Identifying Constraints in Available Production Capacity

An analysis from a production scheduling perspective of a processing facility at Sandvik

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Acknowledgment

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Kristin Egerström and Louise Landin

Abstract

Title

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Background

In 2013, the processing facility West was inaugurated at the Sandvik plant in Svedala. The workshop specializes in machining steel components, which later in the manufacturing process are assembled to stone crushers. In this processing hall, nine different machines perform a variety of machining operations, whereof six are vertical CNC machines. Amongst these six machines, there are some variations in size and mechanical features, but many machines are much alike. To process certain articles, the machines require certain tools and equipment, which are installed by a machine operator, prior to the machining operation.

When the production in West commenced in 2013, the idea was to have a complete set of tools and equipment in all machines, which would make each machine free to produce any type of article, independently of the current jobs running in the other machines. Due to cost benefit reasons, this was, however, not fully implemented, and some tools are shared between multiple machines. This has created insecurity for the production planning at Sandvik, as it is unknown how much the toolset restricts the total production capacity. To avoid the risk of double-booking articles that can not be manufactured at the same time, the Planning and Capacity Department has invested in a new scheduling software, to optimize the production planning. To fully implement this system, all factors that may constrain the production capacity, in terms of tools and equipment, must be identified.

Purpose

The main purpose of this project is to identify the factors that potentially restrict the production capacity in a processing facility at Sandvik, as well as examining how they affect the production efficiency. By recognizing these constraints, the Planning and Capacity Department at the company will be able to optimize the production schedule. A second purpose of this thesis is to provide a recommendation to the company on how to reduce the negative impacts of these constraints.

Research questions

RQ 1. Which constraints related to the production scheduling exist in the processing facility?

RQ 2. What effects do the constraints have on production performance and efficiency?

RQ 3. Which improvements can be made to reduce the impacts of the identified constraints?

Methodology

The research methodology of this master thesis was developed based on the project characteristics, which mainly concerned a problem-solving task. Furthermore, the thesis had elements of descriptive and exploratory studies, which also affected the choice of methodology. To gather information, both interviews and archive analysis were performed. It was also decided to apply several techniques for the data collection, to assure accuracy of the findings. The project was split into three phases, namely preparation, data collection, and analysis. Each phase had a defined output, which was used as a verification that the specific phase had been completed.

Conclusion

The research study showed that three parameters could be concerned as constraining factors for the production in West. All these constraints were physical machining equipment, namely chucks, fixtures, and capture units for toxic gases. The constraints were labeled as such as there was a theoretical risk that the demand for certain equipment would exceed its availability if the planning was not done according to the prevailing equipment capacity. However, the analysis also showed that if the scheduling was done accurately, there would be enough capacity to produce all articles requiring this equipment, given that there was enough time to distribute the production orders before the expected delivery date. For this reason, it was concluded that there is no current need for any further investment analyses. Finally, the most important recommendation to the company was to include the above-mentioned parameters in the new scheduling tool, in order to avoid double-bookings of the identified constraints.

Keywords

Production planning · Production equipment limitations · Constraint management · Theory of Constraints · Single Minute Exchange of Die · Overall Equipment Effectiveness · Toolset capacity

Table of Abbreviations

AOR	Availability-Occupancy Ratio
CM	Cellular Manufacturing
CNC	Computer Numerical Control
DBR	Drum-Buffer-Rope
ERP	Enterprise Resource Planning
FMS	Flexible Manufacturing System
HMS	Hybrid Manufacturing System
MTO	Make To Order
MTS	Make To Stock
OEE	Overall Equipment Effectiveness
SMED	Single Minute Exchange of Die
SWB	Scheduling Workbench
TOC	Theory of Constraints
TPM	Total Production Maintenance

Dictionary

English	Swedish	Explanation
Article	Artikel	Distinct product component that is manufactured in the factory and constitutes a part of the final assembled product. All articles have a unique article number.
Changeover time	Ställtid	Time to prepare a machine to process a batch of a new type of article, which often includes changing equipment inside the machine. The machine is not running during this time and does not perform any value-adding activities.
Capture unit	Utsug	System installed in some machines to trap toxic gases that are generated during the processing of specific iron materials.
Chuck	Chuck	Metal plate used to fixate rotation-symmetric components during processing in a machine.
Constraint	Begränsning	Factors that affect the available production capacity. The term is used synonymously with the word *limitation*.
Detail	Detalj	Specific item of a certain article number. The term is used interchangeably with the words *component* and *part.*
Equipment	Utrustning	General term to describe physical devices used in the production.
Faceplate	Planskiva	Metal plate that is permanently fixated in the machine, onto which the details are attached during the processing.
Fixture	Fixtur	Equipment used to fixate components of any geometry during processing in a machine.
Foundry	Gjuteri	Factory building where components are cast of melted steel.
Horizontal CNC machine	Horisontell CNC-maskin	Processing machine that performs operations on a detail in a horizontal direction.
Jaw	Back	Metal supports that hold the detail in place during processing in a machine. The jaws are either attached to the chuck or directly to the faceplate.
Job	Jobb	The processing activity of one detail.

Net runtime	Total kalkyltid	Estimation of the total fastest operating time to process a certain number of details.
Pallet	Pallet	Same as faceplate but can be transferred in and out of the machine.
Processing facility	Bearbetnings-anläggning	Building in which steel components are machined. The term is used interchangeably with the words *processing hall, machining facility,* and *machining hall*.
Product	Produkt	Completed item that is ready for sales or delivery. Consists of assembled parts.
Setup time	Omställningstid	Time to switch between two processing jobs. i.e. the time when the machine is standing still from the completion of one job until the initialization of the following one.
Stop time	Stopptid	Time when the machine is standing still during available production hours. May be for both necessary and unnecessary reasons, i.e. both machine preparation and breakdowns count as stop time.
Tool	Verktyg	Equipment used to perform processing activities. Examples of tools are drills, cutting tools, mills, and lathes.
Vertical CNC machine	Vertikal CNC-maskin	Processing machine that performs operations on a detail in a vertical direction.

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1. Introduction

The introductory chapter describes the context of the master thesis and the project background. It provides a concise description of the company and the problem formulation. The purpose of the project is further on defined along with three research questions and delimitations. This first chapter ends with a brief description of the disposition of the report.

1.1. Context

Production scheduling allocates resources and processes flow in a manufacturing facility in order to meet the facility's performance criteria. It also helps maximize operational efficiency and is used to support the alleviation of constraints or bottlenecks in a production system by scheduling them to optimize their capacity. An efficient scheduling tool is especially of importance when complex scheduling occurs, such as in facilities with shared resources, parallel activities, or when synchronization of operations is needed (Mejía and Montoya, 2009). This could also happen in facilities where multiple routings are possible or where floating bottlenecks occur.

Multiple routings are common in facilities where machines can process several different types of details. This is the case in a Flexible Manufacturing System, which is a production method consisting of a collection of numerically controlled machines with a multifunction ability which is interconnected by an online network (Chen and Chung, 1996). Scheduling in a system like this becomes complex due to the several different routing options it allows. Shared resources, which according to Krajewski et al. (2019) are commonly used in batch production processes, is another factor that requires a scheduling tool that can optimize their usage. A facility where floating bottlenecks occur, i.e. temporary bottlenecks, requires a scheduling tool that can quickly respond to these changes and that can predict future narrow bottlenecks.

The origin of this thesis is at a plant for heavy industrial manufacturing, in a processing facility that machines steel components. In this type of industry, there are a few processing machines that are placed in a workshop. These machines are used to perform a large variety of machining operations. Some of the processes performed are milling, drilling, and turning. By each machine, there is one operator that is responsible for loading and unloading the machine, as well as running the correct program for the specific job. The operators are also responsible for preparing the machines with the correct set of tools and properly attaching the details to the machine.

The production is done in batches, i.e. several details of the same article type are manufactured in a sequence. The scheduling of the production is based on a combination of specific customer orders and a projected demand forecast. Once the details are completed, they are placed in an inventory before they are treated with some type of protection against rust. The following activities are dependent on the layout of the facility and industry setup. The components could be sold as spare parts or moved to an assembly hall, where the finalized products are constructed.

1.2. Background

Sandvik AB is a global engineering company that operates within tooling systems for metal-cutting and manufacturing of powder-based alloys and advanced stainless steel. The company is active in a variety of industry segments, such as aerospace, energy, and construction sectors. The production site in Svedala, where the project that is subject to this report took place, operates within the area of mining and rock technology. It manufactures and assembles stone crushes for the mining industry.

In 2013, the machining hall West was inaugurated at the Sandvik plant in Svedala. In this facility, three machine groups are currently installed. Each one of these groups consists of three machines, which are operating on a three-shift basis. Two of the groups consist of vertical CNC machines, whilst the machines in the third group are horizontal CNC machines. To produce different products, the machines require various tools and equipment, which are set up by the machine operators prior to machining. At the launch of West, the intention was to rig all the machines with the necessary equipment. Due to financial reasoning, this was however not fully achieved. Therefore, some of the mountable tools are shared between several machines. Furthermore, some equipment is customized for specific products and there is only one such unit in the workshop.

The production order of the manufacturing in West is managed by the Planning and Capacity Department at Sandvik Svedala on a weekly basis. To determine the weekly manufacturing sequences, a manual scheduling tool, called M3, controlled by the Production Manager is used. Complications arise as the scheduler assumes that the set of tools is complete for all machines, i.e. that there occur no limitations in the availability of mountable equipment. The tool also lacks knowledge regarding which articles that share the same production equipment. This entails a risk for planning two production orders at the same time, although it may not be possible to manufacture simultaneously.

During 2020, the aim is to introduce an additional feature in the scheduler which would automatically plan the production sequences after capacity and priority. The new feature would also allow the weekly plan to form a daily sequence schedule. The intention behind adding the new feature in the scheduling tool is to decrease the time spent planning the production sequences and to optimize the efficiency of the production. The new feature should also lower the risk of potential errors when scheduling, as the limitations of produced details may be complex.

1.3. Delimitations

Although three machine groups exist in the processing facility West, only the limitations of the two vertical CNC machine groups will be investigated in this project. This delimitation has been made in order to get a better focus on the two machine groups with the largest amount of possible limitations.

Throughout the project, only limitations in the facility that will affect the scheduling tools will be considered. Other limitations that might risk affecting the lead time but can not be foreseen by the scheduling tool or the planning staff shall be noted but shall not be further investigated. Such unforeseen events may, for example, be a sudden lack of operators.

The project will not consider potential introductions of new details in the production. The reason being that new details seldom gets introduced and that the forecast of future limitations of unknown details would be too complex to map.

1.4. Problem Formulation

To accurately plan the production in West, the production planners at the Planning and Capacity Department must recognize all factors that could affect the available production capacity. Any parameters that affect which articles can be manufactured simultaneously must hence be taken into account in the planning phase, to avoid interruptions in the production. The existing constraints must thus be identified and verified, which is the starting point of this project.

If all constraints are not properly identified, manufacturing jobs that require the same setup of equipment suffer the risk of being scheduled at the same time. If severe overlaps in scheduling occur, in terms of jobs needing to be replanned and postponed, there will be a high risk of delays in the production and consequently in the delivery accuracy. The severity and regularity of delays caused by these constraints need therefore to be identified. Also, the extent to which these parameters cause problems must be analyzed.

To improve the current planning process, a new scheduling tool will be implemented in the factory. This system will optimize the production schedule of the articles when considering the existing constraints that restrain the production capacity. The available machine hours will then be optimally used for value-creating activities, i.e. processing operations. In order to fully implement this tool, all these parameters must be identified.

1.5. Purpose

The purpose of this master thesis is to investigate which factors restrict the production capacity in West, in terms of availability of tools and equipment that are required for various processing operations. The research study aims to further analyze the effect these constraints have on the production efficiency and to which extent they cause delays or other production disruptions. Additionally, the purpose is to suggest future improvements and potentially minor adjustments in the scheduling process, to eliminate the risks of lost machining capacity that these limitations carry. Also, the thesis intents to evaluate if there is a need for any specific investments to improve the production capacity further.

1.6. Research Questions

The report will be centered around three research questions, to fulfill the purpose of the project. The research questions are meant to grasp the aim of the project clearly and concisely, and each chapter throughout the project will be focused on answering them.

RQ 1. Which constraints related to the production scheduling exist in the processing facility?

RQ 2. What effects do the constraints have on production performance and efficiency?

RQ 3. Which improvements can be made to reduce the impacts of the identified constraints?

1.7. Objective

The objective of the project is to establish a more effective and reliable production in West by improving its planning process. By having all constraints and their respective impacts known, the planned production time can be better utilized. This will, in turn, lead to improved value-creating production. The objectives of the master thesis are stated below.

i) Identify and map potential constraints in the processing facility
ii) Evaluate how the constraints affect the production efficiency
iii) Evaluate if any investments would benefit the productivity
iv) Propose improvements to minimize the negative effects of the constraints

Besides the academic report that presents the research, the deliverables of this master thesis are an executive summary as well as an oral presentation of the project. There will be two occasions for the presentation seminars, one at Lund University and one at Sandvik. Furthermore, the project will result in a compilation of all the specific details concerning the constraints and associated articles, which will be handed over directly to the company. The final output of the project is a guide for how the tasks have been carried out. This document will support Sandvik when performing the same analysis in the other processing workshop at the Svedala plant, which is named East.

1.8. Disposition

The structure of this report consists of six chapters. In this section, the content of each chapter will briefly be described.

Chapter 1: The first chapter introduces the project and explains the context of the project, its background and a brief description of the company. The introduction then moves on to describe the problem formulation along with the purpose of the project, research questions, and delimitations.

Chapter 2: In the second chapter, the methodology used for the project is presented. Its research design, strategy, and method are described, as well as the data collection techniques, quality assurance, working procedure, and limitations.

Chapter 3: The third chapter summarizes the theoretical background to the project. The chapter starts by discussing different manufacturing strategies and production concepts. The following subchapter describes how resource utilization can be measured, and which factors are the most critical to measure in a production facility. This chapter ends with theoretical references to constraints management and introduces the Theory of Constraints.

Chapter 4: In chapter four, the empirical study of the project is presented. It summarizes the background of Sandvik as a company as well as the history of the industrial plant in Svedala. Further, it illustrates the layout of the processing facility West and the machines that are the main subject of this thesis. The most central part of the chapter concerns the results from the data collection, which conclude the constraints that potentially could affect production efficiency. The final section of the chapter verifies the constraints that are relevant to consider in the analysis.

Chapter 5: Chapter five presents an analysis of the project findings. The chapter starts with an analysis of the current situation in West. The facility layout is first described, and data over the expected occupancy rate for identified constraints are thereafter presented. Articles that run at the highest rate, so-called high-runners, are identified and analyzed. Thereafter, the manufacturing flexibility of the facility and its importance for alleviating constraints is analyzed. Variations in changeover times and their impact on efficiency are then presented. The chapter ends with an analysis of the current need for investments.

Chapter 6: In chapter six, the research questions formulated in the introductory chapter are answered. The conclusions refer to the information obtained in the empirical study and the results of the thesis analysis. The chapter also concludes a recommendation to the company, both related to future work and other improvements related to the scheduling of the production in West.

Chapter 7: The seventh and final chapter discusses the findings and results of the thesis. It enlightens new perspectives on the project and how the task was carried out. The discussion also reflects upon future work and how to perform similar work in another factory. Furthermore, the chapter reviews potential sources of errors that could be of importance for the interpretation of the project results.

2. Methodology

This chapter presents the methodology used to carry out this master thesis project, which is formed by the research design. First, the research strategy behind the work is described, which in the following section is used to determine appropriate research methods for the study. Next, two techniques for data collection are introduced, which relate to the chosen methodologies. The quality assurance of the work is then presented, followed by a description of the working procedure. In the final section, the limitations of the project methodology are brought up.

2.1. Research Design

The research design is the general approach that is used in a project, which is necessary to answer the research questions. It is formed based on these questions and will include explicit objectives for the study. Furthermore, the research design will present the sources for the data collection, as well as how to find and analyze the information. The design is a verification that the outline of the research is planned and carefully thought through, prior to the start of the data collection (Saunders, Lewis and Thornhill, 2016). Each aspect of the design will be presented in the following sections of this chapter.

2.2. Research Strategy

According to Runeson and Höst (2008), different research methodologies are suitable for serving various purposes. Before determining which method to apply to this master thesis, it is hence necessary to reflect on the overall project characteristics and the major project objectives. Runeson et al. (2008) suggest that a research project can be categorized as four different types of studies, namely as a descriptive, exploratory, explanatory or problem-solving study. This is based on Robson's classification of the purposes of inquiry (2002). These types are briefly presented in bullet points below.

- *Descriptive* studies aim to examine and describe a situation or phenomenon.
- *Exploratory* studies seek to understand in-depth how something works or is performed.
- *Explanatory* studies search for casualties and explanations of a situation or a problem.
- *Problem-solving* studies intend to solve an identified issue and improve an existing situation.

The project that is the subject for this report is mainly a problem-solving study, although there are also descriptive and exploratory elements. More precisely, the first part of the project is a descriptive study, as the current situation must be outlined to obtain the foundation of the project. The second phase concerns exploratory research, which includes a thorough analysis of the production process, from the planning at the Planning and Capacity Department to the physical execution in the processing hall. The major project task can commence once these two steps are accomplished, which is to improve the current system and to suggest how the identified problems could be solved, i.e. to perform the problem-solving study.

2.3. Research Method

Höst et al. (2006) conclude that there are four common methods for master thesis work within the area of applied science, which should be considered when deciding the type of methodology. These are surveys, case studies, experiments, and action research. A brief explanation of each method is presented below.

- *Survey* is a method that compiles standardized information from a specific population, which often is implemented by using questionnaires or interviews.
- *Case study* concerns an empirical method that seeks to in-depth investigate one or multiple situations or phenomena. This method presumes that minimal impact is made by the researcher on the studied object.
- *Experiment* regards a comparison of two or more alternatives, where a few factors are isolated, and one is manipulated, and the effects are measured.
- *Action research* aims to change or influence the situation that is the subject of the research study.

For the different methods, the empirical data collection may be of either a quantitative or a qualitative character. Whilst quantitative data regards numbers and classes, qualitative concerns descriptions and pictures (Runeson et al., 2008). Two methods that use quantitative primary data are surveys and experiments. Case studies and action research are usually characterized by qualitative primary data.

Another attribute that varies for the different methods is the design, which may be fixed or flexible. A fixed design is when the research questions are set and defined at the start of the project. A flexible design, on the contrary, concerns researches that develop gradually as the project progresses (Höst et al., 2006). Surveys and experiments are in general methods of a fixed nature, while case studies and action research are more flexible in the design.

As stated in the previous subchapter, the choice of methodology is dependent on the nature of the project. Höst et al. (2006) suggest that each methodology relates to a specific project purpose, i.e. either descriptive, exploratory, explanatory or problem-solving studies. An overview of the methodology characteristics and their respective objectives is presented in Table 2.1 below.

Table 2.1. Research methodology characteristics (source: Authors; developed from: Runeson et al., 2008)

Methodology	Primary objective	Primary data	Design
Survey	Descriptive	Quantitative	Fixed
Case study	Exploratory	Qualitative	Flexible
Experiment	Explanatory	Quantitative	Fixed
Action research	Problem-solving	Qualitative	Flexible

As the three most relevant objectives of this project are to perform descriptive, exploratory and problem-solving studies, this master thesis will include elements of several methods. As presented in the table above, the most appropriate methods are thereby survey, case study, and action research.

2.4. Data Collection Techniques

To carry out the various methodologies related to a project, a number of techniques for data collection may be applied. Based on the research strategy of this master thesis, two techniques mentioned by Höst et al. (2006) are more relevant to use, namely interviews and archive analysis. These are presented in the following sections.

2.4.1. Interviews

Data collection through interviews is more or less structured questionings on a certain topic, which is of interest to the research. The different approaches are used for various purposes of a study. According to Robson (2002), the interview styles can be divided into three categories, which are unstructured, semi-structured, and fully structured interviews. In an unstructured interview, the questions are asked as broad and general concerns. The conversation will consequently take form depending on the interviewee, as people with different backgrounds have various knowledge and are unequally interested in talking about certain subjects. A fully structured interview is, on the contrary, based on outlined questions that appear in the same order for all interviews, as in a survey based on questionnaires. In the case of a semi-structured interview, the questions are planned, as in a fully structured interview, but the order may vary in different interview situations. This structure allows both improvisation and deeper exploration of a subject while ensuring that all questions have been covered during the interview (Runeson et al., 2008). A summary of the different interview techniques is presented in Table 2.2 below.

Table 2.2. Summary of interview techniques (source: Authors; developed from: Runeson et al., 2008)

Methodology	Unstructured	Semi-structured	Fully structured
Typical focus	How individuals qualitatively experience the phenomenon	How individuals qualitatively and quantitatively experience the phenomenon	Researcher seeks to find relations between constructs
Interview questions	Interview guide with areas to focus on	Mix of open and closed questions	Closed questions
Objective	Exploratory	Descriptive and explanatory	Descriptive and explanatory

To collect information about the operators' working experience in West, interviews will be carried out. The objective of the interviews is to gather information about which issues the workers consider to be limiting factors. As the aim will be both to confirm that the identified limitations are accurate as well as to investigate if there are additional ones, the interview has both a qualitative and quantitative purpose. As supported by Saunders et al. (2016), the interview form should, thereby, be semi-structured. This will allow both open and closed questions to be asked. In addition to the prepared interview sessions, the information will be gathered from unplanned meetings and discussions with employees at the company. This could be described as spontaneous unstructured interviews.

2.4.2. Archive Analysis

Archival data refers to documentation that exists independently from the specific research and for other reasons than to be used in the ongoing study. This means that the document may contain more material than what is relevant for the current project, or only parts of the sought information. Furthermore, archival data is not structured as data but is rather organized as project documentation or a meeting protocol. For this reason, it is important to carefully validate the data and to examine its relevance for the project. (Höst et al., 2006)

The archive analysis that will be performed in this project is based on technical documentation from the processing facility West. This includes Excel-files with article machining data and registers over production volumes. One of the most important documents for the project concerns a list of all articles that are produced in West and their respective production equipment used during the processing. Furthermore, some archival data is found in the scheduling software system M3 and in the machine surveillance program RS Production.

2.5. Quality Assurance

To assure that the results obtained in a project are accurate, some potential risks should be considered and avoided throughout the work. Höst et al. (2006) conclude that a study may have credibility in different aspects, and present three categories of legitimacy. These categories are reliability, validity, and representativity. The essences of the first two categories, i.e. reliability and validity, are presented under their respective subheading below, as well as how they relate to the current project. The representativity, however, relates to projects that aim to propose solutions for general situations, which is not the objective of this thesis. For this reason, this quality aspect will not be further discussed.

2.5.1. Reliability

Reliability regards the extent to which different research methods generate consistent results, concerning random variations in the data collection. If a research method produces equivalent results repeatedly, it is thereby considered as reliable. A precondition to this reliability is that all measurements have been performed under the same conditions. (Höst et al., 2006)

Saunders et al. (2016) make a distinction between internal and external reliability. According to their definition, internal reliability concerns the consistency of the research project. This reliability may be ensured by involving several researchers in the project, who will conduct interviews or observations independently. By comparing the researchers' data and analyses, the reliability may be evaluated. External reliability regards, on the other hand, if the data collection technique would produce accurate results in another situation. Two examples of such a variation are if the research would be performed by another researcher or take place on another occasion. It is important to avoid the risks of unreliable data, as a collection of wrong information will bring inaccurate results and interpretations. Saunders et al. (2016) mention four major threats to research reliability, which are summarized in Table 2.3.

Table 2.3. Summary of threats to reliability (source: Authors; developed from: Saunders et al., 2008)

Threat	Definition and explanation
Participant error	Any factor that could negatively affect how a participant answers or performs. For example, if the interview takes place when the participant is unrested or hungry.
Participant bias	Any factor that could generate false answers from the participant. For example, if the participant is afraid of not being anonymous and thereby gives inaccurate positive answers.
Researcher error	Any factor that could affect the researcher's interpretation. For example, if the researcher is not attentive or does not understand the subtle meanings of an answer.
Researcher bias	Any factor that could alter the researcher's reporting of the answers. For example, if the researcher has motives to find certain explanations or has a subjective view of the situation.

In this project, it is necessary to consider the reliability in all stages of the data collection. It will be especially important to recognize the potential threats during the interviews with the working staff in West. The participant error is a potential risk, as the workshop employees have physically demanding jobs and may be stressed, tired or hungry at various times of their workdays. Also, the participant bias could be a risk factor, since the operators know that the current project potentially could generate an equipment investment in the facility, which could lie in their interests. Thereby, they could have incentives to portray their working situation in various ways.

Regarding the threat of researcher errors, it is positive that the project is done in a pair of two, as this means that the data is always analyzed twice by different individuals. As for the researcher bias, this is a smaller risk, as none of the authors of this report is involved in the company or have any incentives to manipulate the results. However, it is always important to question preconceptions and subjective ideas of how things work, although there are no personal reasons for affecting the project outcome.

2.5.2. Validity

The validity of a research project regards the relation between the objective of the study and the research that is done. Consequently, for a data collection to be valid, it must measure what the study aims to analyze or explain. Similar to the reliability concept, the validity aspect may be categorized as internal or external. The internal validity determines if there is a correlation between two variables in a specific scenario. External validity demonstrates if there is any general relevance for the findings of the research, which are applicable in another situation (Saunders et al., 2016). In this study, internal validity is the most relevant aspect to consider, as it does not lie within the scope of the project to apply the results to a general situation.

To reduce the risk of invalid data collection, which in turn brings incorrect results, Höst et al. (2006) suggest a technique named triangulation. In short, this approach means to use different methods for studying the object or phenomenon that is the subject of a certain research project. This technique is also recommended by Saunders et al. (2016), who elaborate it and establish that by using at least two independent sources or methods of data collection, the validity will be increased. In this thesis, multiple methods will be used to avoid the risk of invalidity. One of the most crucial parts of the project includes mapping the equipment limitations in West, which will be done by interviews with the operators as well as archival analyses. Furthermore, the number of interviews will be as many as is required to find convergence in the answers. In other words, when no new information appears, the data collected from the interviews will be considered as finished.

Another technique to reduce invalidity is participant validation, which also is proposed by Saunders et al. (2016). This involves confirming the accuracy of the research data by sending it back to the participants of the study. Thereby, errors or mistakes may be identified and corrected. In this project, this will be done iteratively, as new findings will be sent back for confirmation both to the staff in West and to responsible employees at the Planning and Capacity Department.

2.6. Working Procedure

To carry out the objectives of this master thesis, the work will be done in three distinct phases. These are a preparation phase, a data collection phase, and an analysis phase. Each one is characterized by its internal purpose and expected output. Table 2.4 presents a concise description of the contents of each phase, their respective purposes, and outputs. In the subsequent sections, the stages will be described more in detail.

Table 2.4. A brief overview of the project phases (source: Authors)

Phase 1: Preparation	**Phase 2: Data collection**	**Phase 3: Analysis**
1. Perform background research 2. Formulate research questions 3. Establish an interview guide 4. Compile theoretical references	5. Complete interviews 6. Collect archival data 7. Verify accuracy of the findings 8. Define the current situation	9. Rank the constraints 10. Select prioritized findings 11. Develop solutions 12. Propose recommendation
Purpose: Plan the project and complete a theoretical foundation.	**Purpose**: Collect the empirical data and validate the findings.	**Purpose**: Develop, motivate and evaluate solutions.
Output: Research questions and interview guide.	**Output**: Compilation of verified data and situation analysis.	**Output**: Recommendation to the company.

2.6.1. Preparation Phase

The first step of the working process will be to initiate background research of the subject. This includes collecting information from the company about the current situation and the previously experienced problems, which is required to set the project objectives. This allows the research questions to be formulated and the expected outcome of the research will thereby be specified. Next, the interview guide for the empirical data collection will be developed. The final step of the first project phase is to collect the related theory to the research, which will be done by literature studies. The purpose of the preparation phase is to plan the work and to connect the project to a theoretical context. The specific output will thereby be the research questions and the interview guide.

2.6.2. Data Collection Phase

In the second phase, both qualitative and quantitative data will be collected for the empirical study. This concerns completion of interviews and analyses of archival data, which will be searched for in documents and Excel files from the company. Once the information is gathered, it will be revised and verified from other sources, to finalize the quality assurance. Thereby, the current situation compilation can be completed. The purpose of the data collection phase is to compile and verify the empirical data. The outputs are the results from the empirical data collection, i.e. the verified empirical data, and a description of the current situation.

2.6.3. Analysis Phase

The final phase will be initiated by ranking the constraints found in the previous phase. This will be based on their relevance to the project and the feasibility of potential solutions. The constraints that are classified as high-priority will then be selected to conclude future improvements. The two last steps will then be to develop solutions and to suggest recommended actions to the company, based on both empirical and theoretical research. The purpose of the analysis phase is to generate qualified solutions to the problem. The output of the final phase will be a recommendation to the company, such as an investment proposal or a suggested action plan.

2.7. Limitations

There are potential limitations that are important to recognize and take into account when determining the extent of the data collection process. One aspect concerns the identification of potential constraints by the interview methodology, as there is no definite way of determining when all information has been gathered. It has been determined to perform as many semi-structured interviews as necessary to obtain convergence in the answers. This means that as long as new potential constraints are identified from the answers, more interviews will be performed.

Another action to prevent a one-sided view of the problem is to interview a variety of people. That is, talking to employees that work in different departments and have different perspectives on the situation. During the first period of the project, there will be several unstructured interviews with people working in the production hall with both the physical processing and management of the production, as well as staff at the Planning and Capacity Department.

3. Theoretical References

The theoretical background of the project will be presented in this chapter. In the first subchapter, a general overview of how manufacturing strategies will correspond to different types of production. Thereafter, four types of manufacturing methods will be described. In the following subchapter, a technique to measure the utilization of resources in manufacturing facilities is described. In the last subchapter, the principles behind constraints, how they are defined and how they can be identified, are further investigated with the help of the Theory of Constraints.

3.1. Monitoring Fabrication

3.1.1. Product-Process Matrix

Manufacturing strategy can according to Samson (1991) be defined as competing priorities and key decisions taken in a manufacturing system to gain a comparative advantage. The manufacturing strategy of an organization can be decided by analyzing which position in the product-process matrix it has. The product-process matrix was first introduced by Hayes and Wheelwright (1979) and is a tool used to analyze the best suitable manufacturing process for a certain product. The matrix is presented in Figure 3.1.

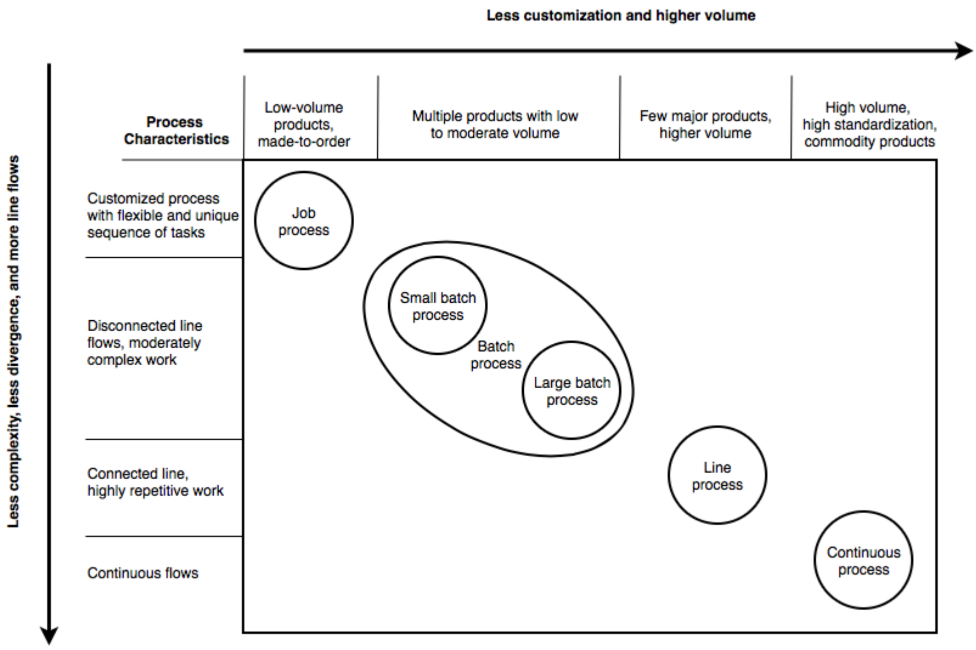

Figure 3.1. Product-process matrix (source: Authors; developed from: Krajewski et al., 2019)

The matrix brings together three elements; volume, product customization, and process characteristics. The position in the matrix gives a good indication of the organization's weaknesses and strengths; an organization will have difficulties performing optimally when incorrectly positioned. In the product-process matrix, Hayes and Wheelwright (1979) describe four ways of organizing the resources around the process, which are called process choices. These four process choices are presented in bullet points below.

- Job process
- Batch process
- Line process
- Continuous-flow process

According to Krajewski et al. (2019), in a job process, products are manufactured to specific customer orders. This is called a make-to-order (MTO) strategy. These products are highly customized and are made in low volumes. A highly flexible manufacturing process is required in a job process due to the unique operations for each specific order.

Batch processes are the most common process choice in manufacturing organizations. Products produced in batch processes are often MTO. Since the same or similar parts are produced repeatedly, products are made in higher volumes in batch processes compared to job processes. Its process flow is, therefore, less flexible. Batch processes are distinguished as small batches or large batches, depending on the product volume and customization. Large batch processes may run more efficiently than small ones, as their frequency of changeovers and setups are lower. Although, small-batch processes are more flexible and do not require as large inventories as large-batch processes do. Shared resources for batch processes are common. They are therefore often more complex to plan and schedule, as shared resources need to be taken into account.

In a line process, volume and standardization are high. This allows resources to be centered around the products, and equipment is often specialized for the product. Low inventory is held between the operations as divergence in the production is low. Line processes are often a make-to-stock (MTS) manufacturing strategy, where finished goods await in stock until the customers place an order.

A continuous-flow process is a high-volume standardized production with rigid set line flows and no divergence. The name derives from the way material moves through its process, commonly a liquid, a gas or a powder. In a continuous-flow process, the material never stops until a whole batch is finished.

The material will thus always be in a value-creating activity and never in inventory. This is the main difference when comparing a continuous-flow process to a line flow.

3.1.2. SMED

Single Minute Exchange of Die (SMED) is a Lean production method focused on reducing waste in a manufacturing process by minimizing changeover times. The method was introduced by Shingo in 1985 as a result of theoretical and practical examinations of setup improvement. Since its first introduction, it has been acknowledged and widely adopted by industries that are trying to improve their manufacturing practice (McIntosh et al., 2000).

The name, Single Minute Exchange of Die, derives from the goal of reducing changeover times to a single-digit number of minutes, i.e. less than 10 minutes (McIntosh et al., 2000). Changeovers can be defined as the time it takes to change a machine from producing one product to producing another. The term should not be confused with the notion of setup time. Bicheno and Matthias Holweg (2009) defines the setup time as the time it takes to prepare a manufacturing process for production. An example would be the adjustment of equipment that corresponds to the product. Both setup and changeover times are non-value-adding operations, and can both be reduced by using SMED.

The main idea behind SMED is to reduce the changeover times by converting internal operations to external. Internal operations refer to tasks that need to be performed when the machine is not running. External operations can, on the other hand, be completed while the machine is running. Since external elements can be prepared while a machine is still operating, they make the process more effective. (Shingo, 1985) The diagram in Figure 3.2 gives an overview of the production speed during internal and external operations.

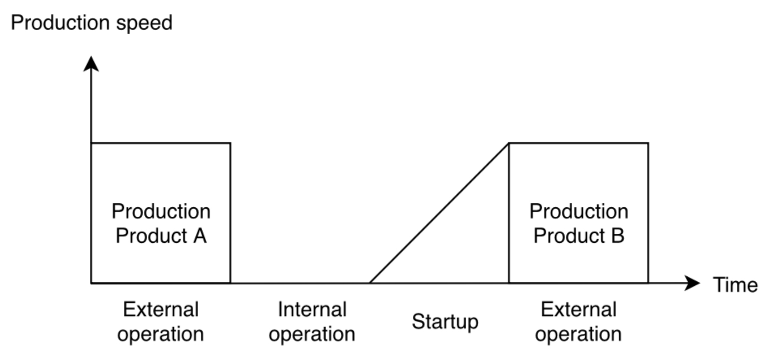

Figure 3.2. Production speed during internal and external operations (source: Authors)

Although operations may vary infinitely depending on the type of equipment and on the specific setting the operation occurs in, Shingo (1985) argues that the basic setup principles can still be made up of a certain sequence of operations. These steps and time distribution are shown in Table 3.1 below.

Table 3.1. Steps and time distribution in a setup process (Shingo, 1985)

Step	Operation	Proportion of time
1	Preparation, after-process adjustment, and checking of raw material, jigs, etc.	30 %
2	Mounting and removing tools, etc.	5 %
3	Centering, dimensioning and setting of other conditions	15 %
4	Trial runs and adjustments	50 %

The first step makes sure that all parts and tools are in the right place and that they are functioning properly. This step also involves the after-processing time when used items are removed, returned and the machine is cleaned, etc. The second step includes the time it takes to mount parts and tools up and down, before and after processing. In step three, centering, dimensioning and setting of other conditions, refers to operations, such as centering, which are necessary to perform the production operation. In the fourth step, trial runs and adjustments are made after a test piece has been produced. This step depends to a great extent on the skills of the operator. Most difficulties in a setup operation concern correct adjusting equipment. The high time proportion in this setup, 50 %, derives from adjustment problems.

According to Shingo (1985), one of the main reasons why machines remain idle, i.e. runs empty, is due to the lack of understanding of internal and external operations. To accurately identify them, the actual shop floor conditions must be studied in detail. A continuous production analysis may be performed with timing with a stopwatch, work sampling study, interviews or videotaping the procedure. Although some of the methods may lead to more accurate results than others, Shingo (1985) emphasizes that informal observations and discussions with workers are often enough for an accurate result.

The SMED concept can be described with four conceptual stages. The first stage, called Stage 0 or Primarily Stage, merely describes the as-if-situation of the targeted manufacturing company that ought to use SMED. The remaining three stages describe how the improvement process should be implemented. The implementation is an iterative process and Stage 1 - 3 should be done in the order best suited for the specific situation. If necessary, some steps may even be executed simultaneously. The stages are further described below.

➢ *Stage 0: Internal and external setup conditions are not distinguished*

This stage mainly states the current situation of the company and points out why the setup conditions are not properly distinguished. According to Shingo (1985), the best practice of setups is often left to be resolved on the shop floor by the operators themselves. This is due to the assumption that employees want to perform well, and setups will therefore automatically be performed as quickly as possible. Although this assumption might be accurate, the optimal setup procedure remains in this case unverified.

➢ *Stage 1: Separating Internal and External Setup*

In this stage, all setup operations should be determined and identified. They should then be distinguished as internal or external. This stage is according to Shingo (1985) the most crucial stage in the implementation of SMED.

➢ *Stage 2: Converting Internal to External Setup*

Each internal operation should in this stage be analyzed to determine the possibility for them to be converted to external operations. It is important to encourage new perspectives and ways of thinking in this stage, as setups that could be made external are often wrongly assumed to be internal. The true function of the internal operation should, for this reason, be re-examined yet another time.

➢ *Stage 3: Streamlining All Aspects of the Setup Operation*

Converting the majority of the operations into external may not be enough to reach the goal of a single-digit number of minutes changeover time. Each elemental setup operation, internal or external, should be streamlined to help support the goal. Streamlining of setup operations is made possible through simplifying, reducing and eliminating movement. An example of this is shown in Figure 3.3 The figure shows movement diagrams before and after implementing SMED in a case study (Van Goubergen and Van Landeghem, 2002).

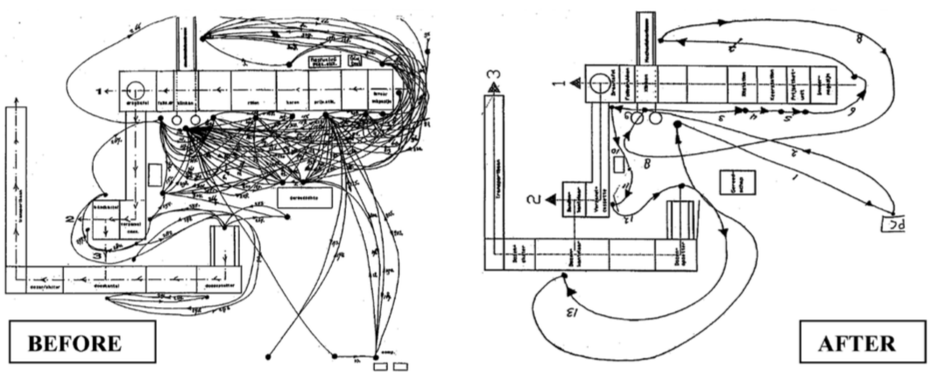

Figure 3.3. Movement diagram before and after SMED (source: Van Goubergen and Van Landeghem, 2002)

3.1.3. Cellular Manufacturing

Cellular manufacturing (CM) is a manufacturing method that makes sure that similar products are manufactured together (Singh, 1993). Similar parts are first grouped into families based on their design and production requirements. They are then produced in a specific cluster of manufacturing processes suited for that specific family of parts. These clusters of manufacturing processes are called cells. An efficient cell has all the required equipment and supplies needed to complete the process of the family. When using cellular manufacturing, the entire manufacturing facility is divided into several groups of cells, a cell layout. An example of how a cell layout can look like is shown in Figure 3.4. The nodes represent operations required to produce a certain product.

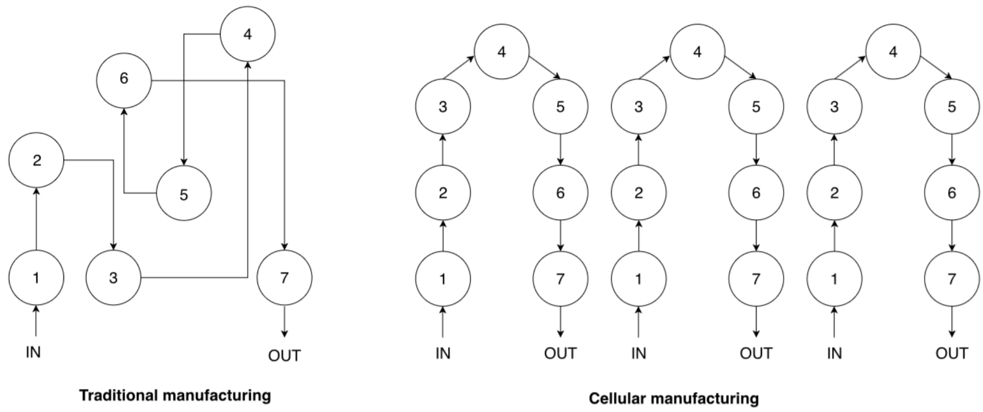

Figure 3.4. Facility layout in traditional versus cellular manufacturing (source: Authors)

Customized products, increasing and unpredictable customer demands are the main reasons behind the growing need for cellular manufacturing. These are demands traditional manufacturing systems have difficulties responding to. Organizing a facility into cells according to cellular manufacturing reduces the setup time, as operations similar to one another may be performed more efficiently when grouped (Mungwattana, 2000). Similar parts tend to have the same tool requirements, which reduces the number of setups of tools as well.

3.1.4. Hybrid Manufacturing

Hybrid manufacturing, or hybrid processes, is a production method that combines machines or processes to achieve a more efficient and productive way of producing parts. (Lauwers et al., 2014) The term hybrid is in this context used to identify processes that combine several different types of technologies. An example of a hybrid process is a multi-tasking machine, also called a hybrid machine. In Figure 3.5, a hybrid machine of this kind is shown. In the curved profile extrusion, the extrusion and bending are combined. Operations such as these would with traditional manufacturing techniques be done separately.

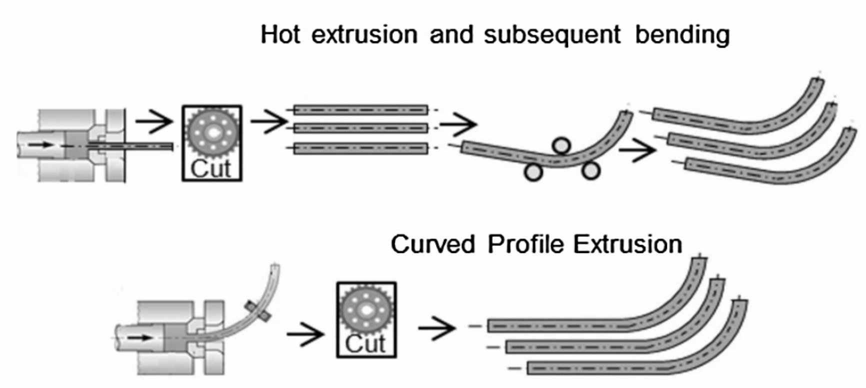

Figure 3.5. Comparison of traditional versus hybrid manufacturing (source: Lauwers et al., 2014)

3.1.5. Flexible Manufacturing

3.1.5.1. Flexible Manufacturing System

Flexible Manufacturing System (FMS) is a production system designed to allow flexibility in a manufacturing system. These changes can either be expected or unexpected, such as a change in production volume due to uncertain demands, variations in process sequences or changes of certain parts being manufactured (Nilsson, 1992). FMS can be described as an automated machine cell that consists of a group of multifunctioning processing workstations which are interconnected by an online network. The whole system is controlled and directed by this network. (Chen and Chung, 1996)

FMS is mainly used by facilities with a batch or a job shop production. It is an especially useful tool when working with MTO strategies. Two kinds of equipment are used in batch producing facilities using FMS; either dedicated machinery tools or unautomated general-purpose tools. The dedicated machinery tools result in increased flexibility but add some cost savings. General purpose machines such as milling machines, drills or lathes are more expensive and less efficient as the dedicated machinery tools but provide more flexibility. FMS often falls under two subcategories; routing flexibility and machine flexibility. Routing flexibility refers to a system's ability to be changed to produce new product types or changed operations on existing parts. Machine flexibility refers to the system's ability to adapt to larger scale changes such as change in volume or capacity, as well as its ability to perform the same operation of multiple different machines in a facility (Rufe, 2013). FMS allows several alternative routings as multiple machines are able to perform the same operations; one operation on a part can be scheduled in several different machines. According to Mejía and Montoya (2009), this complex scheduling is one of the potential operational issues when using FMS and calls for well-developed scheduling tools.

According to Swamidass and Newell (1987), the FMS concept is important for companies' performance, mainly due to recent shorter product-life-cycles and to a more rapid pace of new product introductions. An increasing number of shared resources in facilities, such as shared machines and equipment, has furthermore made the concept of flexible manufacturing even more relevant for manufacturing facilities (Van Goubergen and Van Landeghem, 2002).

3.1.5.2. Measuring Flexibility

Flexibility is often considered as an intangible due to its difficulties to measure (Nilsson, 1992). An attempt was made by Slack (1983) to develop a framework to measure flexibility in manufacturing systems. The work concluded that measuring flexibility in a manufacturing system is a complex task due to three main reasons:

i) It is a measure of potential rather than performance.

ii) There can be no single measure of flexibility applied to all production objectives, such as product specification, quality, volume, and delivery.

iii) It has three dimensions; range, cost and time.

The importance of having short setup times and effective changeover performance has been argued to be the main prerequisites for improving flexibility by several researchers (McIntosh et al., 2001). This is especially of importance when trying to enhance mix flexibility, i.e. being able to efficiently produce several different types of parts or products in the same facility (Bateman et al., 1999).

Slack (1983) suggests an approach for FMS modeling, an approach that should be developed as follows:

- ➢ Assess the types of flexibility which are important to a particular production system, i.e. assess the most likely new demands which could be placed on the system.
- ➢ Audit the capability of the system to react to these new demands.
- ➢ Identify where the system would fail to meet these new demands.
- ➢ Identify ways and costs of providing any new flexibility.

3.2. Overall Equipment Effectiveness

Total Production Maintenance (TPM) is a manufacturing concept first introduced by Nikajima (1988). The main object of the TMP concept is to increase equipment productivity by achieving zero breakdowns and zero defects related to equipment. By keeping equipment in top condition, the production stands a larger chance of running smoothly and efficiently, and thereby increases the equipment productivity.

Overall Equipment Effectiveness (OEE) is one of the tools used to help TMP calculate equipment performance. OEE is a bottom-up approach that measures production effectiveness for individual equipment by identifying losses that reduce equipment effectiveness. These losses are defined as activities that occupy resources but create no additional value. (Muchiri and Pintelon, 2008)

Nakajima (1988) describes six large losses that can be identified when measuring OEE. The losses are divided into three factors; availability, performance and quality rate. Each factor has two associated losses, resulting in the six large losses, which are presented in Table 3.2 below.

Table 3.2. The six big losses (source: Authors; developed from Nakajima, 1988)

Factor	**Loss**	**Cause**
Availability	Equipment failure and breakdown	Unexpected failures or breakdowns in the equipment
	Setup and adjustment	Changes in production requirements during changeovers
Performance	Running at reduced speed	Reduced operational speed due to inept equipment design
	Minor stops and idling	Interruptions due to unexpected temporary malfunctions or empty running machines
Quality	Quality defect and reworks	Inadequate quality caused by malfunctioning production equipment
	Reduced yield during startup	Longer start-up time than usual for machines

The six large losses make up the OEE measuring tool, which is a function of availability (A), performance (P) and quality rate (Q). A 100 % OEE rate means that goods are produced at maximum speed (performance) with the highest quality (quality rate) without any interruptions (availability). It can be calculated using Equation 1 below. The loading time represents the scheduled operation time, and the downtime represents unscheduled operation time, such as equipment failures.

(Eq. 1) $OEE = A \cdot P \cdot Q$

where:

(Eq. 2) $Availability\ rate\ (A) = \frac{Operating\ time\ (h)}{Scheduled\ time\ (h)} \cdot 100$

(Eq. 3) $Performance\ efficiency\ (P) = \frac{Theoretical\ cycle\ time\ (h/units) \cdot Actual\ output\ (units)}{Operating\ time\ (h)} \cdot 100$

(Eq. 4) $Quality\ rate\ (Q) = \frac{Total\ production\ (units) - Defect\ amount\ (units)}{Total\ production\ (units)} \cdot 100$

3.3. Constraints Management

3.3.1. Theory of Constraints

Theory of Constraints (TOC) is a systematic management method used to manage constraints that disrupt an organization's progress towards a goal (Krajewski et al., 2019). The method outlines a process for identifying and relieving constraints and helps increase organizations' profits by making materials flow rapidly through entire process systems.

A constraint is defined by Krajewski et al. (2019) as any factor that limits the output of a system in an organization. A constraint could, for example, be the lack of capital, equipment or planning. When constraints exist, there is a risk that the capacity becomes unbalanced and the overall performance of the system is worsened. Constraints can be either internal or external. Its nature depends on the organizations' relation to the market. If the system within the organization can produce more than the market requires, the constraint is referred to as external. The constraint is referred to as internal when the opposite occurs; when the system can not produce enough to support the market. Common causes of internal constraints are:

- ➢ *Equipment*: Relates to machine, labor or workstations which limits the system capacity
- ➢ *People*: Relates to the lack of skilled people or behavior constraints
- ➢ *Policies*: Relates to written or unwritten policies that might prevent the output

A bottleneck is a type of constraint whose available capacity limits the organization's ability to meet the product volume. The most significant difference between a bottleneck and constraint is that bottleneck refers to a limited resource that can not correspond to the market's demand. A constraint, on the other hand, is a limiting factor that does not correspond to an organization's desired performance. A floating bottleneck is a type of bottleneck that occurs when there is high variability in workload and demands of different operations with non-identical capacities may vary from one day to another. This type of variability increases the complexity of day-to-day scheduling.

Although constraints risk lowering capacity, it is of great importance that a business process has at least one constraint. If nothing prevents a system from producing higher output, the output would, in theory, be infinite. Translated to a real-life system, this would mean that the output would be controlled by the market, which is an undesirable trait. When a constraint's throughput capacity is increased to a point when it is no longer a limiting factor, a so-called "break" in the constraint has occurred. A breakdown, e.g. unexpectedly maintenance stops, should not be confused for a constraint. A breakdown disrupts the throughput unexpectedly only at certain times, whilst a constraint always limits the throughput.

According to Krajewski et al. (2019), the implementation of the practices of the Theory of Constraints should follow the steps below. The steps can also be viewed in Figure 3.6.

1. *Identify the constraint*: Find factors that may be a capacity constraint.
2. *Exploit the constraint*: Schedule the production so that throughput of the bottlenecks will be maximized.
3. *Subordinate all other decisions to constraint*: Non-bottleneck resources should be scheduled in order to support the bottlenecks.
4. *Elevate the constraint*: If the bottlenecks are still constraints after Step 2 and 3, the capacity of the bottlenecks should be increased. This could, for example, be accomplished through an investment.
5. *Do not let inertia set in*: System constraints may shift when other constraints get relieved. Step 1 to 4 must be repeated after a change in order to identify and manage new potential constraints.

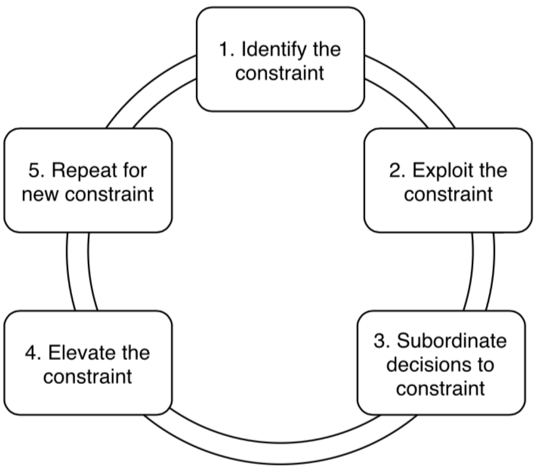

Figure 3.6. Implementation of Theory of Constraints (source: Authors; developed from Krajewski et al., 2019)

A common application that is based on the Theory of Constraints is the drum-buffer-rope (DBR) system. DBR is a planning and control method used to schedule manufacturing processes by regulating the flow of work-in-process materials at capacity-constrained resources. The main idea of the methodology is that the output of a system can never be higher than the tightest bottleneck of a system. Any attempt to produce a higher volume than a bottleneck may allow will lead to excessive inventory.

The bottleneck is referred to as the drum as it sets the beat for the production rate. The drumbeat is thus the highest rate a plant can produce goods when the bottleneck is at its maximized capacity. The buffer in DBR protects the bottleneck from disruption as it plans early flows to the bottleneck and makes sure its capacity is maximized at all times. Lastly, the rope ties the output to the drumbeat. It makes sure the throughput rate of the plant corresponds to the market demand.

3.3.2. Constraints Identification

The identification and management of bottlenecks will differ from the organization's manufacturing process structure (Krajewski et al., 2019). The bottleneck typically tends to lie in the operation with the highest total time per unit processed when the setup time in a manufacturing process is long. It tends to get more difficult as the process gets longer and more complex. Where a bottleneck lies in a manufacturing process can be identified in two ways. Either, it has the highest total time per unit processes, or, it has the highest average utilization and total workload. Bottlenecks should be addressed by either:

i) Take on new customer orders to maximize bottleneck capacity
ii) Schedule bottleneck to maximize its capacity

3.4. Application of Theory

The theory will act as a support for the empirical study and the analysis of the project. It is meant to provide a broad aspect of topics related to the main focus of the project, namely the scheduling-related constraints. Topics including manufacturing strategies, performance measurement, constraint management, and improvement strategies have been brought up in the theory. These subjects are all used to build an understanding of the formulated problem and guidance towards a solution.

Manufacturing strategies such as the product-process matrix, flexible manufacturing system, and cellular manufacturing, are used to provide an overall comprehensiveness of the facility layout and production structure. They are also used to help understand any potential cause-and-effect relationships in the facility, which might be found when analyzing constraints later on. As these topics are based on soft values, they will be collected through structured and unstructured interviews. The performance measurement tool OEE will be used to understand the equipment efficiency related to identified constraints. The performance data will mainly be gathered from archival data. If any lack of data occurs, the information will be provided through interviews. The identification of constraints will follow the implementation steps according to the theory of constraints. The data which will back up its implementation will first be collected through interviews, and then verified through archival data or through second options. Open questions in the interviews will be asked in the empirical study to explore areas of improvement. The theory behind the SMED methods provides an insight into the potential benefits of improvement strategies, as well as why and how they should be implemented.

4. Empirical Study

The first section of this chapter introduces Sandvik AB and how it was founded. The next parts describe the history and design of the production plant in Svedala, and especially the processing facility West. The latter concerns the physical arrangement of the machine groups and their respective machines in the processing hall. The following parts present the production process and how the operators perform their jobs, as well as how the information flow runs from the order reception to the product manufacturing. In the following subchapter, the mapping and verification of the planning constraints are illustrated. Finally, a description of the non-applicable constraints will be presented.

4.1. Presentation of Sandvik AB

Sandvik AB was founded in 1862 by Göran Fredrik Göransson in Sandviken, Sweden. Göransson was first world-wide to mass-produce high-quality steel, using the Bessemer process (Home.sandvik, 2019). The technique had been developed by Henry Bessemer and was patented in 1855, but it had never been realized on an industrial scale nor given satisfactory technical or financial results before Göransson (Encyclopedia, 2020). Today, Sandvik is a global high-tech engineering company that employs over 40,000 people all over the world, whereof 2,700 work within research and development. The company is divided into three business areas, namely Sandvik Machining Solutions, Sandvik Mining and Rock Technology and Sandvik Materials Technology. (Home.sandvik, 2019)

The Sandvik production site in Svedala operates within the area of mining and rock technology. It is a world-leading supplier and global R&D center of stone crushers, which are used in the mining industry (Home.sandvik, 2019). The site was acquired by Sandvik in 2001, from the previous owner Svedala Industri AB, former Svedala-Arbrå (Metso, 2020).

4.2. History of Svedala Arbrå

The Sandvik site in Svedala originates from a mechanical workshop, which was founded in 1882 by Åbjörn Andersson. The company was initially called Åbjörn Andersons Mekaniska Verkstad and the firm specialized in manufacturing agricultural machines. The location of the site had been chosen due to the favorable transportation opportunities from the recently opened railway. Svedala had become a rail junction between the two train lines Malmö-Ystad and Lund-Trelleborg. In addition, the surrounding area was a productive agricultural region, wherefore there were large opportunities in producing such products. (Länsstyrelsen, 2018)

The facility consisted of two buildings, namely a foundry and a workshop. In the 1890s, the company reoriented its business towards manufacturing machines and equipment for brick production. Another product that was fabricated was road construction machines. However, the real breakthrough for the firm came around the year 1900, when the company began producing stone crushers. Due to the convenient location close to the railway, the products were easily transported to customers, which was profitable for sales. The company soon became market leaders in their field. The growth of the industry also contributed to the expansion of the community in Svedala. Due to a significant improvement in work opportunities, Svedala grew from a small church village to a municipality over the following decades. (Länsstyrelsen, 2018)

The company merged with the firm Arbrå Verkstad in the 1900th century and changed names to Svedala-Arbrå. It was acquired by Allis Chalmers and Trelleborgskoncernen and joined the latter in a subsequent company division. The industry then obtained the name Svedala Industrier AB, which in turn was acquired by Sandvik in 2001 (Metso, 2020). Buildings from the original site, Åbjörn Andersons Mekaniska Verkstad, are still active in the production. However, many additional workshops have been built since then. (Länsstyrelsen, 2018)

4.3. Description of the Svedala Plant

The Svedala site includes a number of factory buildings and workshops, in which the various manufacturing steps of the stone crushers take place. The only steel components that are manufactured from scratch at the site are the crushing chambers, which are molded in the Foundry. All other parts of the stone crushers are purchased from external suppliers. In the Foundry, melted steel is poured into sand molds and formed into accurate geometry. The crushing chambers are then processed in the machining hall East, which only treats these details. In the other machining facility, West, all other cast parts are processed. There is also a building for the manufacturing of wear protection and screening media, which is named the Rubber Workshop.

When the components are finished processed in their respective machining hall, they are sent to the Painting, which paints individual parts. Thereafter, the parts are assembled in one of the two halls called the Assembly. One of the halls is solely intended for the largest stone crushers. The last step is to paint the complete products, which is done at the second Painting hall.

4.4. Facility Layout of West

The processing hall West is the newest factory at the Svedala plant, and it was inaugurated in 2013. In this facility, all cast details except the crushing chambers are machined, before they are sent to the

Painting. The machines in West perform several different machining processes, such as drilling, milling, and turning. There is a large variation in the product assortment and most details are made-to-order. There is also a share of the products which are made-to-stock. West has a functional process layout with one operator working at each machine, who is specialized for that work. Experienced operators are, however, often capable of handling multiple machines.

In West, there are nine individual machines, which are categorized into three machine groups. These are named U6, U8, and WFL. The machines in the U6 and U8 groups are all vertical CNC machines, whilst the machines in the WFL group are horizontal CNC machines. As stated in the introductory chapter, this project is delimited to the two vertical CNC machine groups, i.e. U6 and U8, wherefore only these will continuously be considered. The individual machines in these groups are named U6:B, U6:C, U6:D, U8:B, U8:C, and U8:XL.

All machines are equipped with faceplates, on to which the details are attached before the processing. Each machine can fit two different sized faceplates, which allows different sized components to be processed in the same machine. The type of faceplates used is so-called pallets, which are possible to move in and out of the machine. The characteristics of pallets will be further described in the following subchapter.

All U6 machines are of the same size, which is the smallest in comparison to the other. The U8 group has machines of two sizes, two medium and one large. The number of faceplates and their respective dimensions that belong to each machine is presented in Table 4.1 below. Another variation between the machines is whether there is a capture unit for toxic gases. This system is required to process ductile cast iron articles, which generate the poisonous gas phosphine during the machining. The capture units are hence a safety measure to protect the operators working in West. The information about which machines that have a capture unit is also presented in Table 4.1.

Table 4.1. Summary of the machine features (source: Authors)

Machine group: U6			**Machine group: U8**		
Name	Faceplate diameters (mm)	Capture unit (Y/N)	Name	Faceplate diameters (mm)	Capture unit (Y/N)
U6:B	1 x 1250 1 x 1800	No	U8:B	1 x 2000 1 x 2500	No
U6:C	2 x 1250 1 x 1800	Yes	U8:C	1 x 2000 1 x 2500	Yes
U6:D	2 x 1250 1 x 1800	Yes	U8:XL	1 x 3000 1 x 4000	No

4.5. Equipment Description

The vertical CNC machines include several essential parts, which are used to process various articles. Some of this equipment is specific for machining certain articles and are therefore changed between the different jobs. This part aims to introduce the equipment that will be discussed more in the following sections.

4.5.1. Overall Machine Design

All U6 and U8 machines are delivered by a company named Unisign, which is an international supplier of high-end vertical CNC machines. All U6 machines, i.e. U6:B, U6:C and U6:D, are of the model Unicom 6000. The U8:B and U8:C machines are of the Unicom 8000 model and the U8:XL is of model Unicom 8000 XL. All vertical CNC machines in West are capable of performing operations such as milling, drilling, and vertical turning, and the difference between the models is the maximum size of the details. The principal design of the machines is shown in Figure 4.1 below. This machine is, however, another model in the same Unicom collection of vertical CNC machines as U6 and U8, manufactured by Unisign.

Figure 4.1. Principal design of the machines in the U6 and U8 groups (source: Unisign)

4.5.2. Pallets

To improve the utilization of the machines' working capacity, all vertical CNC machines are equipped with two or three pallets. A pallet is a type of faceplate, onto which the detail is placed before it is loaded in the machine. The difference between a pallet and a regular faceplate is, however, that the faceplates are permanently fixated inside the machine. A pallet can, on the other hand, move in and out of the machine. This way, it is possible to load the details outside the processing room, while another job is running. Hence, less time is required to prepare for new jobs while the machines are standing still and the production operates more efficiently. All U6 machines, U8:B, and U8:C have three pallets, while U8:XL has two. Figures 4.2 and 4.3 below illustrate the placement and design of the pallets.

Figure 4.2. The pallet is the circular metal block to the right of the machine (source: Unisign)

Figure 4.3. Four pallets placed on a factory floor (source: Machinio)

4.5.3. Chucks

In order to fixate a detail onto the pallet, some kind of attachment equipment must be used. There is a variety of such equipment, which are suitable for various articles. For rotation symmetric articles, it is often preferred to use a circular block, called a chuck. The chuck is directly attached to the pallet, using four bolts. On the chuck, there are metal supports, named jaws, which hold the detail in place. The jaws move simultaneously towards the center when attaching a detail and will hence fixate the detail in a centralized position automatically. Therefore, the chuck simplifies the attachment procedure considerably, as there is no need for manually adjusting the position of the jaws. The alternative to using a chuck is presented in the next section. The essential design of the chucks is shown in Figure 4.4 below, although it does not portray the same models used in West.

Figure 4.4. A Self-centering chuck (source: SanTool)

4.5.4. Jaws

There is an alternative to using the chuck to attach most articles to the pallet, which is using independent jaws. The jaws are attached directly on the pallet and at least three jaws are required to fixate a detail. The major disadvantage of using the jaws, compared to the chucks, is that the centralization of the detail must be done manually, as each jaw must be adjusted individually. This makes it a more time-consuming process to assure that the detail is in the correct position. However, there is also a flexibility of using the jaws, as they can be used to attach non-rotation symmetric articles. The principal design of jaws is shown in Figures 4.5 and 4.6 below.

Figure 4.5. Three jaws used for CNC machines (source: Drake)

Figure 4.6. Three jaws attached to a chuck (source: Drake)

4.5.5. Fixtures

Besides the chucks and jaws, details can be attached to the pallets by a piece of attachment equipment called fixtures. These are customized to fit different articles, and hence there is a large collection of various fixtures in West. However, there is only one of each fixture, wherefore only one detail of the same article type can be manufactured at the time in the processing hall. The manufacturer of the bottom plate of the fixture is Holmanders Smides & Mek Verkstad, and Svedala Mekaniska produces the fixation parts on top. An example of a CNC fixture is presented in Figure 4.7 below, which however is another brand than those used in West.

Figure 4.7. A CNC fixture (source: Taylor Design Engineering)

4.5.5. Tools

The actual processing activity requires some type of tooling, such as drills, cutting tools, mills or lathes. Each machine has its own set of permanently installed tools, but due to limitations in the machine space capacity, some tools are temporarily installed for certain operations. This way, several machines can share tools that are not used very often. The tools that are not permanently in the machines are stored in tool lockers in the facility. Some examples of CNC machine tools are presented in Figures 4.8 and 4.9 below.

Figure 4.8. CNC turning cutting tool (source: Bhimu Tools & Machinery)

Figure 4.9. CNC end mill cutting tools (source: Xincheng Technology)

4.5.6. Lifting Equipment

As the articles processed in West concern heavy industrial steel components, various equipment is required to enable lifting activities. There are permanently installed cranes at each machine, but different hooks and lifting devices are necessary to lift specific articles. Some examples of such lifting equipment are presented in Figure 4.10 below, which are taken from a different supplier then which is used in West.

Figure 4.10. Lifting equipment with a clamp (left) and with a hook (middle and right) (source: PHM)

4.6. Production Procedure

When the unprocessed details arrive at West, they are placed in an acclimatizing zone for at least 24 hours. This step is important so that the materials have the correct temperature and hence hardness when they are put into the machines. If the material is wrongly tempered, either too soft or too hard, there is a risk that the details obtain inaccurate dimensions after the machining process. This as the material will expand as it becomes warmer. Too hard material also carries a risk of breaking the cutting tools.

The operators in West work on a three-shift basis, i.e. 24 hours per day, five days per week. When a worker begins a shift, it is time to either prepare a machine changeover or to set up a new job. In a machine changeover, the operator prepares the machine for processing another type of article, which requires installing the correct tools inside the machine. During setup, the operator must prepare a new detail for being processed, which is of the same article type as the previous job. Hence, no changes inside the machine are necessary.

When initializing a new job, the operator first picks up the detail in the acclimatizing zone, using an electric truck. If the operator must prepare the machine for a changeover, it must be verified that the machine is rigged with an accurate set of tools. If tools that are not permanently installed in the machine are needed, these must be collected from the external tool lockers and installed into the machine. All steps are done manually, although equipment to facilitate heavy lifting is required.

When the detail has been collected from the acclimatizing zone, the operator must fixate it to the machine. As the U6 and U8 machines have pallets, the operator can prepare the attachment outside the processing room, while another job is running. The operator attaches the detail with the correct equipment, i.e. with a chuck, jaws or a fixture. When the machine is prepared and the detail is attached, the operator can move the pallet to the processing room and run the job, which is pre-programmed in the machine.

It is aimed to process several details of the same article type in one sequence, as this minimizes the changeover times. The products are usually machined in multiple directions, called tempos. To machine another tempo, the detail must be rearranged outside the machine, before it can be processed again. As various tempos require different attachment equipment, the operator usually alternates between the tempos during one sequence. This means that while a detail is being processed in Tempo 1, the operator can prepare another detail, of the same article type, to be processed in Tempo 2 on the pallet outside the machine.

When the details are done being processed, the operators will control the measurements with temperature calibrated tools. If no quality errors are discovered, the details will be put in the storing room for completed goods, where they are picked up by internal trucks at the Svedala plant. They are thereafter transported to the Painting. If any flaws are detected, the details are moved to the reparation zone in West, where cracks and other irregularities are, if possible, corrected. In the worst cases, when the component is too damaged, the detail will be discarded as waste. A schematic illustration of the activities is presented in Figure 4.11.

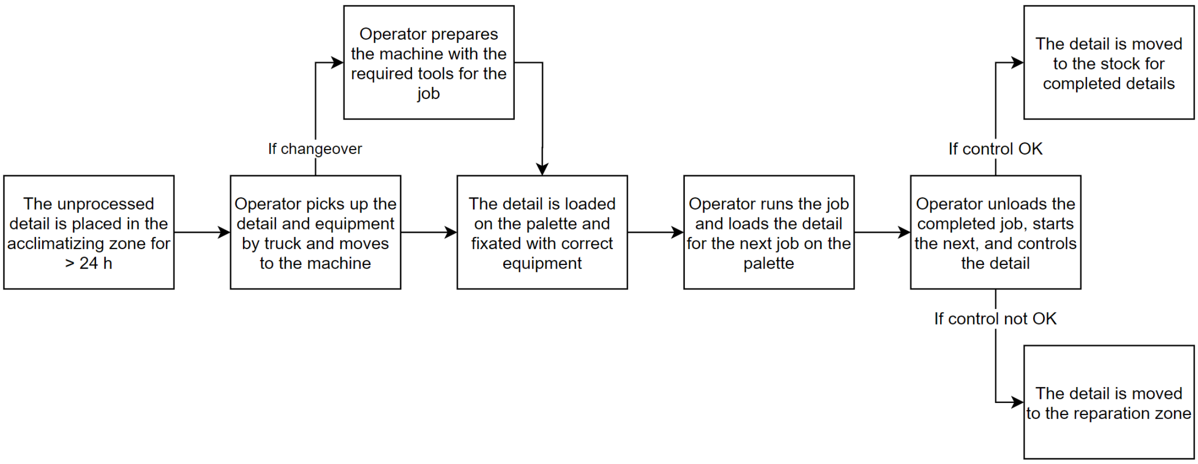

Figure 4.11. A schematic illustration of the activities related to the production in West (source: Authors)

It should be underlined that a delivery delay from West does not necessarily carry a delay to the customer. On the contrary, there are other activities further down the production line that have less capacity available and are hence potential bottlenecks. For example, the articles spend some time in inventory before the painting as well as the assembly.

4.7. Information Flow

The production at the Sandvik plant in Svedala is triggered by manufacturing orders. These are created either by actual customer orders or by demand forecasts, hence the production is based on both MTO and MTS. When an order is created, it is sent to the Planning and Capacity Department. This group is responsible for creating and releasing the manufacturing orders, i.e. scheduling the production, so that the products are delivered on time to the customers.

The scheduling is done in the ERP system Infor M3, which suggests weekly production plans based on the prevailing orders. The suggestion must be approved by the Planning and Capacity Department before it can be released to the production. There is no definite sequence in which the orders should be produced, but there is a status number indicating the prioritization. A list of the order operation statuses used in M3 is presented in Table 4.2. Based on this priority, the operators will schedule the production. The first shift will usually plan the production for the rest of the day.

Table 4.2. M3 operation statuses (source: Authors)

M3 operation statuses	
Status	Description
10	Preliminary
20	Definite
30	Order started/previous operation not started
34	Previous operation ready to start
35	Previous operation scheduled
36	Previous operation started
37	Previous operation partly started
40	Ready to start/previous operation ready
50	Scheduled
60	Started
70	Partly started
80	Done but not closed
90	Done and closed

A restriction of the current M3 system is that it does not recognize all constraints that may block certain orders from being manufactured simultaneously. For example, two orders could require the same attachment equipment to be processed, wherefore they must be produced at different times. This problem has been the reason for initializing the installation of a new scheduling tool called SWB, which is short for Scheduling Work Bench. This system is an expansion of the existing M3 system and is provided by the same software supplier, Infor. Another advantage of SWB is that it will suggest sequenced production based on priority so that it will optimize the production based on available capacity. In order to implement the new system, all constraints must, however, be identified and documented, which is one of the primary goals of this project.

4.8. Mapping Potential Constraints

There were two stages of the procedure to compile the constraints related to the scheduling of the production in West. The first step considered identifying the potential limitations as well as verifying that all possible factors had been taken into account. The second step was to evaluate the impact of the identified constraints, as to determine which ones had actual significance for the planning process. This section will focus on the first stage and the following section will focus on the second stage.

As the background to this master thesis was experienced problems of the production planning in West, the employees had already identified some potential constraints, prior to the project start. It was part of the scope to further investigate whether these had an impact on the scheduling. However, the goal was to map all factors that could interrupt the production due to inaccurate planning. Hence, it was required to identify constraints that had not been discovered by the Planning and Capacity Department.

The mapping was done through two different methods, namely interviews and archive analysis. The first method aimed at qualitatively analyzing the situation in an explorative matter, whilst the second was used to quantitatively collect data about the impacts of the potential constraints. Both semi-structured and unstructured interviews were carried out. This approach was chosen in order to cover both the previously identified constraints, as well as to search for additional factors that had limiting effects of the planning. The archival data considered internal documents from Sandvik Svedala, such as Excel files of production statistics and information concerning the articles produced in West. The following sections will present which constraints and information were found by the respective method.

4.8.1. Interviews

4.8.1.1. Unstructured Interviews

To initialize the data collection, it was necessary to gather information about the previously experienced problems. To get an overall comprehension of the issues and the current situation, several unstructured interviews were performed during the first weeks of the project. These took place during introductory meetings and in general conversations with staff at Sandvik. Hence no interview guide had been developed to collect the data. The people interviewed were both employees from the Planning and Capacity Department and West.

From the unstructured interviews, it was understood that the major issue concerned uncertainty regarding the equipment and available resources in West. When the factory was built in 2013, the idea was to make every machine fully equipped with all the necessary tools and instruments. However, due to cost benefit reasons and to increase the resource utilization, this was not completely implemented, and some equipment is still shared between multiple machines. This has resulted in insecurity at the Planning and Capacity Department, as it carries a risk of scheduling two articles that require the same tools at the same time. Several operators and managers in West reported about events where double-bookings have not been discovered until the last step of machine preparation. At these occasions, the operators have had to tear down the equipment and rig the machine for another article, whilst waiting for the tools to become available. In the worst cases, this has led to internal delivery delays.

The initial interviews resulted in the discovery of four potential constraints. Each one is presented in the following bullet points, in alphabetical order.

- **Capture units**: Articles made of ductile cast iron generate the toxic gas phosphine during the processing, wherefore they require a capture unit in the machine. However, all machines do not have such equipment installed, wherefore these articles are restricted to being produced in specific machines. This information must be included in the scheduling tool, in order to accurately plan the different jobs in the correct machines.

- **Chucks**: Both employees at the Planning and Capacity Department and in West mentioned the chuck as a potential constraint. The rotation symmetric articles are more easily attached to the pallet when using a chuck, as this equipment self-centers the detail. If the chuck is occupied, the fixation must be done manually by jaws, which is a more time-consuming process. In addition, some articles can only be attached by using the chuck, which therefore requires that a chuck is available. From the interviews, it was understood that it is a recurrent problem that all chucks are occupied when needed. In some cases, the operator manages by replanning the production schedule for the week. However, there are also situations when the job must be postponed to the following week, which hence results in an internal delivery delay at Sandvik.

- **Fixtures**: There should be one fixture per article, which limits the production to producing an article in one machine at the time. Hence, even if there is a shortage of a certain article, it can not be produced in two machines simultaneously, as there is only one fixture. However, there is uncertainty about whether there exists one fixture per article or if some articles use the same fixture. This parameter was therefore concluded as a potential constraint.

- **Tools**: Besides the tools that are permanently installed in the machines, there are movable tools that are mounted prior to a certain operation. These are often shared by two or more machines. The M3 system lacks information about which external tools are required for the various operations, wherefore this is assumed as a potential limitation.

4.8.1.2. Semi-Structured Interviews

Once the unstructured interviews had been completed, a deeper understanding of the current situation had been developed. Based on the gathered information, it was possible to construct semi-structured interview guides, which would be used to interview machine operators in West. The purpose of these interviews was to gain deeper knowledge about the operators' working experiences, as well as to learn more about their thoughts regarding the potential limitations in the production equipment. The aim was to get a clearer idea about which of the identified factors that actually affect the operators' work and the production efficiency. Also, the goal was to identify additional constraints that had not yet been discovered.

The first part of the interview focused on general problems that the operators face in their daily work in the factory. The idea was to ask open questions in order to avoid interfering with the operators' spontaneous associations of work-related problems. This would increase the likelihood of finding new constraints.

The second interview part questioned if there had been any recent changes done in the workshop. This was asked to understand if there has been any previous actions or initiatives related to the problem. The operators were also asked if they had any suggestions for further improvements, which would facilitate their future work.

The following part included questions about the identified constraints, and the aim was to understand if they were perceived as such also in the machining hall. In the final part of the interview, the operators were informed about the project task and were asked more precise questions concerning the identified constraints. Once they knew the context of the interview, they were repeatedly asked if they could think of additional constraints in the production.

It was decided that the interviews would proceed until the answers converged, i.e. when no new answers appeared. This would imply that all aspects had been covered. The interviews were performed with eight operators, on the 11th of February 2020. The full compilation of the interview answers is attached in Appendix A. It should be clarified that the answers are recalled by the authors afterward, based on notes from the conversations. It was concluded that the precise formulations had no relevance for the outcome, wherefore the dialogues were not recorded and transcribed, which would have been a more time-consuming method.

The potential constraints mapped during the semi-structured interviews with the operators in West are presented in bullet points below. However, only those factors that in theory could be avoided by accurate planning are included in the list, i.e. suggested limitations such as poor material quality and other purely process-related issues are not presented.

- **Chucks**: A recurring response concerning frequent problems and suggested improvements was that the chucks are often occupied and that the planning should be improved to avoid this problem. There were also reports on details that were postponed until the following week, due to the unavailability of this equipment.

- **Fixtures**: The operators did not mention fixtures as a limiting factor during the open questions. On the more specific questions, some responded that there have been incidents when articles that use the same fixture have been scheduled at the same time. This, however, was not perceived as a major problem, as these articles are produced rarely. In addition, the U8:XL machine has its own fixtures, and is not concerned by this problem at all. There were also operators answering that the fixtures were not at all a problem.

- **Jaws**: When the chucks are occupied, some articles are instead attached to the pallets by using jaws. This procedure requires more manual work of the operator, as the detail is not automatically centered symmetrically. This is also a more time-consuming process. The interviews confirm that there is uncertainty about whether the jaws are shared between the machines and if there is a risk for capacity shortage due to this item. If all jaws are occupied when needed, there is, in theory, a risk for production delays. This equipment will hence be further investigated and is considered a potential constraint.

- **Lifting equipment**: There were some reports on incidents when lifting equipment, such as hooks and chains, was occupied or missing. Different articles require various lifting equipment, but they are not custom made for the articles. Hence, the lifting tools are to some extent shared between the machines.

- **Tools**: Some tools are used to process multiple articles. The operators mentioned that the tools are sometimes missing or broken. In these cases, they must spend time searching for the tool or constructing a new one. A new arrangement of the tools has however carried an improvement in finding the tools faster.

4.8.2. Archival Data

The archive analysis concerned a quantitative study of the situation, which resulted in a completely objective data collection. A number of documents were used to find the data that was searched for. Most information was gathered from technical documentation in West-specific Excel files and the ERP system M3. Some of the information concerned the required equipment for all articles machined in West, annual production volumes, and average processing times There were also separate documents over the articles that require the chucks in the production.

The information gathered from the archival analysis is summarized in Table 4.3. All previously mentioned potential constraints were, however, not associated with a document, wherefore all are not presented.

Table 4.3. Summary of information gather during archive analysis (source: Authors)

Potential constraint	Information
Capture units	As previously presented, there are three machines that have a capture unit installed, namely U6:C, U6:D, and U8:C. There are several articles that require capture unit in each machine group: ➢ 21 articles produced in the U6 group require capture unit ➢ 13 articles produced in the U8 group require capture unit
Chucks	There are three chucks in West, two with a diameter of 900 mm and one with a 600 mm diameter. The latter is only used in one machine, namely U6:C, used to produce top bushings. The larger chucks are used in all U6 machines, as well as in U8:B and U8:C. In total, 25 articles use chucks, namely: ➢ 2 articles are top bushings, which use the 600 mm chuck in the U6:C machine ➢ 16 articles use the 900 mm chuck and are produced in any U6 machine ➢ 7 articles use the 900 mm chuck and are produced in the U8:B or U8:C machine
Fixtures	There are fixtures that are shared between multiple articles: ➢ 1 fixture is used for producing 7 articles ➢ 2 fixtures are used by 4 articles ➢ 35 fixtures are used by 2 articles The remaining fixtures are used for one unique article.
Tools	The average machine stop time due to searching for tools vary between the machine groups: ➢ In the U6 group, the average stop time is 0:17:23 h:min:sec ➢ For the U8:B and U8:C machines, the average stop time is 0:15:06 h:min:sec ➢ For the U8:XL machine, the average stop time is 0:19:21 h:min:sec

4.9. Verification of Findings

This section presents the final verification of the accuracy of all previously identified constraints. For those factors that could not be supported by archival data, feedback sessions were scheduled with responsible managers. These meetings were arranged to confirm whether the constraints affect production efficiency. Table 4.4 summarizes the identified potential constraints, how their respective impact was verified, and whether they are determined as a limiting parameter for the scheduling of the production in West. The factors which in the table are labeled “Actual constraint” will be further discussed in the following analysis chapter.

Table 4.4. List over the final verification of the potential constraints (source: Authors)

Potential constraint	Verification method	Impact
Capture units	The constraining impact of capture units was confirmed by the archive analysis, which showed that multiple articles require that capture units are installed in the machines.	Actual constraint
Chucks	The archive analysis showed that the chucks are used by several articles and the planning must be done with respect to this constraint.	Actual constraint
Fixtures	The limitation of the fixtures was verified by the archive analysis, which showed that 38 fixtures are used by at least two different articles.	Actual constraint
Jaws	According to one of the process engineers in West, there is one set of jaws per machine, hence these are not a limiting factor. However, there are different jaws used by the chucks, which could be a limiting factor.	Not a constraint
Lifting equipment	According to one of the CNC operators in West, there is enough lifting equipment to cover the need in the processing hall. Even if a lifting tool is occupied, the waiting time does not have a significant impact on production efficiency.	Not a constraint
Tools	The average stop time due to the search for tools exceeds 15 minutes in all machine groups. Also, there is a large variation in the stop times, which indicates that this is an issue that could be improved. There is, however, no data that confirms that the tools are a constraining factor for being used by multiple articles.	Actual constraint

4.10. Non-Applicable Constraints

Some factors which are outside the scope of the project were brought up in the interview's open questions. These were factors that might potentially lower the efficiency of the production but have no direct connection to the scheduling as they can not be predicted. The non-applicable factors are presented in Table 4.5 below.

Table 4.5. Non-applicable factors (source: Authors)

Factor	**Information**
Angle head	Angle heads which operate in all machines break approximately 2 - 4 times a year due to collisions and wear. It takes about 1.5 - 8 weeks to repair and during the repair period an angle head can be borrowed for approximately 30,000 SEK. A new angle head costs about 200,000 - 1,400,000 SEK depending on the model.
Chuck and fixture condition	Chucks and fixtures are under the risk of sudden breakdowns as they are not checked up upon on a regular basis.
Detail delivery position	When details are wrongly positioned at delivery, the operators must themselves change the direction of the details.
Material quality	The material quality of the details is controlled through samples and variations may vary for details which are not controlled. Both too soft or too hard materials risks resulting in unwanted dimensions. By being aware of the quality, the machines can be adjusted accordingly.
Pedal wire length	The wire length to the pedal which is required to be pressed down when changing the tools of the U8:XL machine is shorter than desired. The wire length makes it more difficult for the operator to reach the mounting area, especially when handling heavy tools. Therefore, operators need therefore at times to ask for assistance from other operators to help them press down the pedal.
Steel swarf	Steel swarf does not break as expected when processing material with an unforeseen quality. When the swarf gets longer than expected, it forms into larger clusters which the machines can not remove automatically. The swarf must then be removed by the operators by hand.
Tool breakdown	Breakdowns of tools happen mainly due to wear or when material quality is harder than expected. When this happens, the operator must either borrow tools from another machine or assemble a new tool.

As these factors can not be predicted by the scheduling tool they are assigned as non-applicable factors. They will therefore not be further analyzed, as they are outside the scope of the project. They are instead left to be investigated in future work.

5. Analysis

This chapter is introduced by a summary of the current situation in West. Firstly, its manufacturing strategy is analyzed. Thereafter, the expected occupancy rate of the identified constraints is studied. High-runners and their dependence on identified constraints are then investigated, and West's manufacturing flexibility and its impact to help alleviate constraints are discussed. After an analysis of changeover times, this chapter ends with an analysis of the current need for potential investments.

5.1. Current Situation

5.1.1. Monitoring Fabrication

When analyzing West's manufacturing strategy with the help of the product-process matrix, presented in Figure 3.1, three elements are regarded; volume, product customization, and product characteristics. West produces articles in relatively low volumes at the time. The products are made in several editions and their design may be altered quickly as customer demand may change. They are thus not one of a kind, but neither highly standardized. West produces multiple products with disconnected line flows and moderately complex work. In the product-process matrix, West should hence, in theory, belong to the small-batch process category. This position corresponds well to how the facility is operating in practice as well. Being positioned on the diagonal in the matrix gives a good indication that the facility's manufacturing strategy is correctly matched to the products being produced, whereas being found outside the diagonal would correspond to an inefficient strategy. Due to West's position in the product-process matrix, sharing equipment that is only used at certain times is an efficient way to reduce unwanted costs. Although, this makes scheduling more complex and increases the demand for proper scheduling.

The three verified potential constraints, namely capture units, chucks, and fixtures, can according to the Theory of Constraints be named as internal constraints. They may inhibit the production system from sufficiently responding to the market demand if not properly acknowledged. Another type of constraint mentioned in the Theory of Constraints is bottlenecks. They are defined as a type of constraint that refers to a limited resource, and the three verified potential constraints can according to this definition all be referred to as bottlenecks. These three bottlenecks can further be described as floating bottlenecks, as their throughput may differ from one day to another. Having all verified constraints being floating bottlenecks, the drum-buffer-rope system is not applicable in this context. In order to use the drum-buffer-rope system as a method, it requires a drum that will set the production rate for the entire production. This is something a floating bottleneck does not do. For the production in West, the three verified constraints are not only floating, but they are also only affecting a certain number of articles but far from all articles. Neither the chucks, fixtures or machines without capture unit can, therefore, be set as a drum.

The machines in West are multi-tasking machines, also known as hybrid machines. Using this type of machine in West is an efficient and productive way of processing parts that would otherwise have required several other machines. The hybrid machines suit well into the layout of the facility. The layout resembles a cellular manufacturing facility as similar products that are produced in similar ways are produced in a specific area. Although, the cells should theoretically be independent of each other with their own set of tools and equipment when practicing cellular manufacturing, which West does not have.

5.1.2. Consequences of Identified Constraints

To minimize redundant costs, it is relevant to examine if less frequently used equipment can be shared amongst several machines. This action is supported by the recommendations for an organization with batch process manufacturing to share the available resources. It is also of relevance to examine to what extent the shared resources will impact the scheduling, as some shared resources will be used at a higher rate than others.

The aim of the analysis in this subchapter is to investigate the consequence of each identified constraint. Their extent will provide an understanding if future potential investments should be further investigated to elevate them. The identified constraints that will be analyzed in this section have been derived from the list over the final verification of potential constraints, as described in Table 4.4. These constraints are capture units, chucks, and fixtures.

In the analysis, the demand prognosis for the next coming year for each of the three constraints has been calculated. This was done by first identifying which articles are concerned by each constraint, then analyzing their respective theoretical operating time and their expected production volume. This comprises an estimation of the expected occupancy rate of the constraints for the next coming year. By putting the number of expected hours of occupancy against the total available production time, the ratio between available and expected occupancy time can be calculated. This measurement was developed by the thesis authors, to simplify the comparison of occupancy for the different constraints. The so-called Availability-Occupancy Ratio (AOR), shown in Equation 2 below, presents the proportion of the available production time that is occupied by a production order. This is measured as a percentage and the value is always rounded up to the nearest integer. If the ratio is close to 100 % or even exceeds this value, it means that the constraint risks failing in meeting the expected demand. In such a case, it should be analyzed more closely if an investment is necessary to increase the production capacity. The following text will also discuss the free capacity margin for each constraint, which simply refers to the remaining percentages to reach maximum capacity utilization, hence 100 % subtracted by the AOR.

$$(Eq.\ 5)\quad Availability - Occupancy\ Ratio\ (AOR) = \frac{Expected\ occupied\ time\ (h)}{Available\ time\ (h)} \cdot 100$$

The analysis is based on the forecasted demand in production volumes starting in February 2020 and 12 months ahead. Seeing that the prognosis is stretched out over a year, it is assumed that there will be a continuous flow in demand and that the articles are distributed evenly throughout the year. This is a moderate simplification of reality, as all three constraints are floating bottlenecks. In other words, their respective demand varies and is highly dependent on how the production orders are scheduled. Nevertheless, the AOR still provides an indication to how much of the constraints' capacity will be occupied by the forecasted production orders.

The available operating time in West is 36,000 hours per year, allocated over the nine machines. Hence, each machine has a yearly available operating time of 4,000 hours. This time corresponds to 80 % of the scheduled time, i.e. the hours when the factory is manned minus the time for breaks. The available time will be the same throughout the analysis for all constraints. For the constraints' occupancy time, only the actual operating time will be considered, meaning that the setup time will be excluded. This due to the variation of the number of articles being produced per batch.

5.1.2.1. Capture Units

Table 5.1 describes the expected occupancy time for articles made of material that require a machine with a capture unit, for the next coming year. The U6 and U8 machines with capture units have a theoretical free capacity margin of 56 % respective 59 %. These values are concluded high enough to theoretically meet the demand, wherefore no investment in additional capture units should be necessary.

Table 5.1. Availability-Occupancy Ratio for machines with capture unit (source: Authors)

Machine group	Number of machines with capture unit	Expected capture unit occupancy (h)	Available operating hours (h)	Availability - Occupancy Ratio	Further need for investment investigation
U6	2	3,492	8,000	44 %	No
U8	1	1,618	4,000	41 %	No

5.1.2.2. Chucks

Table 5.2 describes the expected occupancy time for all chucks in the next coming year. The 600 mm chuck will, on a 12-month average, be able to meet the expected demand with a free capacity margin of 61 %. The 900 mm chucks will be able to respond to the demand with a margin of 76 %. The chucks are hence not a risk for constraining the demand, given that the scheduling is done accordingly.

Table 5.2. Availability-Occupancy Ratio for the chucks (source: Authors)

Chuck type	Number of chucks	Expected chuck occupancy (h)	Available operating hours (h)	Availability - Occupancy Ratio	Further need for investment investigation
600 mm	1	1,539	4,000	39 %	No
900 mm	2	1,867	8,000	24 %	No

5.1.2.3. Fixtures

As presented in the empirical study, there are 38 fixtures that are shared between multiple articles, whereof 35 fixtures were required by two different articles each. When analyzing the AOR for these 35 fixtures, it was concluded that all had a free capacity margin of more than 85 % each. Consequently, none was considered as a potential constraint that needed additional actions or analyses. The remaining three fixtures will, for the sake of simplicity, be named A, B, and C. The fixture A is shared between 7 articles, and the fixtures B and C are shared between 4 articles each.

Table 5.3 describes the expected occupancy time for each fixture in the next coming year. It shows that fixture A will have a free capacity margin of 76 %, fixture B a margin of 62 %, and fixture C a margin of 90 %. None of the fixtures is thereby eligible for further investment investigations.

Table 5.3. Availability-Occupancy Ratio for fixtures (source: Authors)

Fixture name	**Number of articles using the fixture**	**Expected fixture occupancy (h)**	**Available operating hours (h)**	**Availability - Occupancy Ratio**	**Further need for investment investigation**
A	7	928	4,000	24 %	No
B	4	1,482	4,000	38 %	No
C	4	400	4,000	10 %	No

5.1.2.4. Tools

It was found through the interviews that tools are commonly not being scheduled so that overlaps occur. For this reason, as well as the complexity linking tools that articles require with existing tool sets in the facility, the Availability-Occupancy Ratio does not apply to this constraint. However, there is a large variation in the machine stop times that result from searching for tools, wherefore this factor has been further investigated. Figures 5.1 - 5.3 below present the histograms over the number of stops within each time interval. The data is split up for the U6 machines in one group, the U8:B and U8:C in another one, and for the U8:XL alone. This is done as the machines share tools within the above-mentioned constellations.

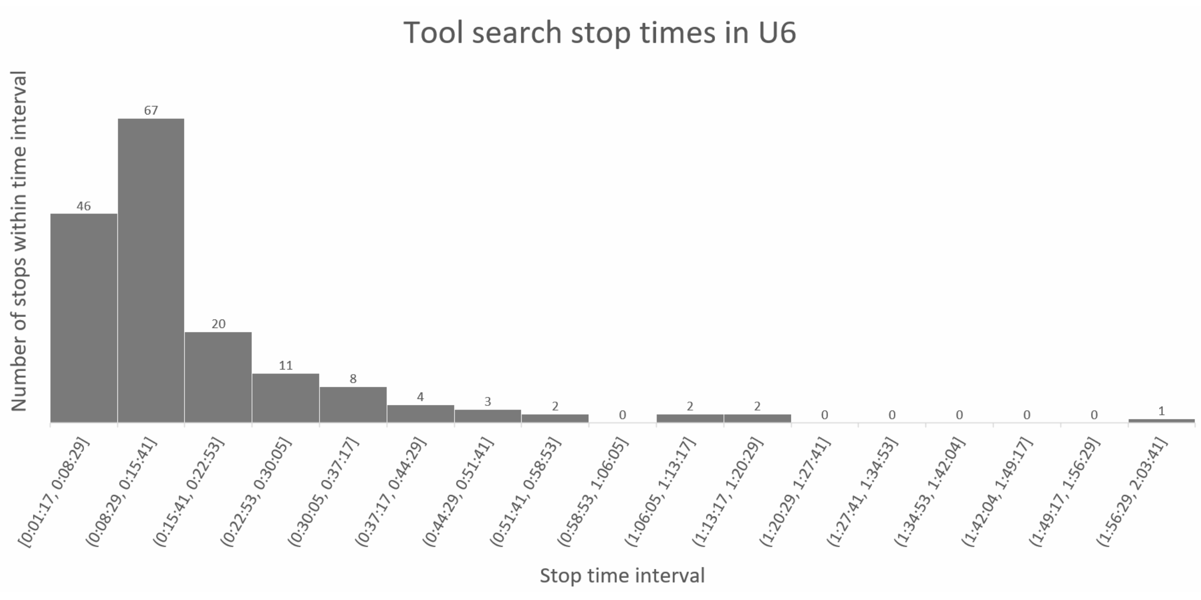

Figure 5.1. Tool search stop times in the U6 group (source: Authors)

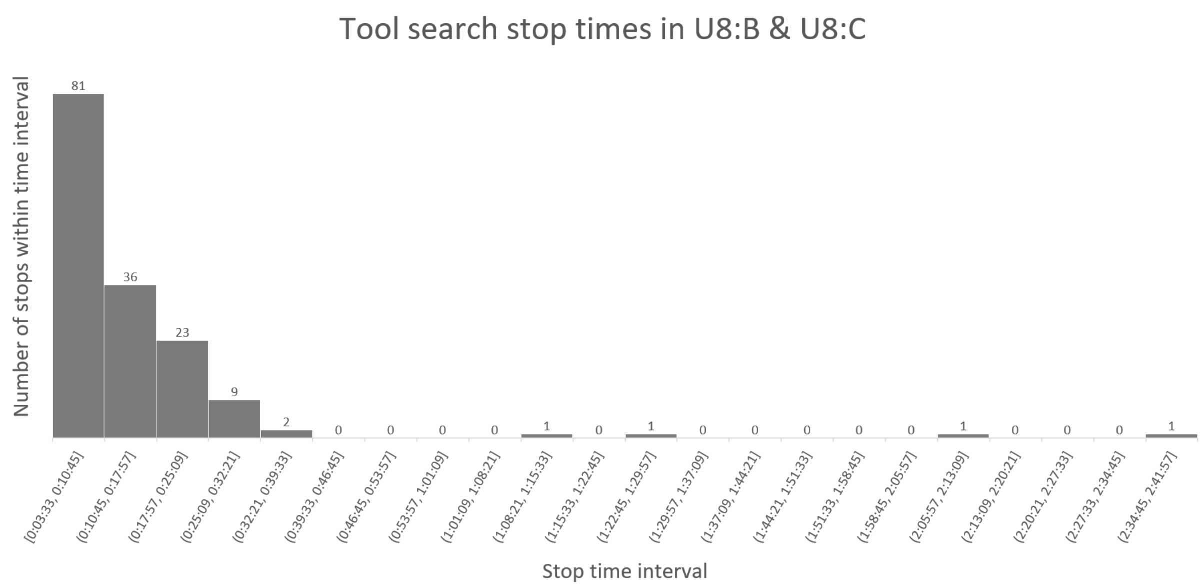

Figure 5.2. Tool search stop times in the U8:B and U8:C machines (source: Authors)

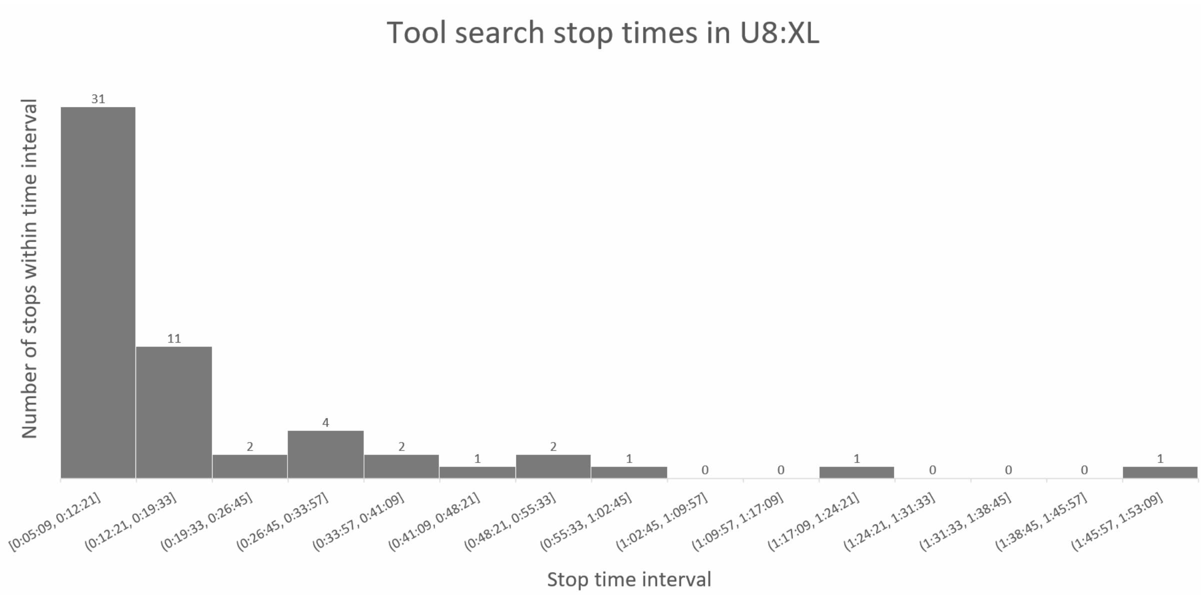

Figure 5.3. Tool search stop times in the U8:XL machine (source: Authors)

The diagrams above show that for all groups, the majority of the stops lie below a value of 20 minutes. In each diagram, there are a couple of outliers that have much higher values. In the RS Production program, some of these values had comments that briefly presented the cause for the stop. There was a large variety of explanations, but it was concluded that rarely was the problem that the tool was occupied by another running job. Often, the reason was that it was difficult to find the tool or that it was stuck in a crashed machine. However, it should be underlined that the explanations provided were not enough to draw any further conclusions about this type of machine stops. This would require a more extensive analysis, which does not lie within the scope of this project. Table 5.4 below presents further the variation in stop times caused by searching for tools, as registered in RS Production.

Table 5.4. The variation in registered stop times due to tool search in the U6 and U8 machines (source: Authors)

Machines	Minimum stop time (h:min:sec)	Maximum stop time (h:min:sec)	Mean stop time (h:min:sec)	Median stop time (h:min:sec)
U6 group	0:01:17	1:58:01	0:17:23	0:12:27
U8:B & U8:C	0:03:33	2:35:43	0:15:06	0:10:13
U8:XL	0:05:09	1:52:53	0:19:21	0:11:27

According to the SMED principle, it is desired that the total setup time does not exceed 10 minutes per job. Table 5.4 above presents the average stop times that results from searching for tools are between 15 and 20 minutes in all machine groups. This result indicates that it should be aimed to reduce the time spent on this activity. Parallels can be drawn to the results of the case study visualized in Figure 3.3, which shows that the movement of the operators were reduced significantly by implementing the SMED principle.

Even though the search for tools is considered unnecessary waste in West, it is not directly connected to the planning of the production. Hence, there is no way to minimize the risk for machine stop times caused by tool search by making adjustments in the scheduling phase, nor can any parameter be added to the SWB tool. For this reason, the tools are not a constraint in terms of limiting factors that can be monitored by the Planning and Capacity Department. However, this should be further investigated in future projects. More comments on the effects of the current tool situation and potential future work will be discussed in the last chapter of this report.

5.1.3. High-Runners

The archive analysis of the technical documents in West showed that there is a large variety in the annual production volumes of the various articles. The articles that are manufactured in large scales are referred to as high-runners and are critical components as they constitute a large proportion of the yearly production and hence total revenues. The previous sections confirmed that there is enough capacity to produce all articles that are affected by the constraining factors. However, it is relevant to analyze which of the high-runners are concerned by these constraints, in case of equipment breakdown or other risks that could affect the availability of required equipment.

Figures 5.4 and 5.5 below illustrate the production volume distribution for the articles processed in the U6 and U8 groups. The data considers the forecasted production volumes from February 2020 and one year ahead. The diagrams reveal that the majority of all articles are manufactured in volume intervals of 1 - 20 and 21 - 40 units per year. In both groups, there are only a few articles that are produced on a larger scale.

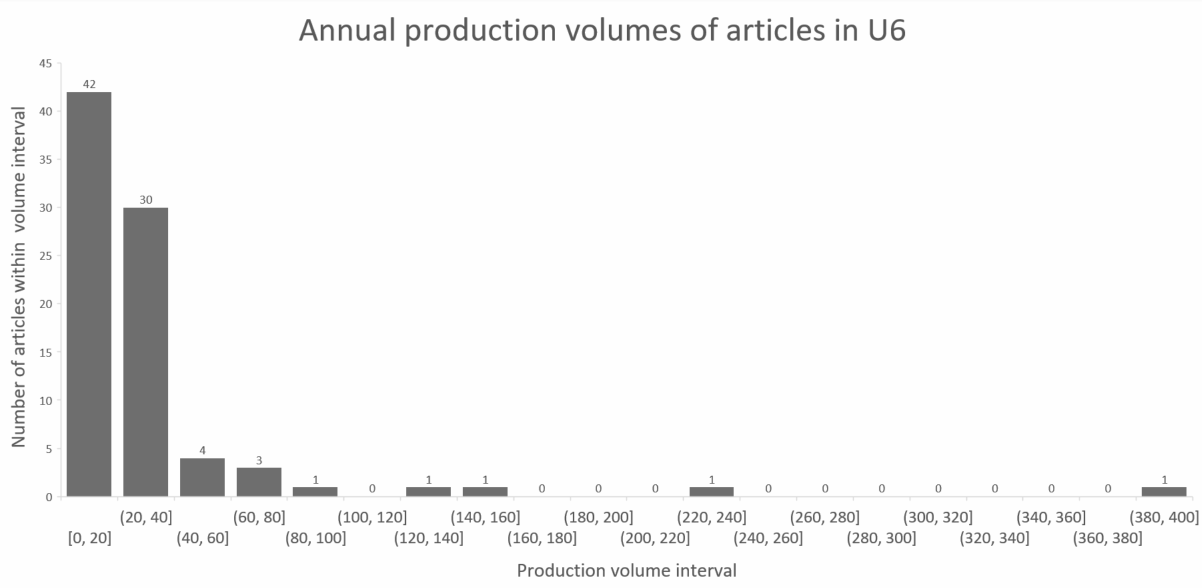

Figure 5.4. Production volume distribution of articles processed in the U6 group (source: Authors)

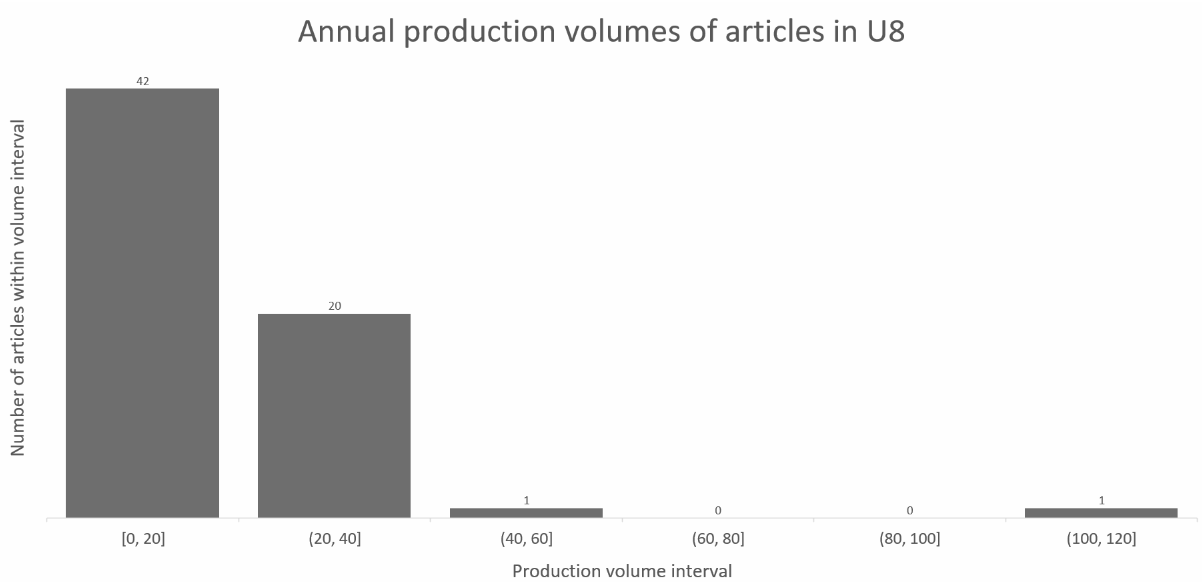

Figure 5.5. Production volume distribution of articles processed in the U8 group (source: Authors)

The high-runners are defined as the 10 % most produced articles in each machine group. As 84 articles are processed in the U6 group and 64 in the U8 group, there are 8 respective 6 articles that are defined as high-runners. Tables 5.5 and 5.6 below summarizes which constraints are related to each of these articles.

Table 5.5. Summary of high-runners in the U6 group (source: Authors)

Article name	Annual volume	Processing time (h)	Chuck (Y/N)	Fixture (Y/N)	Capture unit (Y/N)
A1	390	3.1	Yes: 600 mm	No	Yes
A2	240	1.7	No	No	No
A3	154	3.5	Yes: 900 mm	No	No
A4	132	2.5	Yes: 600 mm	No	Yes
A5	100	3.5	Yes: 900 mm	No	No
A6	78	1.5	No	No	No
A7	70	1.8	No	No	Yes
A8	65	3	Yes: 900 mm	No	No

Table 5.6. Summary of high-runners in the U8 group (source: Authors)

Article name	Annual volume	Processing time (h)	Chuck (Y/N)	Fixture (Y/N)	Capture unit (Y/N)
B1	108	4.8	Yes: 900 mm	Yes*	No
B2	42	4.5	Yes: 900 mm	No	No
B3	38	8.5	No	Yes*	No
B4	38	6	No	No	No
B5	37	10	No	No	No
B6	35	8.5	No	No	No

* The two fixtures used to process article B1 and B3 are both used by two articles each.

The analysis of the high-runners showed that five articles are not limited by any of the constraints, whereof two are within the U6 group and three within the U8 group. The other articles have at least one factor that must be considered when scheduling the production. Although it is not necessary to take any actions towards these articles at this stage, it is important to be aware of how these articles rely on the condition and functionality of these parameters. Further analysis of the AOR for each constraint associated with these high-runners is presented in Table 5.7 below. It hence presents how much of the constraints' available production time is used by the respective articles.

Table 5.7. Analysis of high-runners that are dependent on any constraint (source: Authors)

Article name	Annual volume	Processing time (h)	Total time per year (h)	AOR of chuck	AOR of fixture	AOR of capture unit
A1	390	3.1	1,209	*600 mm* 31 %	N/A	*U6:C* 31 %
A3	154	3.5	539	*900 mm* 7 %	N/A	N/A
A4	132	2.5	330	*600 mm* 9 %	N/A	*U6:C* 9 %
A5	100	3.5	350	*900 mm* 5 %	N/A	N/A
A7	70	1.8	126	N/A	N/A	*U6:C/U6:D* 2 %
A8	65	3	195	*900 mm* 3 %	N/A	N/A
B1	108	4.8	518	*900 mm* 7 %	13 %	N/A
B2	42	4.5	189	*900 mm* 3 %	N/A	N/A
B3	38	8.5	323	N/A	9 %	N/A

As shown in the table above, the high-runners utilize a rather small share of the available time of each constraint. The highest AOR value is found for the article A1, which is 31 % of the available production time for the small chuck as well as the capture unit in the U6:C machine. As there is only one 600 mm chuck, there would be some consequences if this unit break, as there is no other chuck to use. However, since there are only two articles that require this equipment in total, a breakdown would most likely not carry significant negative effects. The articles that require the 900 mm chuck are considered as low-risk, as there are two chucks of this size. For article A7, which requires a capture unit, it may be processed in either one of the two U6 machines with a capture unit, namely in U6:C or U6:D. Hence the risk for production abruption of this article is non-significant. Lastly, for the two articles that require fixtures, the AOR is 9 % respective 13 %.

5.1.4. Flexibility

In Step 3 of implementing the practices of the Theory of Constraints, all decisions which might have an impact on the constraint should be subordinated to help increase its capacity. Increasing manufacturing flexibility is one way of doing so. Seeing that a more flexible facility will be able to respond more quickly to changes, it will, as a result, be able to help maximize the utilization of the constraints. Through the unstructured interviews, it was found that orders tend to get pushed forward from its original planned week until the following week due to lack of planning or due to unplanned events, such as breakdowns. Situations like these call for rescheduling. Flexible manufacturing becomes critical at times such as these, as resources may swiftly need to be replanned. Constraints which have not been critical might unexpectedly become so.

Analyzing the flexibility of the manufacturing system in West is done following the four-step-procedure of FMS modeling. The flexibility is viewed from a scheduling standpoint and only provides a general view of the scheduling flexibility. A likely new demand which could be placed on the system would be, as mentioned above, sudden replanning in the production due to delays in the previous week. As the new scheduling tool in SWB will be fully implemented, the capability for the system to react to these new demands are expected to improve. The tool will be able to optimize the scheduling sequences, which will reduce the likelihood of reschedulings. The system would fail to meet these new demands if constraints are not properly identified. In the fourth step in the FMS modeling approach, ways of providing new flexibility should be identified. When trying to improve flexibility, short changeovers and setups times are one of the main prerequisites, especially when dealing with mix flexibility. With this being said, by analyzing and finding ways of reducing changeover and setup times, the manufacturing flexibility will as a result increase. A facility with high flexibility will be able to better utilize the capacity of its constraints.

5.1.5. Changeover Times

RS Production is an OEE program that monitors machine efficiency in West. From the six big losses found in Table 3.2, the setup and adjustment loss will be analyzed in this section. This is the only loss that can be foreseen, and the only loss and has an impact on the scheduling.

All machine stops larger than five minutes get logged in RS Production. In this program, the operators manually enter the cause for the machine downtime. The program does not automatically register which article is processed during the stop, but the operators can choose to add this information as a comment. It is assumed that the operators have little incentives to include this information, although it would have been a simple task. It is hence difficult to connect the registered machine downtimes to certain articles. However, the data concerning the stop times caused by changeovers had enough data points to perform some analyses, whilst the information concerning the stops caused by setups was insufficient. Due to this lack of data, only changeover times will be analyzed, even though time variations for setup would be of relevance as well.

In this analysis, the changeover times of 15 different articles with at least four registered stops have been investigated. In Table 5.8, the articles with the highest time variations of the 15 articles that have been analyzed in each machine type; the U6, U8, and U8:XL, are presented. For the sake of simplicity, the articles are called X, Y, and Z. The third column in the table informs how many times an operator has linked a changeover to a certain article. The average 20 % of the slowest and fastest registered changeover time for the article are presented in column four and five. Their time difference and the average time the changeover for that certain article are thereafter shown.

Table 5.8. Largest variations in changeover times for each machine type (source: Authors)

Article name	Machine	Number of registered times	Average min stop time (h:mm:ss)	Average max stop time (h:mm:ss)	Difference (h:mm:ss)	Average stop time (h:mm:ss)
X	U6	10	0:05:19	0:43:19	0:38:00	0:18:11
Y	U8	7	0:06:05	1:12:03	1:40:38	0:29:22
Z	U8:XL	15	0:05:38	0:56:29	0:50:51	0:25:01

A large variation in changeover times can be seen. This is an indication that different changeover methods are being used by different operators. From the interviews, this statement was confirmed to be accurate. Variations in changeover times mean that these times could potentially be reduced. Reduced changeover times may as earlier mentioned help elevate identified constraints by maximizing their capacity. One of the most efficient ways of reducing changeover times in a manufacturing process is to use the SMED method. Distinguishing the best practice of changeovers will, as a result, lower the time variations.

5.1.6. Overall Equipment Effectiveness

5.1.6.1. Linking OEE to Constraints

Knowing both a facility's OEE and its constraints gives an indication if any improvement may be needed, and more importantly, what type of improvement that would most likely be made. Figure 5.6 below describes four potential scenarios where the OEE and a constraint's Availability-Occupancy Ratio can either be low or high. An ideal placement in the diagram would be in a scenario when the OEE is high and the AOR is at a level just enough to cover the constraint's demand. This placement has been marked with a point in the top middle of the matrix.

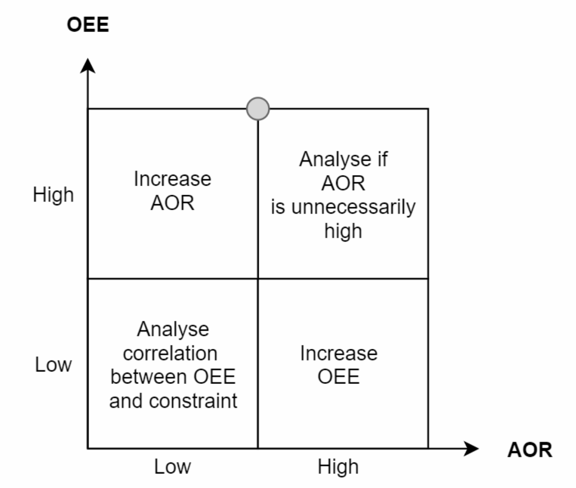

Figure 5.6. Consequences of the relationship between values of OEE and AOR (source: Authors)

Firstly, in the upper left square, the OEE is high while the constraint's AOR is low. This is an indication that the constraint is not affecting the overall performance, but could be if an increase in the constraint's demand occurs. The constraint should be investigated in order to see how the OEE will be affected in a case like this.

In the upper right square, both the OEE and the constraint's AOR are high, meaning that the facility's equipment is operating as desired while the constraint would be able to take on higher demand. Although this is a well-functioning position, it might mean that there is an unnecessary high constraint capacity. It should, therefore, be considered if the constraint's throughput should be increased, or if its capacity should be decreased.

In the bottom left square, both the OEE and constraint's AOR are low. The AOR should in this scenario be increased, as well as further analysis of its correlation to the OEE. If there are no signs of correlation, the OEE needs to be increased on its own. This by looking at the equipment availability, performance or quality of its produced goods.

Finally, in the bottom right square, the OOE is low but the constraint's AOR is high. This proves that the equipment efficiency needs to be increased and that the capacity of the constraint is most likely not the underlying issue. Waste somewhere in the production is in this case happening, but it has not yet been located.

5.1.6.2. Calculation of OEE

The RS Production system was initiated in 2019 in West, and is thus still in its early stages of usage. Only the scheduled production time of the machines, their respective stop times, and the reason for the stops are currently being registered in the system. The RS tool is therefore not used to calculate the complete OEE, since some of its parameters are not being entered in the system. There is also lack of data in the relationships between defected articles and the time when their operation took place. Furthermore, there is a large variation in the times when the deficiencies are discovered. Sometimes, they are recognized immediately after the processing, and repaired right away. In other cases, the deficiencies are discovered a long time after the production is completed. This data makes it uncertain to calculate the value for the quality rate for now. The complete OEE will therefore not be calculated in this analysis, as there is only data to analyze the availability rate and performance efficiency.

Even though the OEE will not be calculated, the availability rate and performance efficiency will still be able to provide a good indication on how efficient the facility is operating. Table 5.9 shows the required data for calculating their values. The planned and registered operating times for the machines in machine groups U6 and U8 throughout the year of 2019 is in the table presented, as well as their total value.

Table 5.9. Planned and registered times for machines in group U6 and U8 2019

Machine Group	**Scheduled time (h)**	**Operating time (h)**	**Net runtime (h)**
U6	12,000	10,328	10,459
U8	12,000	8,861	8,995
Sum	**24,000**	**19,189**	**19,454**

The scheduled time is based on 4,000 available operating hours per machine per year. The operating time is the actual time the machines have been working on details which has been registered in RS. The net runtime is the calculated value of the total expected operating time. This expected value has been generated through previous studies where operators have been clocked while running articles under normal circumstances. The availability rate and performance efficiency has been calculated according to Equation 2 and 3. The result is presented in Table 5.10 below.

Table 5.10. Availability rate and performance efficiency

Machine Group	**Availability rate (A)**	**Performance efficiency (P)**
U6	86.1 %	101.2 %
U8	73.8 %	101.5 %
Average	**80.0 %**	**101.4 %**

An availability rate at 80.0 % corresponds well to the estimated value used by the production planning department. A performance efficiency value at 101.4 % means that the production is performing as expected.

5.2. Investment Analysis

The analysis of the current situation showed that the investigated equipment, i.e. the capture units, chucks, and fixtures, have enough capacity to produce the articles that require these features. According to the practices of the Theory of Constraints, an investment should not be made until a constraint has been identified, exploited and other non-bottleneck resources have been subordinated to the constraint. In this case, the constraints discussed do not restrict the production capacity at this point, wherefore an investment is not relevant to analyze at all.

Another reason for postponing any investment analyses is due to the implementation of the new planning tool, SWB. This system will automatically suggest the optimal production schedule when including all factors that restrict the production capacity. If this tool indicates that the production can not be accomplished within the required time range, it is suggested to look further into ways of increasing the production capacity. This suggestion is supported by the actions proposed in the TOC as well.

6. Conclusion

This chapter will answer the research questions formulated in the introductory chapter, based on the results obtained in the empirical study as well as project analysis. It will also provide a recommendation to the company for future work and other actions to improve the scheduling reliability.

6.1. Answers to Research Questions

Three research questions were at the beginning of the project formulated, to specify the goals of the project and to facilitate the fulfillment of its purposes. Each chapter of the thesis was developed with the intent to answer these questions. The conclusions of the project will to a large extent be based on the answers to the research questions. They also make up a foundation for the recommendations that will be made later in this chapter.

6.1.1. RQ 1. *Which constraints related to the production scheduling exist in the processing facility?*

The criteria for a parameter to be labeled as a constraint is that there potentially could be a higher demand for the equipment than what is available. More precisely, for each piece of equipment that is referred to as a constraint, there is more than one article that requires it during processing. Hence, these parameters carry a risk of being double-booked in the scheduling phase. The empirical study resulted in the identification of three accurate constraints, which all could have an impact on the available production capacity in West. These constraints are all physical equipment and mechanical features, namely capture units, chucks, and fixtures. Each constraint is concisely presented in the following sections.

6.1.1.1. Capture Units

Some articles consist of the toxic material phosphine, which create toxic gases during processing. Due to work environment reasons for the machine operators, these articles carry a requirement that a capture unit is installed in the machine, as to collect these emissions. Amongst the vertical CNC machines, there are three that have a capture unit installed, namely U6:C, U6:D, and U8:C. How many articles that require this feature in each machine group is presented below.

- ➢ 21 articles produced in the U6 group require a capture unit
- ➢ 13 articles produced in the U8 group require a capture unit

6.1.1.2. Chucks

There are three chucks in West, whereof two have a diameter of 900 mm and one has a diameter of 600 mm. The smaller chuck is only used in one machine, namely the U6:C machine. Further, it is only used to produce one type of article. The two larger chucks are used in all U6 machines, as well as in the U8:B and U8:C machines. There are 25 articles in total that require chucks to be processed. More precise information is presented below.

- ➢ 2 articles use the 600 mm chuck in the U6:C machine
- ➢ 16 articles use the 900 mm chuck in any of the U6 machines
- ➢ 7 articles use the 900 mm chuck in either the U8:B or U8:C machine

6.1.1.3. Fixtures

There are many fixtures in West and there is only one unit of each model. Most fixtures are customized for specific articles. However, some articles require the same unique fixture, in order to be attached in the machine. The quantitative information about these fixtures is presented below.

- ➢ 1 fixture is used for producing 7 articles
- ➢ 2 fixtures are used by 4 articles
- ➢ 35 fixtures are used by 2 articles
- ➢ The remaining fixtures are used for one unique article

6.1.1.4. Tools

As no information confirms if there are specific tools that are a scarce resource in the current production in West, the tools are not considered as constraining factors from the planning perspective. Consequently, no parameter can be added in the SWB software to avoid machine downtimes associated with the tools. However, the large variations in machine stop times caused by searching for tools indicate that more work is necessary in this area. This will be discussed in the last chapter of the report.

6.1.2. RQ 2. *What effects do the constraints have on production performance and efficiency?*

In the current situation, neither of the above-mentioned constraints limit the production capacity, given that the scheduling is done properly. The analysis showed that there is enough capacity for the capture units, chucks, and fixtures, to fulfill their respective demand on availability. The results from the Availability-Occupancy Ratio calculations are repeated in Table 6.1 below. As the tools do not constitute a constraint in the sense of limiting the production planning, this aspect is not included in the table.

Table 6.1. Summary of Availability-Occupancy ratio for all constraints (source: Authors)

Constraint	Explanation
Capture units	There are three machines that have a capture unit, namely U6:C, U6:D, and U8:C. The AOR for the respective machines is presented below. ➢ The combined AOR in U6:C and U6:D is 43 % ➢ The AOR in U8:C is 41 %
Chucks	There are three chucks in total which are used by 25 articles altogether. The AORs for the chucks are presented below. ➢ The AOR for the 600 mm chuck is 39 % ➢ The combined AOR for the two 900 mm chucks is 24 %
Fixtures	There are three fixtures that are used by more than two different articles. Their respective AOR is presented below. ➢ The AOR for the fixture that is used by 7 articles is 24 % ➢ The AOR for the first fixture that is used by 4 articles is 38 % ➢ The AOR for the second fixture that is used by 4 articles is 10 %

As mentioned in the previous section, there is enough capacity to fulfill the expected demand of capture units, chucks, and fixtures. This is also confirmed by the results in the table above, as all constraints have AOR below 100 %. A precondition to this is, however, that the scheduling is done enough in advance to have a margin for spreading out the production orders that require the same equipment. As many of the products are MTO, this is important in order to fulfill the requirements on service level and delivery precision.

From the interviews performed at the beginning of the project, it was understood that there are regular incidents when the demand for chucks exceeds the instantaneously available capacity. As the analysis showed that it, in theory, should be enough capacity to saturate the production demand with a large margin, these double-bookings are assumed to be caused by sporadic mistakes in the planning. In other words, two articles that require the same chuck are scheduled at the same time. Another possible explanation for these incidents is unexpected breakdowns, which are not possible to avoid from a planning perspective. It should be underlined that even though the analysis performed concerns the period February 2020 to February 2021, the variation in production volumes for previous years is in this case negligible.

The correlation between the identified constraints and the OEE was not investigated as lack of quality rate data made the OEE calculations too uncertain. The analysis did however provide a correlation analysis methodology. This methodology is recommended to be used in future scenarios when the RS Production system is accurately measuring West's OEE.

6.1.3. RQ 3. *Which improvements can be made to reduce the impacts of the identified constraints?*

Although there is not currently a shortage of available capacity, it is important to recognize the factors that could have an impact on future scenarios. As there are only three chucks in total, a loss or breakdown of one unit could have a significant impact on the production situation and available capacity. The same applies to the capture units and fixtures. This is especially important for the articles that are produced in large volumes, i.e. the high-runners, that use at least one of the identified constraints. The analysis showed that out of the 8 high-runners in the U6 group, only 6 articles were concerned by at least one constraint. In the U8 group, 3 out of 6 high-running articles were dependent on at least one of the constraints.

A measure to prevent failure of the most essential pieces of equipment is to introduce routine checks and continuous maintenance. During the unstructured interviews in the first part of the data collection process, it was understood that the fixtures sometimes break as they are worn out. If the operators regularly registered the condition of the equipment, it would be easier to detect potential flaws or cracks. Consequently, the equipment could be maintained and repaired, or a new one could be purchased before breakdown occurs.

As for the tools and the variations in time spent searching for them, additional investigations must be done. The results obtained in this research have shown that there is a large waste of time caused by this activity, but precise measures are at this stage impossible to propose. A starting point would be to ask the operators to write more details concerning these stops in the RS Production program, which could be used as data for future analysis. Such comments should include which article is associated with the stop and what type of problem caused the downtime.

A final improvement that is suggested based on the results of this research concerns the changeover times. More efficient changeovers will in theory lower the occupancy of constraints and thereby increase their availability. The improvement procedure of decreasing the changeover times should be made following the principles of SMED. According to this method, operations should be made standardized, and internal and external operations should in this scenario be identified.

6.2. Recommendation

Based on the analysis and results of this project, it is recommended that Sandvik adds the three identified constraints in their new scheduling tool, the SWB software. These parameters concern the usage of chucks, fixtures, and the need for capture units. This means that for each article that uses any of the mentioned factors, this information must be included in the program. As new articles get introduced, their constraints need to be added to the scheduling tool. It is of importance to check to see if the article requires any of the constraints identified in this project. Caution should be taken as new constraints may arise as new articles get introduced. It is thus recommended that a newly introduced article is not only checked for required constraints, but also examined if it requires any additional equipment which might entail a risk of being a constraint. Semi-structured and structured interviews are an efficient way of identifying these future potential constraints. They should thereafter preferably be verified through archival data. Changes in known constraints' AOR could also happen due to new introductions. The constraints' AOR should thus be analyzed as changes in production happen.

Concerning future investment investigations and evaluations, it is suggested that Sandvik analyzes the outcome of the planning when the SWB has been fully implemented. As this program automatically will suggest the most optimal production sequence, and even propose multiple options, it will quickly be clear whether there is a shortage in production capacity due to scarcity in equipment availability. If the program fails to propose production schedules that result in accurate product deliveries, the cause will be easily identified in the system. Hence, the need for increasing the equipment capacity will automatically be revealed.

It is further suggested that routine checks are initialized for the production equipment in West. This could be done by the operators themselves, as a step in the preparation of a new machining job. This would be a precaution that could minimize the risk for unexpected equipment breakdowns and allow for maintenance or orders of new equipment to be done in time.

Concerning the tools that are not permanently installed in the machines, it is recommended that Sandvik looks further into the variations in time spent searching for them. This activity equals machine downtime, and it is recommended that additional work is initialized. Such a project should further investigate the reasons for this issue, as well as propose future actions to reduce the machine downtimes caused by the search for tools. One measure that should be taken as soon as possible is to have the operators write more details concerning the machine stops, such as the associated article and the specific reason for the stop. This composes necessary data for future analyses of this issue.

It would furthermore be recommended to make the changeovers more standardized to achieve a lower spread in changeover times. This would mean that the changeovers would be based on best practice and thus reducing the risk of unnecessary operations. Changeover times would as a result be lowered, leading to increased flexibility in the production and increased constraint availability. Analyzing the best practice of a changeover will create an ideal operating time. It is this ideal time that should be used when measuring the performance efficiency instead of using the net runtime. The net runtime is as for now based on an average operating time and not the ideal case. This means that the performance efficiency is being measured against expectancy instead of an idealistic time.

Lastly, the authors have developed a guide to how similar projects can be carried out. It is suggested that for the implementation of SWB in the processing facility East, Sandvik may follow the steps described in the manual attached in Appendix B of this report. This handbook provides general instructions on how to initialize the work, how to perform the analysis and verify the results, and which output documents are expected. It presents the same workflow as applied in this project, including important takeaways that should be emphasized. The guide also summarizes the scope of the project and its main objectives.

7. Discussion

In this chapter, the findings from the analysis and conclusion are discussed from new angles and perspectives. In the first section, the results of the research questions are reflected upon. Followingly, factors that could affect the reliability of the findings are presented. The chapter ends with a discussion concerning future work and studies.

7.1. Discussion of Results

The objectives stated in the introduction were throughout the project fulfilled as they were set out to be. This included the executive summary and the oral presentations at Lund University and Sandvik. Furthermore, the complete compilation of the research findings was handed over directly to the company, which contained the specific details concerning which articles were associated with the identified constraints. Also, a guide for how to perform a similar project was developed, which is attached in Appendix B.

As presented in the analysis, no investment analysis was made as the capacity of the identified constraints was found to be enough to produce the associated articles. Important to notice is that the data throughout the analysis is based on the average of a 12-month prognosis and thus supposes that there will be an even flow of production demand concerning the constraints. Overlaps might arise in a scenario where articles that require the same constraint need to be produced within the same time frame is higher than the calculated 12-month average. In times like these, the bottlenecks may get more narrow than expected. As the new scheduling tool in SWB will optimize events as such, this factor was not further investigated. The analysis does not either consider the possibility of increased capacity demand due to unexpected breakdowns. This was not investigated as unforeseen events, such as breakdowns, were set as a delimitation. The high-runners were instead identified in order to get an idea of which articles that are at a higher risk of being overscheduled in times of breakdowns of identified constraints.

7.2. Reliability of Findings

As previously mentioned, the analyzed data is based on a 12-month prognosis of the forthcoming production volumes. Naturally, this carries some uncertainties to the accuracy of the actual outcome, as the forecasts are to some extent estimations. However, this was not considered as a major risk for the reliability of the results, as it is assumed that Sandvik makes forecasts based on accurate data and that they have well-developed routines for such work.

When analyzing the changeover and setup times, a lack of data was found to be a limiting factor. The changeover and setup times are only sporadically linked to certain article numbers in RS Production, which causes uncertainties. As too few articles were linked to certain setup times, these could not be analyzed at all. Further to investigate within this area is the operators' general decision makings, when linking a changeover or setup time to an article number. Somewhat accurate results can be drawn if this happens randomly, under both normal and abnormal circumstances. The data can not, on the other hand, be considered as accurate if an operator notes a changeover or setup time during only abnormal circumstances. Furthermore, the RS Production only registers machine stops over five minutes. Any unnecessary machine stops shorter than five minutes will therefore not be registered and consequently not analyzed.

Data collection through interviews, both structured and unstructured, was found to be a useful approach to get an overall comprehension of experienced problems and issues in the workers' day-to-day tasks. All three of the final identified constraints were first recognized through this method. Throughout the interviews, biased respondents were seen as a hazard for inaccurate responses. As archival data was used to verify the identified constraints, the impartiality of the constraints could still be assured.

Several delimitations were made at the beginning of the project. One delimitation was to disregard potential new product introductions. This was done as there was vague information about future product launchings. It was also determined that it would complicate the analysis radically, as there are many other aspects to include when introducing a new article. The analysis may thus require a recalculation if new products are introduced.

The result for the availability rate and the performance efficiency shows high values for both machine groups. Although, some uncertainties regarding the results can be found. The availability rate is based on an estimated value of the scheduled time and not an exact time. To get a more accurate number, the actual scheduled time for the previous year needs to be further investigated. The scheduled time is also assumed to be equal for all machines, which might not be the case. The performance efficiency shows that the production is running faster than the calculated ideal time. This could be an indication that the net runtime is based on an average operating time, and not on the ideal time.

The setup time is not included when calculating the constraint's AOR. These values only account for the net runtime, i.e. the expected operating time. The reason being that the setup times are not being labeled as internal or external, meaning that some parts of the setups can be performed as a machine is operating and some part of the setup times can not. The setup times will also differ depending on the batch sizes about to be produced. As seen in the analysis of the changeovers, there are some variations in how operator's practice changeovers. This gives reason to believe that the same goes for setups. The setup time was therefore not included in these calculations. This means that the occupancy for a fixture or chuck might be higher than presented. Excluding setup times in the AOR calculations was however found to give the most accurate results considering these uncertainties.

7.3. Further Work

Although the analysis showed that no new investments of additional equipment and tools should be needed, in terms of reducing overlaps in the planning, investments may still be useful to increase the efficiency of the production. This could, for example, be done by reducing the operators' walking distances, according to the SMED principle. By investing in one toolset per machine, unnecessary movements could be limited. As discussed in the time distribution in a setup process presented in Table 3.1, only 20 % of the total time will be found in Step 2 and 3 in an average facility. 30 % of the time distribution will, however, be found in Step 1, which includes the movements to prepare and set up the machine. Further research could, therefore, include analyzing internal and external operations in more depth. The variations in changeover times that were found in the analysis further support this statement. The OEE for West should furthermore be calculated in order to draw conclusions about its correlation to identified constraints. To get an as accurate number as possible, an ideal operating time after implementing the concept of SMED is recommended to be made.

Concerning the variations in machine stop times caused by searching for tools, more work should be done to further comprehend the reasons for these downtimes. Currently, the operators can choose to add comments to the stops in the system RS Production, but this is optional. As the existing information is not enough to draw any conclusions about which measures to take to reduce these stop times, it is suggested that every machine downtime is not only registered but also explained in a comment. For instance, which tool is concerned should be described. This would provide a starting point for further analyses about how the tools affect production efficiency. This study should also investigate if any particular tools often cause stop times. Such a result would indicate that an investment potentially is relevant to consider.

Since West is the only facility that has been investigated in this project, it is unsure whether its output risk constraining the entire production. In other words, if there currently exists larger bottlenecks in other facilities in the production chain, a delay in West might not affect the delay for the final assembly and hence customer delivery. For this reason, it would be of relevance to know if any foregoing or succeeding processing steps is a limiting factor. If West were to be found as the bottleneck itself, it would be relevant to investigate if any further equipment should be invested. If West were to be found located before a bottleneck, the importance of a high production rate would be lower.

Investigations in how the production may be affected by breakdowns could furthermore be included in future work. This analysis should focus on hazardous equipment that is more likely to have a breakdown. Another interesting perspective is to investigate the equipment used by the high-running articles. Such a project should examine the experienced breakdown frequency, the number of articles affected, and the time and cost to repair or replace the equipment. Also, the cost to have an extra set of that specific equipment ready at hand should be analyzed. A prevention strategy for each of this equipment would moreover be beneficial to reduce the likelihood of potential breakdowns.

In a scenario where it is desired to measure the impacts of constraints on production performance, the AOR can be a useful tool. If the AOR is either low or at a normal level, the constraint can be considered having a low negative impact on production performance and efficiency. A high AOR indicates that the constraint needs to be further investigated, and potentially that an investment analysis is required. The constraint's current and desired AOR should in a scenario like this be determined, and the consequence of the loss in throughput rate should be analyzed. To find out which improvements can be made to reduce the impacts of identified constraints in a future scenario, the OEE - AOR diagram in Figure 5.6. can be used as support. The area of improvement may be found by identifying where on the axis the facilities OEE and the constraint's AOR is located.

7.4. Contribution

This thesis has made contributions to research by developing a general methodology for the identification of constraints in organizations. As mentioned above, this general methodology has been summarized in the guide attached in Appendix B. It is recommended to use the same methodology as has been used in this project for similar future projects, which the guide can be used for. The thesis has also provided a way of measuring the availability of constraints by developing a ratio between its availability and occupancy. Both the theoretical references as well as the methodology which is used in the thesis covers general areas of interest and may both be used in various settings; they are not only limited to processing organizations. The way the thesis contributes to academia is through the awareness of the correlation between constraints and performance efficiency in an organization it raises, as well as the importance of effective production scheduling. The analysis provides a more case-specific approach which is not as general as the methodology, but may still be used as a source of inspiration to future research.

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Appendix A

Compilation of interviews with machine operators in West

These interviews were performed with eight machine operators working in the production hall West, on the 11th of February 2020. The purpose of the interviews was to gain deeper knowledge about the operators' working experiences, as well as to learn more about their thoughts regarding the potential limitations in the production equipment. The aim was to get a clearer idea about which of the identified factors that actually affect the operators' work and the production efficiency. The interviews were also performed to investigate if there could be any additional limitations, which had yet not been discovered by the Planning and Capacity Department.

Följande frågor är öppna och undersöker vilka problem i som kan uppstå i operatörernas arbete samt hur dessa hanteras. Syftet är att få en ökad förståelse kring vilka svårigheter som ofta förekommer i produktionen, oavsett om dessa är relaterade till projektets frågeställning.

Vilka är de vanligaste problem som du stöter på i ditt dagliga arbete? Hur löser du isåfall dessa och hur ofta uppstår dem?

Operatör 1: Kan inte komma på några.

Operatör 2: Kan inte komma på några.

Operatör 3: Det händer att detaljer levereras felvända och man får då vända på dem själv. Uppskattningsvis så händer det en gång i veckan.

Operatör 4: Det händer ca en gång i månaden att stålspån byggs upp på grund av att skäret inte skär av spånet ordentligt och bildar stora spånbollar som fastnar i maskinen. Dessa kan inte tas ut automatiskt som planerat utan maskinen måste då rensas manuellt. Häromdagen tog det ca två timmar att rensa. Detta händer ca en gång i månaden. Ett annat problem är att kvaliteten på detaljernas material varierar. När materialet är för hårt riskerar skäret att gå sönder och för mjuka detaljer blir måtten oftast fel. Detta hade kunnat undvikas om man i förväg förberett maskinen på materialkvaliteten.

Operatör 5: Kan inte komma på några.

Operatör 6: Det skulle underlätta med fler chuckar. Dessutom börjar de bli slitna och därmed mer svårhanterliga.

Operatör 7: Arbetsbelastningen vid montering av verktyg samt vid användning av lyftverktyg. Maskinen är inte byggt för att kunna hålla stora verktyg och måste därför sättas in för hand.

Vid användning av lyftverktyg, vilket sker dagligen, hanteras tunga kedjor manuellt. Varje vecka händer det även att detaljernas materialkvalitet är för låg.

Operatör 8: Backar som saknas, att det finns för få chuckar och att verktyg behövs lånas. Man får då låna från andra stationer. Händer omkring en gång i månaden att chucken saknas.

Följande frågor är öppna och handlar om förbättringar och förändringar i operatörernas arbete. Syftet är att få en ökad förståelse kring vilka tidigare ändringar som genomförts samt vilka specifika önskemål som finns från operatörernas sida.

Har det skett någon förändring som påverkar ditt dagliga arbete den senaste tiden?

Operatör 1: Ingen större förändring har har skett, men en mindre förändring är att det numera är bättre ordning på verktygen efter att verktygsskåp har införts. Tidigare fick inte alla verktyg plats i skåpen.

Operatör 2: Nej.

Operatör 3: Nej.

Operatör 4: Det har införts ett övervakningssystem, RS, där operatörerna ska rapportera när en maskin står still. Detta innebär ibland ett extra stressmoment eftersom man känner sig övervakad.

Operatör 5: Nej.

Operatör 6: Inga större förändringar. Huvudmuttarna körs numera på ett annorlunda vis.

Operatör 7: Nej.

Operatör 8: En ny tavla för morgonmötet har införts.

Har du något förslag på en förändring som skulle underlätta i ditt arbete?

Operatör 1: Mer utrymme för verktyg hade underlättat det dagliga arbetet då det är svårt att nå de bakre verktygen som täcks utav längre verktyg på den främre raden. Dessa verktyg är dessutom relativt tunga vilket inte är optimalt ur ett ergonomiskt perspektiv. Ytterligare så lånas en del av verktygen ut till de andra två U8:orna vilket kan innebära en väntetid på upp emot 20 minuter. Om den maskin som lånat verktygen havererar riskerar väntetiden bli upp emot 4 timmar.

Operatör 2: En ny luftpistol för att blåsa bort spån skulle behövas då den gamla har för lågt tryck. En ny har blivit beställd, men det var över 6 månader sedan och den har fortfarande inte kommit. Dessutom så behövs det fler verktyg. I och med att U8:orna delar jobb så delar de även verktyg, uppskattningsvis ca 20 %. Det händer ungefär en gång i månaden ett verktyg är upptaget vilket kan leda till en väntetid på upp emot 15 minuter.

Operatör 3: Nej.

Operatör 4: Mer frihet och ägandeskap över vad man själv producerar hade varit uppskattat.

Operatör 5: Bättre planering kring vilka jobb som behöver chuck. Det händer nämligen att jobb måste läggas över till veckan efter om detaljer som kräver chuck överlappas.
Operatör 6: Bättre planering kring chucken hade underlättat. Det händer omkring en gång i veckan att den är upptagen när man behöver den och att man får köra ett annat jobb.
Operatör 7: Användning av stroppar till lyftvertygen hade underlättat arbetsbelastningen. Lättare eller enklare handverktyg, alternativt hjälp av en robot vid montering av verktyg, hade ytterligare underlättat arbetsbelastningen.
Operatör 8: Nej.

Följande frågor berör de hittills identifierade eventuella begränsningarna, dvs fixturer, chuckar, verktyg och personalkompetens. Syftet är att förstå om dessa faktorer även upplevs som en begränsning ute i bearbetningshallen.

Finns det operationer som du inte har behörighet eller tillräcklig med kunskap för att utföra?

Operatör 1: Alla ska i egentligen kunna allt, men riktigt så är det inte. Ofta jobbar man på en station under en längre tid och blir därmed specialiserad på den stationen.
Operatör 2: Ja, ofta har man koll på sin egen maskingrupp. Jag jobbar med U8:orna.
Operatör 3: Ja, jag jobbar med U6:orna, främst när de körs på kolstål. Jag kan även köra dem när de körs med tackjärn, men det tar längre tid och händer mer sällan.
Operatör 4: Ja, jag jobbar med U6 och U8-maskinerna, exklusive U8 XL.
Operatör 5: Ja, jag jobbar endast med U6:orna.
Operatör 6: Ja, jag jobbar endast med U6:orna.
Operatör 7: Ja, jag kan arbeta med alla maskiner utom WFL-maskinen, men är specialiserad på U8:XL.
Operatör 8: Ja, jag arbetar endast med U6:orna, aldrig med U8 eller WFL.

Finns det operationer som du inte kan utföra ensam?

Operatör 1: Nej, alla operationer går att göra ensam. Däremot kan en del vara svåra att utföra själv och framförallt så är det inte ergonomiskt att utföra dessa på egen hand. Detta blir särskilt påtagligt vid byte av tunga och otympliga verktyg, eftersom en pedal hållas nere vid bytet. Vid dessa tillfällen ber man ofta en kollega komma och hålla ner pedalen medan bytet sker.
Operatör 2: Nej, men det händer att man behöver hjälpa till att hålla ner pedalen i U8:XL.
Operatör 3: Nej.
Operatör 4: Nej. Vid vissa tillfällen hade det underlättat att vara två, men det är inte nödvändigt.
Operatör 5: Nej, men för en del jobb som kräver många steg hade det underlättat att vara två på.
Operatör 6: Nej.

Operatör 7: Nej, men ibland borde man kalla på hjälp. Det är dock sällan jag gör det.

Operatör 8: Nej.

Händer det att verktyg eller material ibland saknas? Om ja, hur hanterar du det?

Operatör 1: Det händer att verktyg är utlånade, men det är sällan. Det har förekommit att ett verktyg har lånats ut till en maskin som har havererat. Då fick man vänta tills den var igång igen.

Operatör 2: Ja, om de är utlånade till någon annan maskin. Då får man vänta tills maskinen som lånat verktygen är klar.

Operatör 3: Ja, ibland saknas det reservverktyg. Då får man låna från andra, ta isär dem och montera ihop ett nytt verktyg. Ytterligare så delar U6-maskinerna verktyg vilket innebär att man måste låna från varandra.

Operatör 4: Ca 200 verktyg sitter redan i maskinerna och flyttas inte, medan ca 5 verktyg byts ut och ändras efter varje detalj. Eftersom maskingrupperna lånar verktyg från varandra kan det hända att man får vänta 5-10 minuter på att få tillbaka ditt utlånade verktyg. Ibland händer det även att verktyg går sönder och måste bytas ut. Dock så är det något som ingår i ens arbetsuppgifter och anses inte som ett problem.

Operatör 5: Ja, verktyg saknas ofta då de lånas mellan maskinerna.

Operatör 6: Ja, särskilt verktyg som delas mellan maskinerna. Saknar man något får man låna från någon annan eller vänta. Just nu delar de även på en nyckel då U8:ornas nyckel är sönder.

Operatör 7: Ja, det händer varje vecka att verktyg saknas. Detta registreras inte i RS-systemet eftersom den endast registrerar stopp i maskinen på över 5 minuter.

Operatör 8: Ja, verktyg saknas ibland.

Följande frågor undersöker om operatörerna upplever de hittills identifierade begränsningar som problem samt om de har konkreta förslag på andra begränsande faktorer. Syftet är att kunna säkerställa att alla potentiella begränsningar har tagits i åtanke.

De potentiella begränsningar som vi för närvarande hittat är brist på vissa fixturer, chuckar och verktyg. Håller du med om att någon eller några av dessa är en begränsning i produktionen?

Operatör 1: Chuckar används inte i U8:XL maskinen och är därmed inget problem. Eftersom U8:XL maskinen har många egna fixturer så är det inte heller ett upplevt problem.

Operatör 2: Ja, särskilt chucken.

Operatör 3: Ja, särskilt jobb där chucken behövs. Det händer att man i slutet på veckan upptäcker att det är många jobb som kräver chuck och att man får lägga över jobb till nästa veckas planering.

Operatör 4: Chucken är inget problem för U8-maskinerna men ett större problem för U6:orna som använder den oftare. Däremot kan det uppstå problem med fixturerna, särskilt spindelfixturen som används till två jobb. Det händer omkring en gång i halvåret att jobben krockar och man får lägga om planeringen.

Operatör 5: Ja, chucken begränsar ofta. Fixturerna anses däremot inte som ett problem eftersom det är ganska få jobb som kräver samma fixtur.

Operatör 6: Ja, chucken men inte fixturerna.

Operatör 7: U8:XL har inte problem med chucken eller fixturerna. Däremot händer det att verktygen ett problem.

Operatör 8: Fixturer kan vara ett problem, men det har bara hänt en gång.

Kan du komma på några ytterligare potentiella begränsningar som vi borde se över?

Operatör 1: Nej.

Operatör 2: Eventuellt distanser till chucken.

Operatör 3: Nej.

Operatör 4: Lyftdon kan vara begränsande, men är ofta inget större problem. Det händer omkring en gång i halvåret att ett lyftdon är upptaget när man behöver det.

Operatör 5: Nej.

Operatör 6: Spånkross måste tömmas dagligen, ca en gång i timmen.

Operatör 7: Nej.

Operatör 8: Skruvtvingar samt lyftverktyg kan det vara brist på.

Appendix B

Guide to identifying constraints in a processing facility at Sandvik

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This manual is based on the approach used for a master thesis project done at Sandvik during spring 2020. The overall project task was to identify constraining factors in the processing facility West, which limited the available production capacity in terms of physical equipment required for the various machining operations. This document aims to support similar analyses in other facilities at Sandvik. The first part of this document will describe the purpose of the project and the second part will give an overview of the work phases. The following sections will present in detail how the work is initiated, how it is performed, and which information it results in.

Project Scope

The project aims to establish which factors have a constraining impact on the available production capacity from a planning perspective. The task is hence to identify all parameters that could restrict the production in a processing facility at the Sandvik plant in Svedala, in terms of availability of tools and equipment that are required for various processing operations. The research aims to further analyze the effect these so-called constraints have on the production efficiency and to which extent they cause delays or other production disruptions. Once these parameters have been identified, they will be added in the production scheduling software SWB, in order to improve the optimization of the production sequence. Additionally, the purpose is to suggest future improvements and potentially minor adjustments in the scheduling process, to eliminate the risks of lost machining capacity that these limitations carry.

The project scope can be summarized in the following three questions:

- ➢ Which constraints related to the production scheduling exist in the processing facility?
- ➢ What effects do the constraints have on production performance and efficiency?
- ➢ Which improvements can be made to reduce the impacts of the identified constraints?

Overview

To get an overview of the different steps required to perform this project, the workflow is divided into three distinct phases. These are a preparation phase, an execution phase, and an analysis phase. Each one is characterized by its internal purpose and expected output. Table B1 below presents a concise description of the contents of each phase, their respective purposes, and outputs. In the subsequent sections, the stages will be described more in detail.

Table B1. A brief overview of the project phases (source: Authors)

Phase 1: Preparation	**Phase 2: Execution**	**Phase 3: Analysis**
1. Perform background research 2. Complete unstructured interviews 3. Establish a semi-structured interview guide	4. Complete semi-structured interviews 5. Collect archival data 6. Verify the accuracy of the findings	7. Define the current situation 8. Analyze the impacts of the constraints 9. Compile the results of the project
Purpose: Plan the project and get an overall view of the problem.	**Purpose**: Collect the empirical data and validate the findings.	**Purpose**: Analyze the effects and summarize a conclusion
Output: Interview guide	**Output**: Verified data	**Output**: Current situation analysis

Phase 1: Preparation

The first step of this project is to get an overall idea of the current situation and which documents to look into. The aim is to better understand which problems have been experienced in the past and to establish a starting point for the work. The background research includes collecting information about how the company organizes the production and in which operations uncertainties prevail. This is done by general interviews with concerned staff and groups at Sandvik, as well as observations in the workshop.

It is recommended to do this work as impartial as possible, i.e. to have few ideas about which factors to search for. Once the basic idea of the problem has been understood, it is possible to dig deeper into the factors that are connected to the planning of the production. It is hence suggested to gather as much data as possible concerning factors that could reduce the production efficiency, and then to analyze which parameters are relevant to investigate closer. The semi-structured interviews aim to provide additional data about the already identified potential constraints, as well as to discover if any new parameters are of interest. These interviews are most likely done with machine operators in the factory, who experience production disruptions first hand. The output document of the preparation phase is thus a guide to these interviews. This guide should aim at posing open questions about general problems experienced in the workshop, without implying that certain factors are analyzed in the study. Towards the end of the interview, more specific questions can be formulated. This will reduce the liability of influencing the interviewees to mention certain aspects as potential risk factors.

Phase 2: Execution

In the second phase, both qualitative and quantitative data will be collected. The qualitative data concerns the results of the interview sessions. A rule of thumb is to complete as many interviews as necessary to find convergence in the answers. That is, if no new factors are discovered in the interviews, this data collection method is completed. In West, it was necessary to perform eight interviews with machine operators to find convergence.

Based on the answers from the interviews, a list of proposed constraints can be compiled. From this information, the parameters that theoretically could be affected by the scheduling should be highlighted. In other words, the factors that could cause bottleneck situations in production. The following step is to search for quantitative data for these parameters. The qualitative data concerns, for instance, information about which articles are concerned by the identified constraints and which machines are associated with them. Some of this data can be retrieved in the software systems M3 and RS Production.

The final step of the data collection, or the execution phase, is to make sure that the information is accurate and valid. This is partly done in the archive analysis, i.e. the quantitative analysis, but it is also recommended to have follow-up meetings with concerned staff at Sandvik. This step should be done prior to the analysis of the data. This is a way to check that the findings are reasonable and to avoid that any misunderstandings propagate in the following analysis. The outputs are the results from the empirical data collection, i.e. the verified empirical data. This list also constitutes the information that should be added in the SWB software.

Phase 3: Analysis

The last phase of the project concerns the analysis of the verified findings from the data collection. The first step is to formulate the current situation, hence to list all parameters that have been confirmed as a potential constraint in the production. The analysis of these factors aims to clarify to what extent these parameters constrain the production capacity and to identify which issues are most urgent to assess. The analysis points that are of interest to this study are presented below.

- ➢ The total available capacity of each constraint in terms of accessible production hours.
- ➢ The total utilization of each constraint, hence the total time that each article using the constraint occupy it, multiplied by the annual production volume of each article:
  $Total\ Occupancy: \Sigma\ (Processing\ time \times Production\ volume)$

- ➢ The ratio between the available capacity of the constraint and the occupancy of it:

$$Availability - Occupancy\ Ratio\text{:}\ \frac{Total\ occupancy\ of\ constraint\ (hours)}{Total\ availability\ of\ constraint\ (hours)} \times 100\ [\%]$$

The Availability-Occupancy Ratio (AOR) presents the proportion of the available constraint capacity that is used by all its associated processing activities. A value close to 100 % indicates that the equipment is almost fully utilized, and hence there is a large risk of over-scheduling the constraint. In a case where the value even exceeds 100 %, the conclusion is that the constraint can not meet the required demand on available capacity. In both these cases, a further investment analysis should be performed. A low value is interpreted as there is enough capacity to fulfill the expected demand, and there is no need for further investigations to increase capacity. Another important consideration is the likelihood of machine or equipment breakdown. If there is a high risk for production downtimes, increased capacity, and thus new investments might be necessary to meet the required demand.

Besides the values of the constraints presented above, it is interesting to perform an analysis of the articles produced in large volumes, the so-called high-runners. These are defined as the 10 % most commonly produced articles in the facility. This analysis should map which constraints are associated with the high-runners, which will visualize the dependency of potentially hazardous equipment. Another aspect that could be relevant to include in the project is potential new article introductions. If it is forecasted that additional articles will be manufactured, their expected occupancy time should also be analyzed to obtain a valid result.