around 0.29 – 0.44 shift's production compared to the start level.

These simple simulations are to demonstrate the effects of different cases that temporarily lower the capacity of the converting process on the WIP storage. During these types of scenarios the Feeder keeps on producing material at the same pace as before these capacity alterations in converting which results in the contents of the WIP storage increasing. What changes is that production plan is changed so that material is not produced to the converting machine which experiences a temporary capacity reduction. On the other hand, more material is produced to the remaining converting machines during this time. When the problem has been solved on the converting machine or maintenance is done, production planning alters the Feeder production plan to continue producing material to the converting machine in question.

The simulations show, however, that the pace at which the Feeder runs compared to the converting process is the main variable in the WIP level fluctuations. The higher the processing speed at the Feeder compared to the entirety of the converting area the faster the WIP storage fills up. High Feeder pace and problems or maintenance in converting was not simulated. But this intuitively increases the rate at which the WIP level increases.

In reality, converting machines are up and running 56 % of the time and down for setups 17 % of time. The rest of the time (27 %) is dedicated mainly to disruptions, preventive maintenance, lunch breaks and weekly cleaning. The before mentioned unplanned stoppages on converting machines take up to 15 % of the entirety. If material waiting is added, the value adds up to 18 %. This means that the converting process is down because of disruptions almost one fifth of production time. If this 18 % was eliminated, running time would increase to 68 %, setup time to 21 % and rest of time would add up to 11 %.

4.3 The effects of detected problems on the production process

The record inaccuracies in the raw material store are problematic for the factory because they might cause a situation where a customer order cannot be produced because there is no material in the storage from which to produce the order. This is the worst case scenario. In most cases there is substitute material available in the storage that can be used to produce the order. The missing material is then substituted with better material. Using substitute materials usually cause more waste in the production process.

Using substitute material causes problems to the production process. At the Feeder there are pre-determined parameters for every material quality. However, these parameters only work for the pre-determined material. Using substitute material always forces to fix the parameters of the machine, which is done by feel. Fixing the parameters by feel causes waste in the process until the optimum settings are found.

Substitute material can also cause some problems in the converting process. However, differences in materials are not often noticed on the converting machines. There are predetermined parameters for different materials in most of the converting machines as well. Like on the Feeder, the parameters need to be fixed by feel to find the correct settings. An advantage of using substitute material is, on the other hand, the fact that as the material is usually better, the quality of the products are better as well.

On some of the converting machines substitute material can cause tool fixing. This then results in downtime of the converting machine during the time the tool is fixed. Then, when the same tool is used again and the material is reverted back to normal, the tool might need to be fixed again – causing downtime on the machine. Additionally, what's problematic for the converting machines is if the material changes during the run. This situation is possible if there has been a little amount of correct material in the raw material store, which has run out during the production on the Feeder and then the rest of the production has been done with substitute material. If the material changes during the run at the converting machine, the produced products are most likely waste as the parameters do not fit the material anymore. It is possible that the situation goes unnoticed for a while. Once noticed, fixing the parameters, and finding and removing waste products take time.

The production time lost due to substitute material is very hard to estimate even for the production operators. This is because every situation is different, and as mentioned earlier, converting machine operators might not even notice the difference in material. And when problems occur, it is hard to estimate if substitute material is the cause. But what can be estimated is the cost of the substitute material compared to the pre-determined material. The production system does not offer an easy way of finding out when material has been substituted. It would be possible to go through every single order and see what material has been used to produce it, but, it would take weeks to go through tens of thousands of orders one by one and check the materials. Therefore, this estimation is done based on a tracking done by the warehouse operators. They were asked to make a list of all instances when material is substituted. This list of the period from 2nd to 27th November is presented in Appendix B.

During the tracking period, measured in percentages, 5.25 % of Feeder production was done with substitute material. The raw material prices are updated monthly. The cost of every substitute material was calculated using November 2017 prices. The substitute material used during this time period added up to a loss of -11 639,74 €. Estimating the cost of substitute material from May 1st to the end of October based on the produced amount of material on the Feeder gives a loss of -97 565,40 €. Furthermore, estimating the cost of substitute materials over the last 12 months gives a cost of -183 338,61 € more than using the correct materials.

Now, it has to be noticed that the majority percentage of using substitute material is because of challenges in raw material supply. This also changes seasonally and has not been taken into account in the above calculations. The challenges were estimated to be abnormally high this time of the year. Therefore, the monthly cost is most likely between 10 000 - 15 000 €, which makes the yearly cost between 120 000 - 180 000 €. Now, tracking of substitute material usage because of inaccuracies in item records has not been tracked. After talking with warehouse operators, Feeder operators and production planners, it was estimated that about 10 - 15 % of substitute material is used because of item record inaccuracies. Therefore, using this estimation about 1 000 - 2 250 € is lost monthly because of item record inaccuracies. The yearly figures add up to about 12 000 - 27 000 €. A more precise estimation would require a longer tracking period of all substitute material and noting every situation when item record inaccuracy is the cause.

A full WIP storage can be interpreted to be a cause for material waiting in converting, but it is not the root cause. When the WIP storage fill rate reaches 80 % it causes the Feeder to stop, and if at that point the WIP storage does not contain a close to even amount of material in production hours for each machine, it might eventually lead to starvation on some of the converting machines. But this is not because of the capacity of the WIP storage. This is because the Feeder has produced more than the converting machines have been able to process for a certain period of time, and production has not been scheduled evenly between the converting machines for one reason or another. There is lack of synchronization between the processes.

A total of 35:00 of starvation in converting over a period of 12 months was identified as being caused because of Feeder stopping due to lack of space in the WIP storage. The division of the 35 hours between the converting machines was presented earlier in Table 12. About 6.6 % of the output of Converter 1 go straight to packaging and create output for the factory. The percentage out of 20:27 equals 1:21. If that time could have been used to producing average products at Converter 1, the output of the factory would have been about 2.9 % of daily budget production bigger over a period of one year. The 20:27 of Converter 1 material waiting did not cause further material waiting at Converter 2 or Converter 3.

All of the other converting machines create output for the factory, and with similar calculations if the material waiting time could have been used to running average material at average pace the following output additions would have been possible. The percentages are out of the daily budget of finished goods for the entire plant. Converter 3 could have run about 5.9 % more, Converter 5 about 7.9 % more, Converter 6 about 2.9 % more, Converter 2 about 2.8 % more and Converter 4 about 1.2 % more. In total, the starvation caused by Feeder stopping due to lack of space in WIP storage has caused at most 23.5 % of a daily production budget less output over a period of 12 months. This number corresponds to about 0.1 % of finished goods over a period of 12 months. Therefore, the starvation on the converting machines caused by the Feeder stopping due to lack of space in the WIP storage is not a big problem.

The total amount of disruptions in converting were considered quite significant as 27 % of production time is spent on other activities than setups and running. These disruptions cause the converting process to run slower and partly cause the WIP storage to fill up. The effect of converting disruptions on the output of the factory on a 12 month period is presented in Table 13. If the 18 % of disruptions discussed earlier (colored gray in the table) could be used for setups and running, the converting process would potentially generate over 21.5 % more output annually. If those disruptions were reduced even by half or one third, there would be potential to about 6.7 – 10.7 % of more output annually. There is definitely room for improvement there.

Table 13. *The effect of converting disruptions on the output of the factory*

Event	% of production time	Effect on output (%)
Weekly cleaning	3,9 %	4,3 %
Start of day / job change	3,5 %	5,3 %
Machine repairing (<4h)	3,3 %	3,8 %
Material waiting	3,1 %	3,1 %
Tool fixing	2,5 %	3,6 %
Clearing disruptions	2,4 %	3,3 %
Lunch break	1,6 %	1,8 %
Material defects	1,6 %	1,4 %
Automatic break	1,0 %	1,2 %
Preventive maintenance	1,0 %	1,2 %
Arrival	0,7 %	0,9 %
Crew arrangement	0,7 %	0,9 %
Lack of space	0,6 %	0,8 %
Failure in the waste system	0,3 %	0,4 %
Machine repairing (>4h)	0,3 %	0,4 %
Other stoppage	0,2 %	0,3 %
Lack of work	0,1 %	0,0 %

5. DISCUSSION AND SUGGESTIONS

5.1 Discussion on the findings of the data analysis

The data gathering and analysis section examined the two inventory related problems given by the case factory management: raw material store inventory record inaccuracies and WIP storage related disruptions in production. Sources of inaccuracy in the raw material store were found and also causes for WIP storage related disruptions in the production process were found.

The detected sources of inaccuracy in the raw material store could be classified into system error, human error, and both. The six possible sources of inaccuracy found are summarized below:

- Incorrect way of working with partly used material
- Human errors in entering received amounts of material to SAP
- Inexplicable missing transactions in SAP
- Delayed logging of transactions in SAP
- Misplacement of items
- Continuous kg inaccuracy in Russian items

It was estimated that the costs caused by inventory record inaccuracies are around 12 000 - 27 000 € annually. A more precise estimation would require a longer tracking of used substitute material due to record inaccuracies, as the information is not available in the system. Substitute material does not only cause raw material costs, but can also result in unnecessary problems in the production process. The main function that is suffering from the record inaccuracies is production planning and scheduling, and the problems need to be considered from that point of view.

In the present situation, only the amount in kilograms of different items is stored in the system – and can be inaccurate. As Figure 5 in chapter 4.1.5 shows, most of the record inaccuracies were estimated to occur between the WMS and SAP. The production planners have no information in the system about the number of items or other information regarding the items – except for the partly used items inventory stored in the WMS. No single unused items' information is stored in the system. Also, the warehouse operators have no idea what amounts the system records show on different items because they have no access to the records in the system.

What was found regarding the WIP storage was that the storage can be considered to be constraining the production process when full, but it is not the root cause for disruptions in Feeder production. The root cause is that the converting machines are not able to process the amounts of material that the Feeder is feeding them at a higher pace. On the other hand, the situation can be interpreted so that the Feeder is producing too much material considering the current state of the converting process. Every temporary capacity or performance decreasing in converting leads to an increase in the fill rate of the WIP storage. These events include planned stoppages or unplanned difficulties, disruptions and breakdowns.

It can be seen in the 12 month production data in Appendix E that when the WIP level is lower, the Feeder can produce well, even though converting is not performing as desired. But in situations when the WIP level is higher, the Feeder performance depends almost fully on the performance of converting machines. Therefore, a clear pattern can be seen in the process: the Feeder runs at a high pace as long as it can in terms of the WIP storage, and is then stopped to let the converting machines lower the WIP storage level. This means that there is free capacity at the Feeder that cannot be used.

The converting process is clearly dictating the pace of the system as about 82 % of the factory output goes through the converting machines. In simulating average production it was found that the Feeder can only run at 85.5 % of budget pace. Therefore, the converting process is the constraint of the system.

5.2 Linking the analysis with the literature

The sources of inventory record inaccuracy are consistent with the literature, as common sources of error are improper processing of items, database errors, poor data synchronization, data lags, errors during inventory counts, shrinkage and misplacement. Even low discrepancy between physical inventory and recorded inventory produce suboptimal system performance according to the literature, and is found true in this study as well. The inventory records are 98.8 % accurate and problems are still caused in the production process, production planning and scheduling.

According to the literature it is a fundamental principle that material flow and information flow go hand in hand. It is essential to know everything about an item in stock. This is definitely not the case in the case factory’s information systems. It is argued in the literature that inventory record inaccuracies can be dealt with either by prevention/correction or developing robust policies that work even with inaccurate records. RFID technology is also considered a good solution for the problem because of the transparency it provides. The literature also introduces cycle counting as a tool of keeping inventory records up to date. In cycle counting, a selected number of items are counted every day. It can be performed by stock keeping unit or by location for example. At the case factory some items are counted on a frequent basis but no strict policies exist.

The converting process was identified as the constraining resource of the production system through data analysis. TOC says that the pace of production should be set according to the constraining resources because they limit the overall output of the plant. As the constraints limit the throughput of the system, all efforts are devoted to maximizing the capacity of these resources. The goal is to break a constraint condition and thereafter identify the next constraint.

The converting process is constraining the system partly because there are too many disruptions in the process. The amount of events other than running or setups is quite high – 27 % of the whole production time. There are a lot of activities there that do not add value to the process. These are seen as waste according to the lean philosophy. It is clear that the performance/capacity of the converting process is lower than the Feeder. However, increasing the capacity of the WIP storage is not seen as a solution in reducing WIP storage related disruptions in the process. Because of the higher capacity and running pace of the Feeder, increasing the WIP storage capacity would most likely lead to higher amounts of WIP products.

What's more, the capacity of the WIP storage is consistent with the literature, which says that the number of different materials the Feeder can produce simultaneously largely determines the WIP storage capacity. The WIP storage capacity should be 1 - 2 shifts on plants where the Feeder can produce two materials simultaneously. The capacity of the WIP storage was calculated to be around 2.35 shifts of average production. However, according to the literature sizing of the converting area is an important factor for plants pursuing lean manufacturing. The converting area should be sized according to the pull principle of lean meaning that the entire converting section should have at least 10 - 15 % higher capacity than the Feeder. Therefore, an overloaded WIP area can be compensated with an increase in converting capacity.

The limited capacity of the WIP storage is actually more of a positive thing. It prevents the Feeder from overproducing extensively compared to the converting process. The WIP storage area of the factory is in no means large as it fits roughly two shift's production. This means that the lead time of the production system is at maximum roughly one day. At a low WIP fill rate the production lead time is only a few hours. Higher inventories would make it is easy to hide inefficiencies allowing problems to go unresolved. The lean approach to inventories is to pare them down – defining low inventories as the result of successful problem solving. Furthermore, higher amount of WIP products would make it physically more difficult to move things around and cause disruptions in production. Higher inventories also consume working capital of the business.

5.3 Suggestions for improvement

To be able to get rid of the inventory record inaccuracies causing problems in the production process, all of the sources of error need to be eliminated or their effects reduced significantly. The best solution to accomplish the above goal is to update the WMS. This update needs to enable reading the information of every delivered item to the system – including all the required information from planning and scheduling point of view. This information is also necessary for general warehouse management. The WMS needs to also include the placement of items in the warehouse. Updating the WMS system would give the production planners access to real time item records. The potential information flows from the raw material store to production planner – if the system is updated – are presented in Figure 7 below.

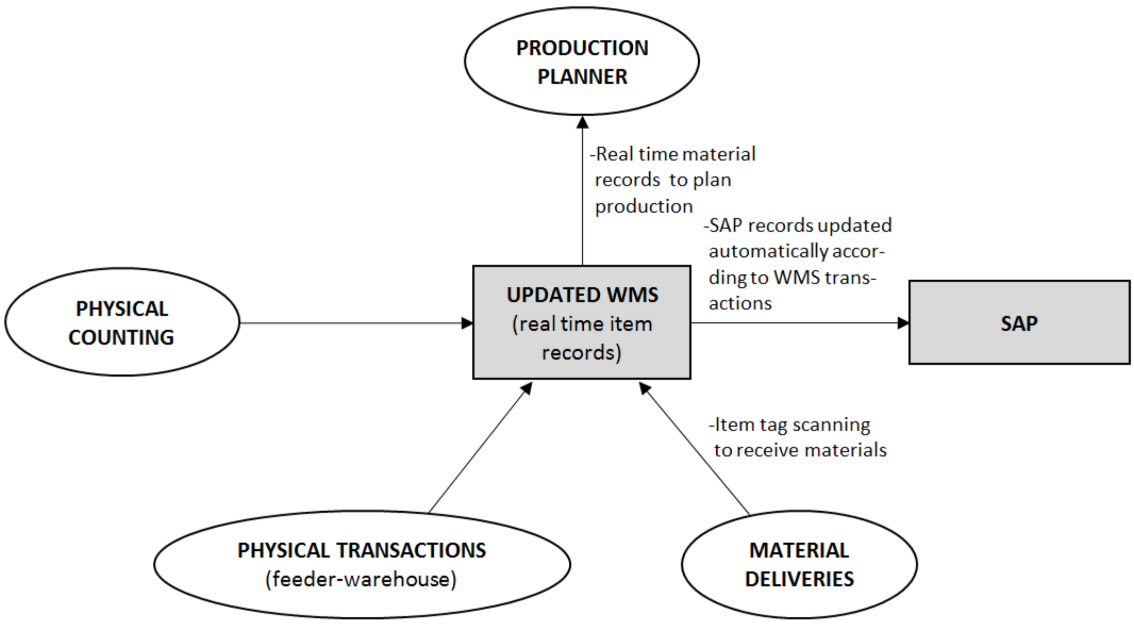

Figure 7. *Likely information flows if WMS is updated*

By updating the system incorrect way of working with partly used items, missing transactions and delayed logging should not be a problem for production planning anymore. It is possible that some inaccuracies exist between the communication of the WMS and SAP but it should not disturb scheduling. Human errors in receiving and misplacing materials are still possible but their possibility is reduced as the information and locations of items are found in the system. Updating the system gives a chance of 12 000 - 27 000 € of material cost savings annually. This is due to having accurate item records which result in better performance in operative purchasing due to more accurate forecasting, which leads to a decreased amount of substituting materials.

If a system update is not considered, there are some other possible solutions related to the way of working to control the situation. The solutions are not as certain as a system update because they always include a human factor. First of all, the incorrect way of working with partly used items needs to be corrected to reduce about 25 % of the inaccuracies. Also, the warehouse operators need to be given access to the system records of warehouse items at some level, because they are the ones that work with the items and can report inaccuracies if they detect any.

The delays between the physical transactions and SAP logging lead to the fact that the best time of doing physical counting of items is at the start of the morning shift. At that moment the chances of pending transactions in the system are the lowest. The possibility of warehouse operators doing physical counting at the beginning of the morning shift needs to be examined. The amount of different materials counted could be for example 5 or 10 per day and they would vary daily. Or alternatively, the warehouse could be divided into a few sections which are counted daily. There is a great chance that doing physical counting at the start of the morning shift fully eliminates the incorrect manual correction of item records due to pending transactions.

The placement of items can sometimes be a problem especially with substitute workers. Maintaining a document based layout of the warehouse showing the placement of different materials could reduce errors in this category. The layout could be Excel-based and updated by the production planners. When changed, a new document would be provided to the warehouse operators. The document could be stored in the forklift. Human errors in entering received amounts of materials to the system is hard to correct. Every operator knows how it is done but errors still happen because of the manual nature of the task.

Based on the thinking of TOC, the suggestions for improvement in the production process focus on elevating the constraining resource of the process (converting process). Firstly, the performance of the converting process should be improved, and secondly, increasing the capacity of the converting process should be examined.

The performance is improved by dedicating more resources to eliminating non-value adding disruptions on the converting machines. Regarding scheduling, in trade-off situations converting machines should always be favored over the Feeder. The focus should be on minimizing disruptions and breakdowns and maximizing the uptime of the converting machines. There is a significant amount of output available from reducing disruptions in the converting process. Reducing the disruptions leads to lesser unpredictable performance decreases and better production scheduling which leads to better control of the WIP storage area.

Increasing the capacity of the converting process to better utilize the pull principle of lean is suggested. Investing in a new converting machine would probably shift the constraint of the production system from converting to the Feeder. At that point converting machines should be able to process everything that the Feeder is feeding them and WIP product levels would be kept at a minimum – not causing WIP related disruptions in the process. The capacity of the Feeder would be utilized more fully. The Feeder would be setting the pace of the whole system. If disruptions were to occur at the converting machines the lost time could be made up since the Feeder is setting the pace of production. Managing the pace of production through one machine is easier than through six machines. Therefore, if there is market demand, increasing the capacity of the converting process is suggested.

6. CONCLUSIONS

The objective of this thesis was to study and solve two inventory related issues at the factory, namely finding the causes of inventory record inaccuracies in the raw material store and investigating whether the capacity of the WIP storage is constraining the production process. The main research question was to determine the effects of the identified inventory related problems on the total output of the factory. To find the answer to the main research question current raw material store management policies were investigated along with factors causing item record inaccuracies. WIP storage management policies and the root cause of WIP storage related disruptions in the production process were investigated.

The reviewed literature included the principles of lean thinking, TOC and inventory management. Answers to the research questions were found mainly by analyzing the gathered data, but also by observing processes and interviewing operators. The inventory management literature was referenced to find improvement suggestions regarding the inventory record inaccuracies. Principles from lean thinking and TOC were on the other hand used in constructing improvement suggestions regarding the WIP storage related events.

Before the research began, it was argued by many in the organization that the reasons of item record inaccuracy had to have something to do with the information systems. This turned out to be true. However, human factors were also found to have a considerable effect on the inaccuracies. Similarly, the WIP storage was considered constraining the production process. This was found true to some extent, but the underlying reason was found to be the performance difference between the converting machines and the Feeder – and the reasons behind it.

Updating the WMS in the raw material store was seen as the best option in eliminating item record inaccuracies. This would provide cost savings in the form of less substituting of materials due to accurate records and better forecasting. However, the situation can be controlled with physical counting policies to some extent. What's questionable about physical counting is, that warehouse operators may be reluctant towards doing physical counting of items. Another concern is their ability to perform the physical counts. The days also vary quite a lot in the raw material store. Some days there is so much to do that physical counting would probably not fit in. Therefore, the extent to which physical counting can be applied is limited.

The converting process was seen as the constraining resource of the system that should be elevated. More resources need to be dedicated to reducing non-value adding disruptions in the converting process. Additionally, increasing the capacity of the converting process should be examined. The system needs to be looked at as a whole rather than focus on individual machines – at least between converting and the Feeder. The difference in capacity/performance between the operations means that there will always be some idle time either in converting or on the Feeder. In the present situation, idle time occurs on the Feeder because it performs better compared to converting. If converting capacity was higher, the situation would be reversed.

Like every study, this one had limitations as well. A tight schedule was definitely a limiting factor of the study. It was especially limiting the time of data gathering and observing. More sources of inventory record inaccuracy might have been found by dedicating more time to gathering data and observing the processes. Also the effects of the sources of inaccuracy could have been better estimated with more data. Additionally, the impact of record inaccuracies on the use of substitute material and its effect on raw material costs could have been better determined.

Including production planning and scheduling in detail to the WIP storage issues would give additional valuable insights on the production process. However, the entirety of the function is so wide that including it in this study was not possible. Another factor that should be considered is the fact that average production figures were used in the calculations and simulations of this study. In reality, production is never average. There are many varying factors which include for example product characteristics, job sizes, setup times, run times and disruptions. These factors need to be kept in mind when reading this study.

The study was based on historical data gathered from a 12 month period, from which scenarios were constructed. Therefore, the study considers how production has been operated before, not what the future direction is. Hafez (2017) studied one of the production lines and suggested pursuing increased job sizes. If increasing job sizes is pursued in all production lines, the cycle time of the Feeder would increase. This would lead to the level of WIP products increasing which would mean that the WIP storage capacity might not be sufficient – contrary to the results of this study. However, this is an intuitive conception of the subject. The situation needs to be simulated to form a solid understanding of the consequences.

REFERENCES

Ballard R.L. (1996) Methods of inventory monitoring and measurement, Logistics Information Management, Vol. 9(3), pp. 11-18.

Bruccoleri, M., Cannella, S. & Porta, G.L. (2014). Inventory record inaccuracy in supply chains: the role of workers' behavior, International Journal of Physical Distribution & Logistics Management, Vol. 44(10), pp. 796-819.

Callen, J., Fader, C. & Krinsky, I. (2000). Just-in-time: A cross-sectional plant analysis, International Journal of Production Economics, Vol. 63(3), pp. 277-301.

Cannella, S., Framinan, J.M., Bruccoleri, M., Barbosa-Póvoa, A.P. & Relvas, S. (2015). The effect of Inventory Record Inaccuracy in Information Exchange Supply Chains, European Journal of Operational Research, Vol. 243(1), pp. 120-129.

Chaudhari, C.V. & Mukhopadhyay, S. K. (2003). Application of Theory of Constraints in an integrated poultry industry, International Journal of Production Research, Vol. 41(4), pp. 799-817.

Crandall, R.E. & Burwell, T.H. (1993). The effect of work-in-progress inventory levels on throughput and lead times, Production and Inventory Management Journal, Vol. 34(1), pp. 6-11.

DeHoratius, N. & Raman, A. (2008). Inventory record inaccuracy: an empirical study, Management Science, Vol. 54(4), pp. 627-641.

Delaunay, C., Sahin, E. & Dallery, Y. (2007). A Literature Review on Investigations Dealing with Inventory Management with data Inaccuracies, 2007 1st Annual RFID Eurasia, pp. 1-7.

Eroglu, C. & Hofer, C. (2011). Lean, leaner, too lean? The inventory-performance link revisited, Journal of Operations Management, Vol 29(4), pp. 356-369.

Fullerton, R. & McWatters, C. (2001). The production performance benefits from JIT implementation, Journal of Operations Management, Vol. 19(1), pp. 81-96.

Fullerton, R., McWatters, C. & Fawson, C. (2003). An examination of the relationships between JIT and financial performance, Journal of Operations Management, Vol. 21(4), pp. 383-404.

Goldratt, E.M. (1990). What is this thing called theory of constraints and how should it be implemented? North River Press, Great Barrington (MA), 160 p.

Gunn, B. & Nahavandi, S. (2000). Determining the optimum level of work in progress using constraint analysis and computer simulation, Assembly Automation, Vol. 20(4), pp. 305-312.

Gupta, M.C. & Boyd, L.H. (2008). Theory of constraints: a theory for operations management, International Journal of Operations & Production Management, Vol. 28(10), pp. 991-1012.

Hafez, K. (2017). Tuotantoerien kasvattaminen ja sen kustannusvaikutukset, Master of Science thesis, Tampere University of Technology, Faculty of Business and Built Environment. Tampere. 60 p.

Heese, H.S. (2007). Inventory record inaccuracy, double marginalization, and RFID adoption, Production and Operations Management, Vol 16(5), pp. 542-553.

Hellström, D. & Wiberg, M. (2010). Improving inventory accuracy using RFID technology: a case study, Assembly Automation, Vol. 30(4), pp. 345-351.

Hines, P., Holweg, M. & Rich, N. (2004). Learning to evolve: A review of contemporary lean thinking, International Journal of Operations & Productoin Management, Vol. 24(10), pp. 994-1011.

Kang, Y. & Gershwin, S.B. (2005). Information inaccuracy in inventory systems: stock loss and stockout, IIE Transactions, Vol. 37(9), pp. 843-859.

Kasanen, E., Lukka, K. & Siitonen, A. (1993). The Constructive Approach in Management Accounting Research, Journal of Management Accounting Research, Vol. 5, pp. 241-264.

Koumanakos, D.P. (2008). The effect of inventory management on firm performance, International Journal of Productivity & Performance Management, Vol. 57(5), pp. 355-369.

Laakso, O. & Rintamäki, T. (2001). Production and converting of corrugated board, Finnish Corrugated Board Association, Jyväskylä, 150 p.

Li, M. & Wang, Z. (2017). An integrated replenishment and production control policy under inventory inaccuracy and time-delay, Computers and Operations Research, Vol. 88, pp. 137-149.

Liker, J.K. (2004). The Toyota way: 14 management principles from the world's greatest manufacturer, McGraw-Hill, New York, xxii, 330 sivua p.

Melton, T. (2005). The benefits of lean manufacturing: What lean thinking has to offer the process industries, Chemical Engineering Research and Design, Vol. 83(A6), pp. 662-673.

Murphy, P. & Wood, D. (2008). Contemporary Logistics, 9th edition, Upper Saddle River, NJ : Pearson Prentice Hall cop., 415 p.

Nanfang, C., Kaijun, L. & Tian, W. (2008). Rapid response with TOC methodology, 2008 International Conference on Service Systems and Service Management, pp. 1-7

Norris, D., Swanson, R. & Chu, Y. (1994). Just-in-time production systems: a survey of managers, Production and Inventory Management Journal, Vol. 35(2), pp. 63-66.

Owen, J.H. & Huang N. (2007). Local improvements that degrade system performance: case studies and discussion for throughput analysis, International Journal of Production Research, Vol 45(10), pp. 2351-2364.

Pinnington, T. (2005). The corrugated industry: In pursuit of excellence, Brunton Technical Publications Ltd, 387 p.

Robson, C. (2002). Real world research: a resource for social scientists and practitioner-researchers, 2nd ed., Blackwell Publishing, Oxford: Malden, MA, xxii, 599 p.

Santos, J., Wysk, R.A. & Torres, J.M. (2006). Improving production with lean thinking, Wiley, Hoboken, New Jersey, 264 p.

Saunders, M., Lewis, P. & Thornhill, A. (2009). Research methods for business students, 5th ed ed., Prentice Hall, Harlow, xxxi, 614 p.

Shams-ur Rahman (1998). Theory of constraints: A review of the philosophy and its applications, International Journal of Operations & Production Management, Vol. 18(4), pp. 336-355.

Smith, D. (2000). The measurement nightmare : how the theory of constraints can resolve conflicting strategies, policies, and measures, St. Lucie Press, Boca Raton, Fla, xxii, 184 p.

Stevenson, W. (2014). Operations Management, 12th edition, McGraw-Hill, 904 p.

Stoop, Paul P.M. & Wiers, Vincent C.S. (1996). The complexity of scheduling in practice, International Journal of Operations & Production Management, Vol. 16(10), pp. 37-53.

van der Vorst, J.G.A.J., & Beulens, A.J.M. (2002). Identifying sources of uncertainty to generate supply chain redesign strategies, International Journal of Physical Distribution & Logistics Management, Vol. 32(6), pp. 409-430.

Vollmann, T., Berry W. & Whybark D. (1997). Manufacturing planning and control systems, 4th edition, McGraw-Hill, 836 p.

Vollmann, T., Berry W., Whybark D. & Jacobs, F. (2005). Manufacturing Planning and Control for Supply Chain Management, 5th edition, McGraw-Hill, 712 p.

Wang, H., Chen, S. & Xie, Y. (2010). An RFID-based digital warehouse management system in the tobacco industry: a case study, International Journal of Production Research, Vol. 48(9), pp. 2513-2548.

Womack, J.P., Jones, D.T. & Roos, D. (1991). The machine that changed the world, Harper Perennial, New York, 323 p.

Womack, J. & Jones, D. (2003). Lean thinking: banish waste and create wealth in your corporation, Rev. and updated, New York: Free Press, 396 p.

APPENDIX A: THE LAYOUT OF THE RAW MATERIAL STORE

Data removed for confidentiality reasons.

Figure 8. *The layout of the warehouse showing material conveying routes to the Feeder*

APPENDIX B: COST OF SUBSTITUTE MATERIAL CALCULATIONS

Table 14. *Tracking and calculating of substitute material costs over a period of 2.11.2017 – 27.11.2017*

Data removed for confidentiality reasons.

APPENDIX C: THEORETICAL CALCULATIONS OF WIP STORAGE CAPACITY

The percentages of Feeder output divided between converting machines and the material division on converting machines are presented in Table 15.

Table 15. *Percentages of Feeder output and material divisions on converting machines*

Data removed for confidentiality reasons.

From this data the capacity of the WIP storage was calculated to be about 2.35 shifts. The situation is visualized in Figure 9. Table 16 shows how the contents of the WIP storage would be divided between the converting machines. The WIP storage is divided to two pictures to have the entirety on one page in a readable size.

Data removed for confidentiality reasons.

Figure 9. *Theoretically full WIP storage visualized*

Table 16. *Contents of the WIP storage in the theoretical capacity calculations*

Data removed for confidentiality reasons.

APPENDIX D: FEEDER STOPS DUE TO NO SPACE IN WIP STORAGE 11/2016 – 10/2017

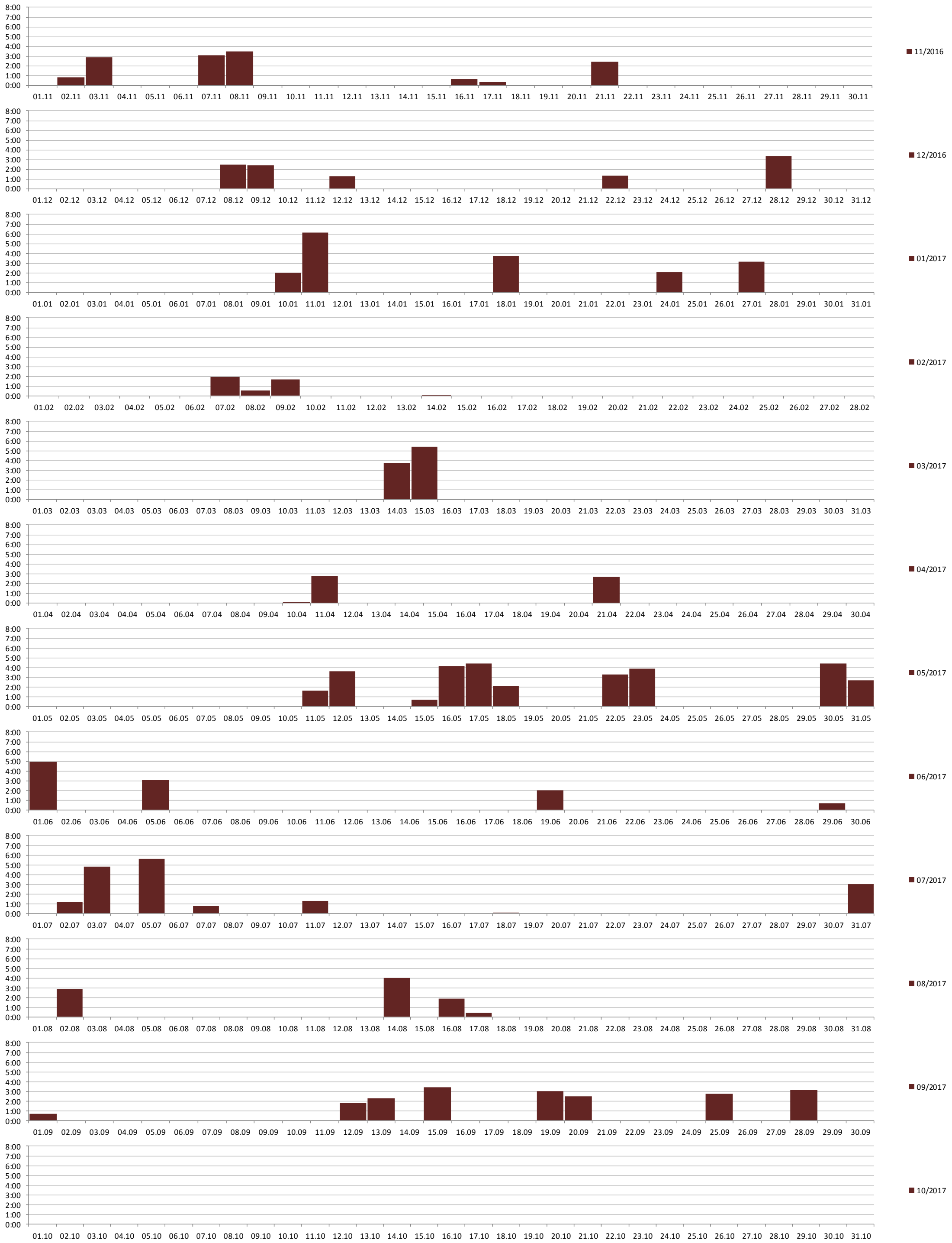

Figure 10. *Feeder lack of space visualized over a 12 month period*

Table 17. *Feeder lack of space monthly figures*

11/16	13:37	**01/17**	17:05	**03/17**	9:11	**05/17**	30:44	**07/17**	16:39	**09/17**	19:39
12/16	10:46	**02/17**	4:13	**04/17**	5:28	**06/17**	10:39	**08/17**	9:13	**10/17**	0:00

APPENDIX E: PRODUCTION DATA 11/2016 – 10/2017

Data removed for confidentiality reasons.

Figure 11. *Lack of space, lack of material and production data, Nov '16*

Data removed for confidentiality reasons.

Figure 12. *Lack of space, lack of material and production data, Dec '16*

Data removed for confidentiality reasons.

Figure 13. *Lack of space, lack of material and production data, Jan '17*

Data removed for confidentiality reasons.

Figure 14. *Lack of space, lack of material and production data, Feb '17*

Data removed for confidentiality reasons.

Figure 15. *Lack of space, lack of material and production data, Mar '17*

Data removed for confidentiality reasons.

Figure 16. *Lack of space, lack of material and production data, Apr '17*

Data removed for confidentiality reasons.

Figure 17. *Lack of space, lack of material and production data, May '17*

Data removed for confidentiality reasons.

Figure 18. *Lack of space, lack of material and production data, Jun '17*

Data removed for confidentiality reasons.

Figure 19. *Lack of space, lack of material and production data, Jul '17*

Data removed for confidentiality reasons.

Figure 20. *Lack of space, lack of material and production data, Aug ‘17*

Data removed for confidentiality reasons.

Figure 21. *Lack of space, lack of material and production data, Sep ‘17*

Data removed for confidentiality reasons.

Figure 22. *Lack of space, lack of material and production data, Oct ‘17*

APPENDIX F: FEEDER LACK OF SPACE AND ITS RELATION TO CONVERTING

Table 18. *Situations when Feeder lack of space has caused starvation in converting machines and production data on those days*

WIP LEVEL	FEEDER output	FEEDER stop	DATE	CONV 1	CONV 2	CONV 3	CONV 4	CONV 5	CONV 6	CONVERTING TOTAL	CAUSED STARVATION
very high	-5 %	2:53	**03.11.16**		-62 %	-3 %		-9 %	-1 %	-6 %	Converter 5 (0:53)
very high	-10 %	3:03	**07.11.16**				-22 %	-13 %	-32 %	-5 %	Converter 3 (2:04)
very high	2 %	3:27	**08.11.16**			-8 %	-21 %		-100 %	11 %	Converter 1 (0:55)
											Converter 3 (3:25)
very high	-6 %	2:27	**21.11.16**		-19 %	-28 %			-61 %	-7 %	Converter 1 (3:10)
high	-26 %	2:24	**09.12.16**	-100 %	-47 %	-71 %		-34 %	-69 %	-34 %	Converter 5 (0:31)
average	19 %	1:18	**22.12.16**		-27 %					29 %	Converter 1 (0:49)
high	-17 %	3:45	**14.03.17**			-2 %	-56 %				Converter 1 (1:12)
high	-28 %	3:02	**15.03.17**	-2 %	-11 %		-24 %	-6 %		-4 %	Converter 1 (2:02)
											Converter 6 (2:31)
high	-24 %	2:42	**21.04.17**		-2 %				-38 %	11 %	Converter 5 (0:46)
											Converter 4 (0:42)
high	-30 %	4:26	**17.05.17**	-9 %	-2 %		-72 %	-24 %	-29 %	-27 %	Converter 3 (1:16)

											Converter 1 (1:27)
high	**-12 %**	3:53	**23.05.17**	**-20 %**	**-20 %**		**-23 %**		**-33 %**	**-2 %**	Converter 1 (1:26)
average	**-12 %**	1:43	**30.05.17**		**-3 %**		**-39 %**		**-15 %**	**-7 %**	Converter 2 (1:43)
average	**-8 %**	1:46	**19.06.17**		**-35 %**	**-67 %**	**-34 %**			**-16 %**	Converter 1 (0:18)
high	**-38 %**	2:52	**05.07.17**	**-14 %**		**-8 %**	**-29 %**	**-16 %**		**-7 %**	Converter 1 (0:27)
high	**-51 %**	3:00	**31.07.17**	**-44 %**		**-39 %**	**-17 %**	**-26 %**	**-17 %**	**-14 %**	Converter 1 (7:13)
average	**-9 %**	2:53	**02.08.17**	**-27 %**	**-28 %**				**-30 %**	**-1 %**	Converter 5 (0:42)
average	**-11 %**	0:25	**17.08.17**		**-9 %**	**-10 %**	**-42 %**	**-1 %**		**-11 %**	Converter 1 (1:28)

Table 19. Feeder lack of space when converting is not interrupted and production data on those days

WIP LEVEL	FEEDER		DATE	CONV 1	CONV 2	CONV 3	CONV 4	CONV 5	CONV 6	CONVERTING TOTAL	CAUSED STARVATION
	output	stop									
high	**8 %**	0:49	**02.11.16**		**-39 %**	**-42 %**	**-57 %**	**-18 %**		**-29 %**	-
very high	**12 %**	0:38	**16.11.16**		**-11 %**			**-11 %**		**14 %**	-
very high	**23 %**	0:20	**17.11.16**	**-55 %**					**-46 %**	**40 %**	-
high	**-11 %**	2:27	**08.12.16**	**-31 %**	**-31 %**	**-5 %**		**-46 %**		**-17 %**	-
high	**-8 %**	1:16	**12.12.16**	**-36 %**	**-48 %**	**-12 %**				**-1 %**	-
high	**-20 %**	3:20	**28.12.16**					**-29 %**		**14 %**	-
average	**10 %**	2:01	**10.01.17**			**-59 %**	**-15 %**			**-4 %**	-
average	**-41 %**	6:07	**11.01.17**	**-2 %**		**-32 %**	**-45 %**	**-45 %**	**-24 %**	**-23 %**	-
high	**-18 %**	3:44	**18.01.17**				**-13 %**	**-11 %**		**2 %**	-
average	**-6 %**	2:05	**24.01.17**			**-3 %**	**-25 %**	**-2 %**	**-16 %**	**11 %**	-
high	**-24 %**	3:08	**27.01.17**	**-31 %**	**-23 %**	**-32 %**		**-25 %**	**-32 %**	**-12 %**	-
high	**8 %**	1:57	**07.02.17**	**-18 %**	**-24 %**					**6 %**	-
high	**10 %**	0:32	**08.02.17**	**-12 %**	**-6 %**					**11 %**	-
high	**0 %**	1:42	**09.02.17**					**-13 %**		**15 %**	-
high	**-64 %**	2:44	**11.04.17**				**-29 %**	**-11 %**		**4 %**	-

high	2 %	1:35	11.05.17	-5 %	-2 %				-34 %	5 %	-
high	-24 %	3:38	12.05.17				-17 %	-24 %	-18 %	-6 %	-
high	18 %	0:42	15.05.17	-16 %		-38 %	-25 %		-32 %	-7 %	-
high	-6 %	4:07	16.05.17	-21 %	-21 %	-15 %	-13 %		-14 %	0 %	-
high	-1 %	2:03	18.05.17	-9 %			-8 %	-12 %	-8 %	3 %	-
very high	-10 %	3:17	22.05.17		-17 %			-6 %	-32 %	-3 %	-
average	2 %	2:40	31.05.17		-38 %		-10 %	-49 %		-19 %	-
high	-33 %	4:56	01.06.17				-31 %	-8 %	-52 %	9 %	-
average	-15 %	3:04	05.06.17	-21 %	-43 %	-35 %	-7 %	-11 %	-14 %	-19 %	-
average	12 %	0:40	29.06.17	-29 %	-16 %			-27 %	-35 %	5 %	-
very high	-45 %	1:10	02.07.17	-47 %	-69 %	-1 %				-49 %	-
very high	-22 %	4:48	03.07.17			-7 %			-65 %	3 %	-
average	13 %	0:45	07.07.17	-16 %	-29 %				-43 %	21 %	-
high	5 %	1:15	11.07.17	-14 %					-64 %	23 %	-
high	-19 %	4:01	14.08.17	-20 %	-72 %		-68 %	-36 %	-60 %	-48 %	-
high	-14 %	1:54	16.08.17	-52 %	-4 %	-12 %	-18 %	0 %		-4 %	-
high	19 %	0:43	01.09.17				-59 %		-49 %	-2 %	-
high	10 %	1:49	12.09.17	-36 %	-3 %	-41 %	-7 %		-31 %	-1 %	-

high	**-14 %**	2:18	**13.09.17**	**-40 %**	**-34 %**	**-5 %**	**-53 %**			**-10 %**	-
high	**-19 %**	3:26	**15.09.17**			**-57 %**	**-7 %**		**-11 %**	**2 %**	-
high	**-13 %**	3:02	**19.09.17**	**-26 %**	**-23 %**		**-34 %**		**-43 %**	**-7 %**	-
high	**-6 %**	2:28	**20.09.17**							**40 %**	-
average	**-8 %**	2:44	**25.09.17**			**-8 %**	**-5 %**	**-48 %**		**7 %**	-
average	**-12 %**	3:09	**28.09.17**	**-21 %**	**-20 %**		**-21 %**	**-12 %**		**-7 %**	-

APPENDIX G: SIMPLE PRODUCTION SIMULATIONS

This Appendix contains simple simulations of production in a time period of 48 hours. The aim is to show how the WIP storage reacts to different scenarios in converting. The WIP storage starts at 0.59 shift's production at the beginning and the Feeder runs at a steady pace from the start of the time period to the end, producing 17.6 % of unconverted orders daily. The situation with the converting machines varies from running at the average pace over the last 6 months, at average job sizes and average setup times to including average daily unplanned stoppages also. Converter 6 runs in one shift. Some frequently repetitive cases where maintenance stops are planned to the converting machines, bad performance and machine breakdowns are simulated.

Simulation 1 in Figure 23 shows perfect performance by the converting machines meaning that they do only setups and running with no interruptions. The aim is to show that Feeder budget output can be processed in converting if disruptions are eliminated.

Simulation 2 in Figure 24 shows the Feeder running at budget pace, and average daily unplanned stoppages are included in the converting machine performance. WIP level starts exceptionally at 0.29 shift's production. The aim is to show the rate at which the WIP level increases if Feeder is producing at budget pace and converting at average figures.

Simulation 3 in Figure 25 shows converting running average speeds, setup times and average unplanned stoppages. Feeder pace has been fixed to keep the WIP level stable.

Simulation 4 in Figure 26 shows preventive maintenance on Converter 2 from 0:00 - 05:00 and on Converter 1 on 32:00 - 37:00. Converter 2 maintenance affects the WIP level by about 0.15 shift's production.

Simulation 5 in Figure 27 shows preventive maintenance on Converter 5 from 0:00 - 05:00 and on Converter 4 from 32:00 - 37:00. The total effect on WIP level is about 0.29 shift's production.

Simulation 7 in Figure 28 shows bad performance on Converter 1, Converter 4 and Converter 5. The effect on WIP level is about 0.41 shift's production + some starvation on Converter 2 and Converter 3.

Simulation 8 in Figure 29 shows a breakdown of one full shift on Converter 3 and Converter 2. The effect on the WIP level is about 0.35 shift's production.

Data removed for confidentiality reasons.

Figure 23. *Feeder at budget pace and converting at average running speeds, setup times and job sizes, no stoppages*

Table 20. *Production figures of the simulation*

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Data removed for confidentiality reasons.

Figure 24. *Feeder at budget pace and converting at average figures + average stoppages*

Table 21. *Production figures of the simulation*

Data removed for confidentiality reasons.

Data removed for confidentiality reasons.

Figure 25. *Feeder at 85.5 % budget pace and converting at average figures + average stoppages*

Table 22. *Production figures of the simulation*

Data removed for confidentiality reasons.

Data removed for confidentiality reasons.

Figure 26. *Feeder at 85.5 % budget pace and converting at average figures + average stoppages – preventive maintenance on Converter 2 & Converter 1*

Table 23. *Production figures of the simulation*

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Figure 27. *Feeder at 85.5 % budget pace and converting at average figures + average stoppages – preventive maintenance on Converter 5 & Converter 4*

Table 24. *Production figures of the simulation*

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Figure 28. *Feeder at 85.5 % budget pace and converting at average figures + average stoppages – bad performance on Converter 1, Converter 4 & Converter 5*

Table 25. *Production figures of the simulation*

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Data removed for confidentiality reasons.

Figure 29. *Feeder at 85.5 % budget pace and converting at average figures + average stoppages – breakdowns on Converter 2 & Converter 3*

Table 26. *Production figures of the simulation*

Data removed for confidentiality reasons.