Analyzing the production capacity of Company X

Bachelor Thesis

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February, 2021

University of Twente

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Preface

In front of you lies the report of the bachelor thesis that I have created in the final year of the Bachelor's degree Industrial Engineering and Management. The thesis is conducted at Company X[1]. This company supplies a wide range of products for the construction industry. Parts of these products are manufactured by the company itself at its production facility.

First of all, I would like to thank my two supervisors within the company. Although they had a busy schedule, they were always willing to explain the production process within the company and give feedback on the research. On top of this, I would like to thank the quality manager and all other employees within the company since they were always willing to help me if I needed additional information.

Moreover, I would like to thank my first supervisor from the University of Twente, Marco Schutten. Although having physical feedback meetings was not possible due to the corona pandemic, he was always willing to help me and gave a lot of critical feedback on the thesis. This feedback made me reflect on my research and increased the quality of the research a lot.

Lastly, I would like to thank my buddy during the research, Laurens Kok. He helped me to stay motivated during the creation of the thesis and was a good sparring partner to discuss different aspects of the research. This helped me stay on track and improve the academic level of the research.

[1]The company where I executed the research is referred to as Company X due to confidentiality. On top of this, quantitative values provided in the thesis are multiplied by factor Y, or are not shown at all, due to the confidential nature of the data.

Management summary

Introduction
Company X manufactures buckets, tubs and rectangular tubs for different customers throughout Europe. Since the company has grown rapidly the last few year, the production facility of the company has difficulties meeting the increasing demand of its customers. Currently, the production employees have to work a lot of overtime during the weekend to meet this increase in demand. In this research, an optimization model is created to answer the following research question:

"What changes have to be made to increase the production capacity of the production facility, taking into account customer demand?"

Context analysis
The first step taken to answer the research question is a context analysis. This provides the necessary information about the production facility and shows how the production output of the different products is achieved. The context analysis describes the manufacturing process, production roster and product range in detail.

Theoretical framework
The theoretical framework of the research reviews literature on increasing the production capacity of manufacturing companies - like Company X. Two methodologies are found to be effective for increasing the production output: The theory of constraints and Lean manufacturing. Next, we have looked into literature on demand forecasting. This is used to create a demand forecast, which is used later in the research. Lastly, techniques for solving optimization problems are reviewed. The technique that is used in this research, linear programming, is reviewed in more detail so that it can be applied to the case of Company X in a valid manner.

The optimisation model
Based on the literature reviewed, we decided to apply the Theory of Constraints in this research. Specifically, step 4 is applied: Elevating the constraint. This implies possible solutions for the low production output are analysed. Possible ways for removing the bottleneck, the injection moulding machines, are analysed. In order to analyse future production scenarios of the company, a mathematical model is created of the production facility. After creating the optimisation model, it was simplified to make it user friendly for the company. Next, data for parameters used by the model is gathered. The credibility of the model depends on the validity of this data. Therefore, the data validity is discussed extensively for the different parameters.

Experiments
With the simplified optimisation model, experiments for future production scenarios are carried out. The model is created in *Microsoft Excel*. The validation experiment showed the model did not match the real life system performance. Therefore, input data is changed to better reflect the real life system. Four possible production scenarios are analysed.

On top of these experiments, a sensitivity analysis is carried out on the optimisation model to see what changes to the model output when input parameters are changed. This showed that reducing the cycle time and improving the Overall Equipment Effectiveness (OEE) increased the production capacity and value created at the facility.

Conclusions, recommendations and discussion
Based on the experiment results we concluded Company X should start producing in the weekend at the production facility. In this way, the expected demand for 2021 can be met and almost all demand for 2022. It should be noted that this conclusion is based on the findings of the model. Qualitative aspects, like willingness of employees to work during the weekends, is not taken into account in the model. Next to this conclusions, we make several recommendations based on the research findings.

First of all, Company X should start implementing a good cleaning policy for the injection moulding machines. This will likely reduce breakdown time at the injection moulding machines and allows the products to be manufactured at a lower cycle time. This can increase the production capacity of the production facility, since more products can be manufactured in the same time frame. On top of this, the costs of goods sold will decrease.

Second, we recommend the company to reduce and standardise the cycle times at the injection moulding machines. Since there is no standard on cycle times, and there is no good cleaning policy, the cycle times are often higher than they could be, which increases the production costs per product and decreases the production capacity.

Lastly, we advice Company X to use the optimisation model as a supportive decision tool when analyzing future production scenarios. This gives an indication to see whether the production facility is able to meet expected demand, or whether the demand exceeds the production capacity of the facility. When using the optimisation model in the future, the input data used should be validated and changed if necessary, in order for the model to be an appropriate representation of the real life system.

Contents

1 Introduction

This chapter provides an introduction to the bachelor thesis assignment. The introduction consists of the following subsections:

- 1.1 Company introduction
- 1.2 Research motivation
- 1.3 Problem identification
- 1.4 Research design and problem solving approach

1.1 Company introduction

Research is executed for Company X[2] during the bachelor thesis. This company sells different products for the construction industry of which some are produced at the organization itself. The products that are produced at the facility are buckets, tubs and rectangular tubs. For these products, partially automated production lines are established in the production hall of the company. These production lines all contain an injection moulding machine, which uses recycled plastic as the raw material for the different products. After a pallet is fully loaded with products, it goes through the stretch hood machine, which seals the pallet with plastic, and is transported to the warehouse. In the last few years, the company has been growing rapidly and innovations with regards to sustainability and new production lines have been made. In the last year, 2 new injection moulding machines have been purchased, which have lower electricity costs than the older machines.

1.2 Research motivation

During the research, the company was having difficulties creating the desired production volumes for the different product types. This was caused by an increase in sales of around 10% per year. The production facility was close to its production capacity, which means the additional output that can be created is limited. This means that when sales peak, the company was forced to manufacture during the weekends and letting its production employees work a lot of overtime. According to the financial director of the company, the market shows a lot of potential for even more growth. Therefore, the company was interested in seeing how the production capacity can be increased so the increasing demand can be met.

1.3 Problem identification

In order to further increase the production volume, the company wants to increase the output of the production facility. The production lines have been analysed to see what the causes are for the low production output. Figure 1 shows these causes in a problem cluster.

[2]The company where I executed the research is referred to as Company X due to confidentiality. On top of this, quantitative values provided in the thesis are multiplied by factor Y, or are not shown at all, due to the confidential nature of the data.

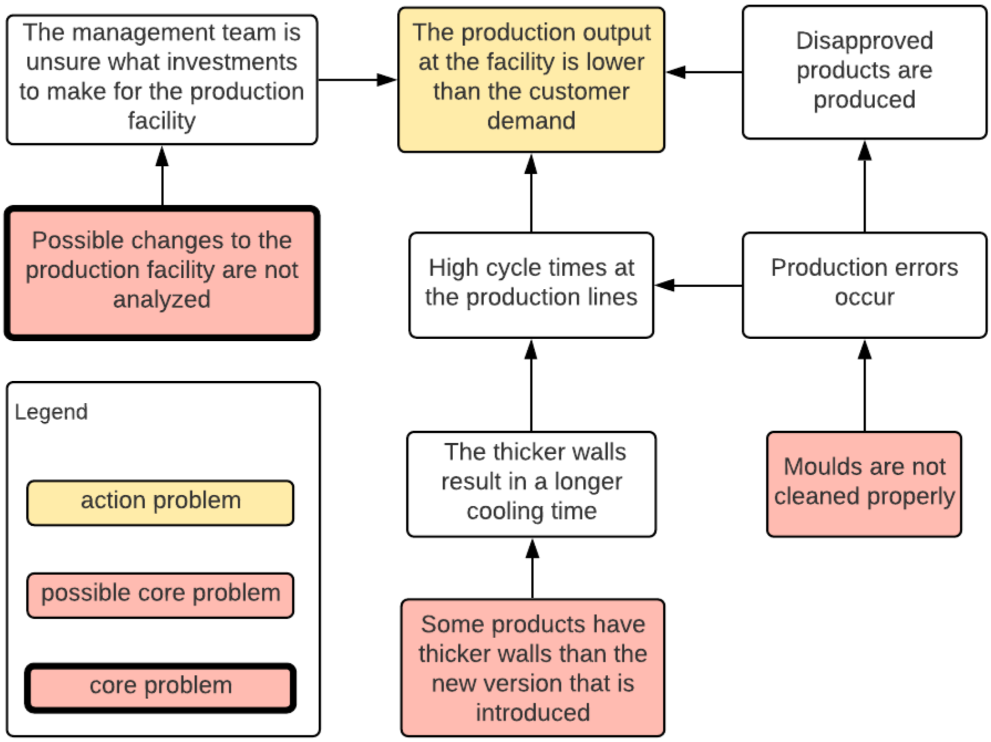

Figure 1: Problem cluster

In the cluster, three problems appear which have no cause of their own. These could be considered as possible core problems to solve during the research. According to Heerkens and Winden (2017), the problem that should be solved should have the highest impact at the lowest cost. In the following paragraphs, an explanation of the problem cluster and a motivation for selecting the core problem is provided.

The first possible core problem depicted in the bottom right of Figure 1, is that *moulds are not cleaned properly*. This results in *production errors occurring* at the production lines. Production errors often cause the products to be of low quality which can therefore not be sold to customers. The problem cluster shows this via the box *disapproved products are produced*. The production errors are often solved by increasing the cycle time at the production line, so that the manufactured products meet quality standards. The box *High cycle times at the production lines* shows this. The problem *moulds are not cleaned properly* is not chosen as the core problem, since the operations manager within the company is currently solving this problem.

The second possible core problem in the center bottom of the figure is that *some products have thicker walls than the new version that is introduced*. Company X often manufactures 2 versions of the same product, where the only difference is the wall thickness. Products with a thinner wall have been introduced to the market since these cycle times are lower than products with thick walls. The old products with thicker walls have a higher cooling time. This results in high cycle times at the production lines. It is difficult to solve this, since some customers are not willing to switch to newer products that have thinner walls. Therefore, this problem is not chosen as the core problem to solve during the research.

The third possible core problem is that *possible changes to the production facility are not analysed*. The management of Company X wants to make investments to the production facility to increase the production output. The company is interested in several investment possibilities for increasing the production output. They are interested to see what happens when production takes place during the weekend on top of the regular production shifts, which are from Monday up until Friday. Moreover, they are interested to see whether investing in an additional production line is desired, because this will also increase the production output.

The management does not know how much the production capacity of the production facility increases when they make an investment in one of these options. Therefore, the management team is unsure what investments to make to the production facility. Analysing these production scenarios gives the management insights in what solution will increase the production output by the desired amount at the lowest costs. Out of the three possible core problems, solving this problem is expected to have the highest impact. Therefore, the core problem is:

Possible changes to the production facility are not analysed.

1.4 Research design and problem solving approach

In order to solve the core problem of this research, the following research question is formulated and answered in this research:

"What changes have to be made to increase the production capacity of the production facility, taking into account customer demand?"

By answering this research question, we aim to solve the core problem the company is facing: *Possible changes to the production facility are not analysed.* The report is structured by different chapters. Each chapter consists of a sub-research question. These questions are formulated for answering the main research question effectively. The following research questions are formulated:

1. **How are the products manufactured and how is the production output achieved?**
This question aims to analyse the current production facility in more detail and therefore provides a context analysis. It provides the necessary information about the production facility to conduct the research effectively. The section analyses the production process, the production roster and the product range manufactured. This question is answered in Chapter 2 through observing the current production facility. Moreover, interviews with stakeholders are conducted when additional information is necessary for answering the research question.

2. **How can the production capacity of a manufacturing company - like Company X - be increased according to literature?**
Chapter 3 answers this question by reviewing literature. The chapter provides a theoretical framework for the research. Specific literature that is reviewed are optimisation methodologies, techniques for solving optimization problems and demand forecasting.

3. **What optimisation method is used for modelling the production system?**
Chapter 4 provides the answer to this research question. A method for analysing possible production scenarios, based on literature, is selected and motivated. After this, a model of the production facility is formulated and simplified. Data for the parameters in the model are gathered and the validity of this data is discussed.

4. **What experiments have to be carried out with the optimization model?**
With the established model, experiments are carried out to analyse possible changes to the facility. First of all, a validation experiment is executed, which shows parameter input data is not valid. After improving the parameter input data, production scenarios the company is interested in were analysed. The experiments can be found in Chapter 5.

A schematic overview of the activities performed for every research question can be found in Table 1.

Table 1: Research design for the sub-research questions

Sub-research question	Research method	Research population	Subjects	Method of data gathering	Method of data processing	Activities performed
1. How are the products manufactured and how is the production output achieved?	Explanatory, broad qualitative	Production facility	Production employees, operations manager	Observation, interviews	Broad qualitative	Analysing the: • Manufacturing process • Production roster • Product range
2. How can the production capacity of a manufacturing company - like Company X - be increased?	Explanatory, deep qualitative	Production companies using injection moulding machines	researchers	Literature study (cross-sectional)	Broad qualitative	Explaining literature reviewed for answering the different research questions
3. What optimisation method should be used for modelling the production system?	Descriptive	Production facility	Operations manager, production employees	Observation and primary data	Deep, qualitative and quantitative	• Motivating the created model • Formulating the model • Gathering data for solving the model
4. What experiments have to be carried out with the optimisation model?	Descriptive	Production facility	Researchers, Management Team	Interviews and observation	Qualitative and quantitative	• Simplifying the optimisation model • Running experiments for production scenarios • Experimenting on sensitive parameters

Based on the answer to these sub-questions, the main research question this study addresses is answered in Chapter 6. On top of answering the research question, limitations of the research are discussed and recommendations are given to Company X, which are based on our findings in this research.

2 Context of the production facility

This section provides information about the production process of Company X. The context of the facility is described by answering the following research question:

"How are the products manufactured and how is the production output achieved?"

The following sections are created to answer the research question:

- 2.1 The manufacturing process
- 2.2 The production roster
- 2.3 Product range
- 2.4 Conclusion

2.1 Manufacturing process

At the production facility, 10 production lines are established on which the buckets, tubs and rectangular tubs are manufactured. Each production line consists of an injection moulding machine. In this machine, plastic material is being sprayed into an injection mould under high pressure. The mould opens up and the product is put onto a conveyer belt when the product is cooled down. After the injection moulding process for a product has finished, the tubs and rectangular tubs have met their final configuration. For buckets this is not the case. These products still need handles to be put on top of the product. This is done with a so called *handling machine*. The machine picks up the product and automatically places the correct handle on the product. For production line 6 & 7 and 8 & 9, one handle machine is used for two injection moulding machines. The manufactured products are stacked on top of each other until the desired stack size is met. Whenever the stack of products is finished, it is transported to the end of the conveyer belt, which can be seen in Figure 2.

Figure 2: Conveyer belt after the products received handles

Whenever a stack of products is at the end of the conveyer belt, production employees put the stack on a pallet. After the pallet is ready according to an established packing scheme, a sticker is put on the pallet, which contains a bar-code of the Stock Keeping Unit. After this, the pallet goes to the stretch hood machine. This machine seals the pallet with a plastic cover, so no dirt or water can be exposed to the products when they are being transported to the outdoor warehouse. After the plastic cover is put on the pallet, the pallet is scanned in the software system to be ready. The logistic team picks up the pallet and transports it to the outdoor warehouse department. In Appendix A, a simplified layout of the production hall can be found. In Figure 3, the process flow of the manufacturing process which takes place in the production hall is presented.

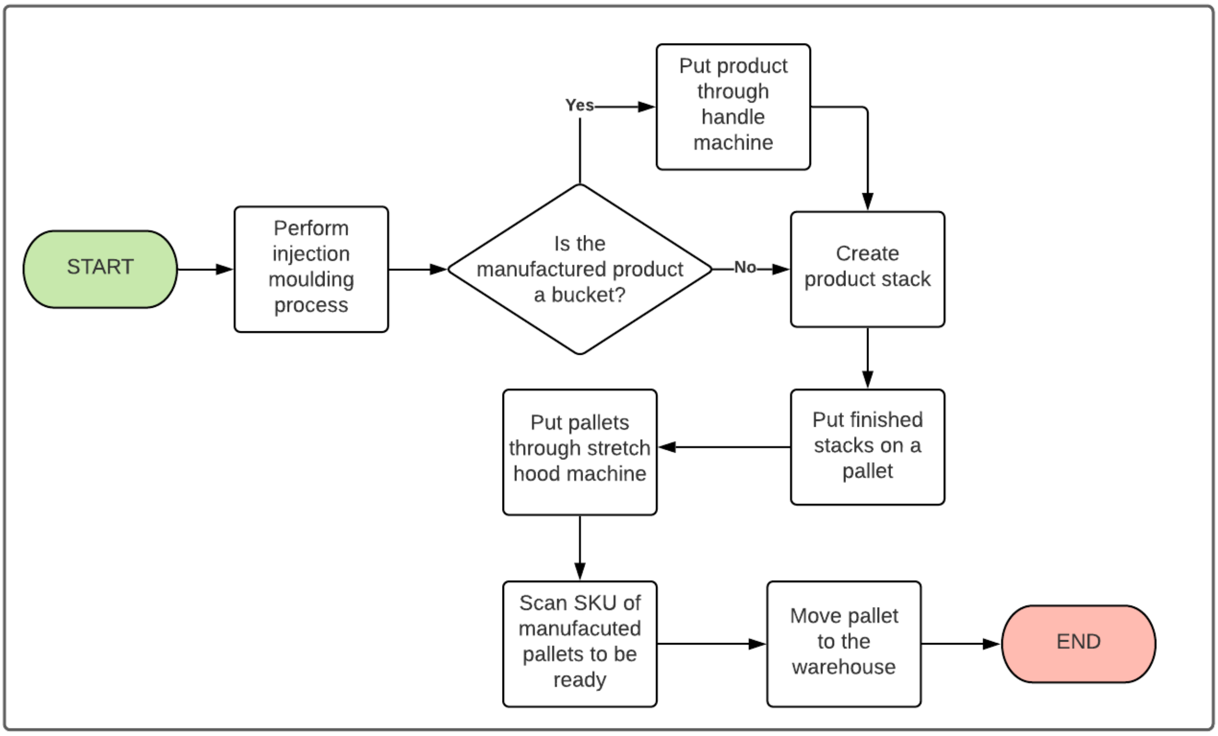

Figure 3: Process flow of the production process

A production batch often consists of several pallets. Whenever an order is finished, the next order that has to be produced at the production line is manufactured next. Sometimes this involves changing the injection mould on the machine, since a different product type might have to be produced. The production planner within the company tries to schedule the production orders in such a way, that mould changes happen as little as possible. Changing injection moulds takes 2 up to 4 hours, which reduces the output of the injection moulding machine.

2.2 Production roster

In the production facility of Company X, production currently takes place 5 days a week, 24 hours a day. This is done with the use of a 3-shift roster. This roster is made up of a morning, an afternoon and a night shift. Every shift lasts 8 hours and 3 production employees work per shift. At 6:00 am on Monday, the morning shift starts. After cleaning all the moulds in the morning, the injection moulding machines are activated and production starts. The shift times can be seen in Figure 4.

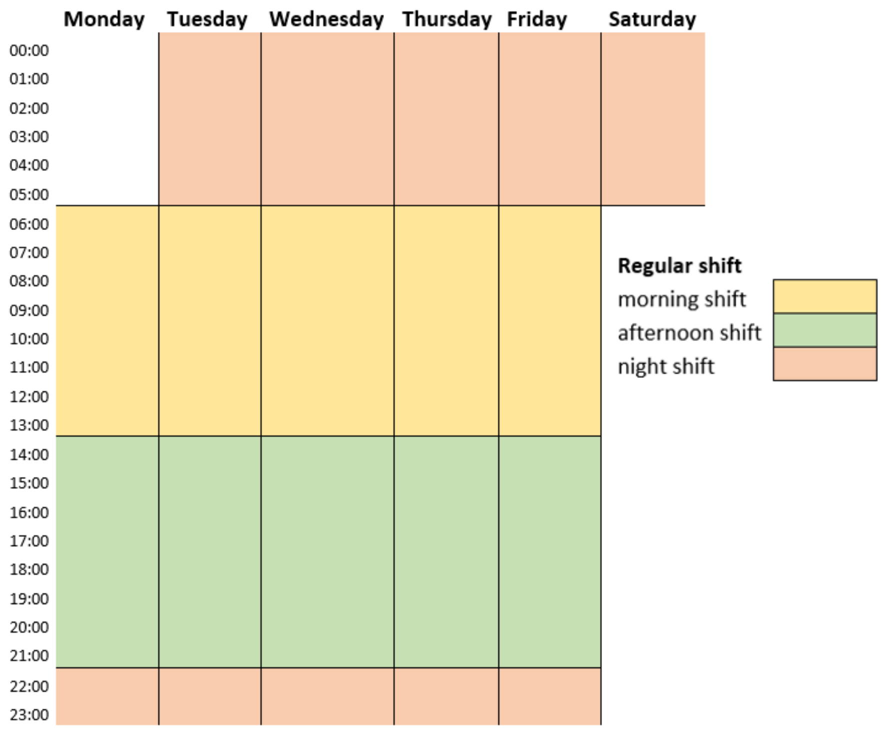

Figure 4: Current 3-shift roster in use

As already mentioned in Chapter 1, Company X is having difficulties meeting the increasing customer demand. In order for the production facility to keep up with this increase, production sometimes also takes place during the weekend, to make sure all orders are manufactured in time. This mostly happens during the peak-season, when the number of incoming orders is high. Currently, this also happens during the weekend, due to the COVID-19 pandemic. The reason for this is to account for sickness and absence in advance. Working overtime during the weekends dissatisfies a lot of the employees.

The production roster Company X uses when production also takes place during the weekend is made up of 5 shifts. This system works similarly to the 3-shift roster. However, 2 additional shifts are used for Saturday 6AM until Monday 6:00AM. This 5-shift roster can be seen in Figure 5. There is an early shift and a night shift. The early shift works from 6AM until 6PM and the night shift works from 6PM until 6AM. The salary of the staff that works during the weekend is higher than during the regular week, due to weekend bonuses that have to be paid.

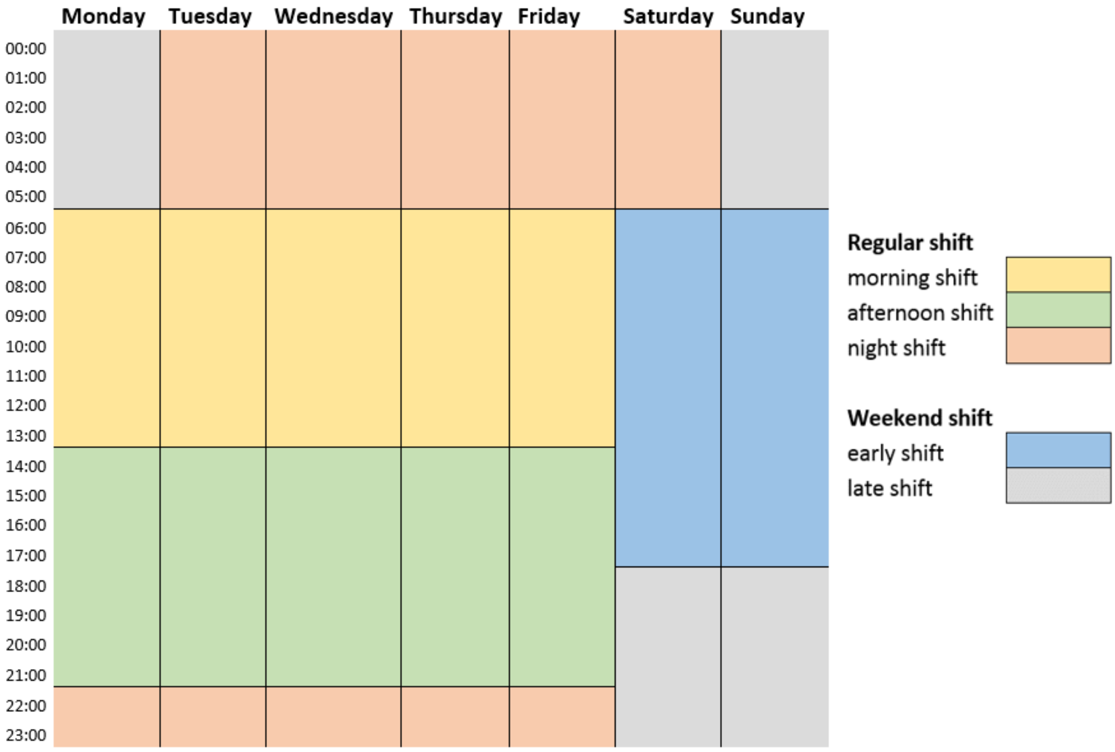

Figure 5: 5-shift roster used

2.3 Product range manufactured

At the production facility, a wide variety of products is produced. The products can be categorised into buckets, tubs and rectangular tubs. Table 2 shows the different products that are produced at the facility[3]. Table 2 does not contain all products, but only the ones which will be manufactured in the future. Currently some products are only produced on rare occasions. In the future, these products will not be produced at the facility in the Netherlands, but in Poland. In Poland, the organization has another facility where production of other product types takes place.

[3]Due to confidentiality, the true products names are not mentioned.

Table 2: Products manufactured at the company

Product
Buckets
Product B1A.1
Product B1A.2
Product B1B
Product B2A
Product B2B
Tubs
Product T1B
Product T2A
Product T3A
Product T3B
Product T4A
Product T4B
Rectangular Tubs
Product R1A
Product R2A
Product R3A
Product R3B
Product R4A
Product R4B

The product name consists of 3 or 4 different variables. The example provided below provides explanation on the product name for Product B1A.1:

- The first variable in the product name is B. This shows that the product is a bucket. Other possibilities are T for Tub and R for Rectangular Tub.
- The second variable shown is a 1. This shows this product has the lowest volume of all buckets. As shown in Table 2, the buckets only have 2 different possibilities for its volume. For tubs and rectangular tubs there are 4 possibilities.
- The third variable of Product B1A.1 is A. There are two possibilities for this variable: A or B. An A represents an old version of the product. This version has relatively thick walls and therefore has a long cooling time. The B represents a new version of the product, which has a relatively thin wall. This causes the cooling time of this product to be short.
- The fourth variable of the product is .1. This presents the handle type of the product. There are two different handle types for the products: .1 and .2. The fourth variable is only shown for 2 products, since all other products only have 1 handle type or do not have handles at all.

There are restrictions on the injection moulding machines in the facility. Not every machine can manufacture every product. For the 10 production lines at the facility, the numbering starts at 4 and ends at 13. All buckets are manufactured at lines 4 up until 9 and all tubs and rectangular tubs are manufactured on lines 10 up until 13. The injection moulding machines at the facility differ from one another. This causes the cycle times of the products to depend on the chosen production line.

Although different customers might order the same product, the products can differ on one aspect: the sticker which contains the bar-code. The bar-code is often referred to as the EAN-code. During the manufacturing of a production order, every product is provided with a sticker that contains a specific bar-code. Some customers that order products allow Company X to put its own bar-code on every product. These products can be classified as Make to Stock production, since these products are manufactured based on forecasted demand.

Other customers prefer to use their own EAN-code. This means that in a production order for some customers, customer specific EAN-codes are put on the products. Sometimes, specific production batches have to be manufactured when such an order comes in, since no stock is kept for most of these products with customer specific bar-codes. These products can be classified as Make to Order products, since no stock kept and the production batches for these customers are based on an incoming order. The production process at Company X can therefore be defined as a hybrid Make to Stock (MTS) / Make to Order (MTO) system (Peeters and van Ooijen, 2020), since both systems are used at the production facility.

2.4 Conclusion

This chapter provides an answer to the question: How are the products manufactured and how is the production output achieved? Section 2.1 describes the manufacturing process at the production facility. The products are manufactured with injection moulding machines, which have restrictions on what products they can produce. Section 2.2 reports on the production rosters which are used at the production facility. When demand is unable to be met with the 3-shift roster, a 5-shift roster is used. In the last section, the different products manufactured at the production facility are described for the future production of Company X.

3 Theoretical framework

This chapter reviews literature that can be used to increase and analyse the production capacity of Company X. The following research question is answered in this chapter:

"How can the production capacity of a manufacturing company - like Company X - be increased according to literature?

This question is answered by making use of the following sections:

- 3.1 Optimisation methodologies
- 3.2 Techniques for solving optimization problems
- 3.3 Demand forecasting
- 3.4 Sensitivity analysis
- 3.5 Conclusion

3.1 Optimisation methodologies

Literature provides several methodologies that can be used to increase the production capacity of an operation. This section describes two of these methodologies, which are applicable to the context of Company X: The Theory of Constraints and Lean Manufacturing. The Theory of Constraints (TOC) is discussed since this methodology is widely used and increases the production capacity by focusing on the bottleneck within the system and improving its performance. At Company X, there is a clear bottleneck in the production system, namely the injection moulding machines. Hence, applying TOC at Company X seems promising and is applicable to the situation of Company X. The other methodology, Lean Manufacturing, is researched since it is used by many big companies the last decades for optimising their production system. The methodology aims to manufacture the desired products at minimal cost. According to Company X, the market for buckets, tubs and rectangular tubs is price driven. Manufacturing at the lowest possible cost is thus important for Company X to be competitive. Applying Lean Manufacturing is therefore reviewed in this section.

Before describing these methodologies, the term capacity is defined. According to Slack et al. (2013), the capacity of an operation is the maximum level of value-added activity over a period of time that the operation can achieve under normal operating conditions. Moreover, they state that providing sufficient capability to satisfy current and future demand is a fundamental responsibility of operations management. When the balance between the capacity of an operation and the demand it is subject to is good, customers demand can be satisfied cost-effectively. Increasing the production capacity of an operation thus increases the production output when there is sufficient demand. Capacity planning and control is the task of setting the effective capacity of the operation so that it can respond to the demands placed upon it (Slack et al., 2013). The two methodologies named for increasing the production capacity of an operation are discussed in the following subsections.

3.1.1 Theory of constraints

Goldratt (1990) describes the Theory of constraints (TOC). He states that TOC focuses on finding and removing bottlenecks, so called constraints, from an operation, since any bottleneck will disrupt the smooth flow of items through processes. By identifying the location of constraints and working to remove them, an operation is always focusing on the part that critically determines the pace of output.

Slack et al. (2013) state that the approach that uses this idea is called Optimised Production Technology (OPT). It is a computer-based technique and tool which helps to schedule production systems to the pace dictated by the bottlenecks. OPT uses the drum-buffer-rope methodology to schedule production systems. Schragenheim and Ronen (1990) state the drum-buffer-rope methodology focuses on the bottleneck within the process and tries to maximise the output of the bottleneck. The drum-buffer-rope methodology implemented in manufacturing organizations enables better scheduling and decision making on the shop floor, according to Schragenheim and Ronen (1990). It synchronises resources and material utilisation in an organisation. Resources and materials are used only at a level that contributes to the organisation's ability to achieve throughput (Rahman, 1998).

The throughput of the system depends on the drum. The drum sets the pace for the whole system and is determined by the constraints of a system. Examples of constrains in a system are bottleneck machines and customer demand. The rope resembles the communication between a bottleneck and the processes before it. It makes sure that activities performed before the bottleneck do not overproduce. Moreover, the methodology suggests keeping a buffer in front of the bottleneck, to make sure when activities before the bottleneck cannot be performed, the bottleneck can still perform its activity, keeping the production active.

Goldratt (1990) provides five steps for the implementation of TOC:

1. Identify the system constraint
2. Decide how to exploit the constraint
3. Subordinate everything to the constraint
4. Elevate the constraint
5. Start again from step 1

These steps show that the TOC is an in iterative process, which eliminates a bottleneck during every cycle of the methodology. Conclusively, Slack et al. (2013) state that TOC is a philosophy which is used in operations management, which overall objective is to increase profit by increasing the throughput of a process or operation.

3.1.2 Lean manufacturing

Another methodology that literature describes to increase the production capacity of an operation is lean manufacturing. This methodology is sometimes also referred to as lean synchronization or 'just-in-time' (JIT). Slack et al. (2013) state lean synchronization is the aim of achieving the flow of products and services which is able to deliver exactly what customers want, in exact quantities, exactly when needed, exactly where required at the lowest possible cost. It is an approach to operations which tries to meet demand instantaneously with perfect quality and no waste.

The lean manufacturing methodology originates from Japan and when first introduced by Shingo (1981), the approach was relatively radical, even for large companies (Slack et al., 2013). Lean manufacturing differs from more traditional approaches in manufacturing, which often contain buffers between different stages. This makes sure that when a breakdown occurs at a stage, the next stage will not notice this immediately, since the buffer can be used to keep manufacturing. The responsibility for solving the problems will be centred largely on the people within that stage, and the consequences of the problem will be prevented from spreading to the rest of the system. In lean manufacturing systems, breakdowns at one stage will immediately be noticed by the following stages, since no buffers are used in these systems. This causes the capacity utilization of operations to often go down initially, since there are no buffers between stages. Several production improvement methodologies are based on the lean manufacturing philosophy. Two of these methodologies are discussed, since these are the most widely used and can be applied to the situation of Company X.

5S-methodology

Bayo-Moriones et al. (2010) states 5S is one of the best-known and most widely used methodologies when facing improvement processes. The methodology was introduced by Shingo (1981) and focuses on improving business processes by using lean manufacturing theory. Osada (2003) refers to 5S as the five keys to a total quality environment. 5S is a system to reduce waste and optimise productivity and quality through maintaining an orderly workplace and using visual cues to achieve more consistent operational results. The 5S pillars that are used for improving business processes are:

- Sort (Seiri): This pillar states that all materials, instructions and tools have to be separated and that all unneeded materials have to be removed.
- Set in order (Seiton): The separated parts have to get an assigned place.
- Shine (Seiso): The workspace and tools have to be cleaned by using a cleaning campaign.
- Standardise (Seiketsu): This pillar suggests all changes made in the first three phases need to be standardised.
- Sustain (Shitsuke): This pillar refers to the process of running 5s smoothly in the future and making changes when necessary.

SMED methodology
Just like the 5S theory, SMED comes from the lean manufacturing philosophy. McIntosh et al. (2000) claim that the Single-Minute Exchange of a Die (SMED) methodology has been at the forefront of retrospective changeover improvement activity since the mid-1980s. The methodology focuses on reducing changeover time between production batches. This is done by making sure all activities that are performed during a changeover are performed before or after the changeover if this is possible. Faster changeover time, particularly in its effect of allowing responsive small batch manufacturing, is acknowledged as a cornerstone of Just in Time (JIT) production (Spencer and Guide, 1995). Reducing the changeover times in manufacturing processes can increase the active run time, which increases production output.

Conclusively, Slack et al. (2013) state lean synchronization has the overall objective to increase profit by adding value from the customers' perspective. This is achieved by eliminating waste and adding value by considering the entire process, operation or supply network.

3.2 Techniques for solving optimization problems

In this section, techniques for solving optimization problems are discussed. Boyd and Vandenberghe (2011) state an optimization problem is the problem of finding the best solution of all feasible solutions. Optimization problems can focus on one objective or multiple objectives. In the last case, optimization problems make a trade-off between different objectives.

Kumar et al. (2017) state there are three different types of techniques for solving optimization problems, namely: the heuristic method, mathematical methods and evolutionary methods. In general, heuristic techniques try to find a good solution for the problem, that does not have to be optimal. Heuristic techniques are often used in situations where finding the best possible solution is extremely hard/impossible to find using mathematical methods. Evolutionary methods are algorithms which are based on the evolution of species (Deb, 2005). Deb (2005) states that although an evolutionary optimization is a simple abstraction, it is robust and has been found to solve various search and optimization problems of science, engineering and commerce. Examples of these methods are the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) (Kumar et al., 2017). Examples of mathematical models include linear programming, integer programming, a combination of these and dynamic programming. These models can find optimal solutions (Kumar et al., 2017). In Subsections 3.2.1 and 3.2.2, a better look is taken at mathematical models for solving optimization problems.

3.2.1 Linear programming problems

Linear programming is a mathematical method for solving optimization problems. In linear programming, a function is maximised/minimised by finding the optimal values of the decision variables. Boyd and Vandenberghe (2011) and Winston (2009) suggest using Dantzig's Simplex method for solving the problem. This can be done with the use of computer software, which is able to solve LP-models in a short amount of time (Boyd and Vandenberghe, 2011). When one aims to solve an LP problem, a model can be designed by using the following steps:

1. **Decision variables:** According to Winston (2009), the first step is defining the relevant decision variables, which describe the decisions to be made for optimising the objective function.
2. **Objective function:** The next step is formulating the objective function of the model. The objective function always *minimises* or *maximises* some linear function of the decision variables.
3. **Constraints:** These are the restrictions which the model must satisfy to reflect the real world accordingly. These constraints are always a linear function of the decision variables. The constraints which are formulated often consist of different parameters (e.g. available production time). There are different restriction types, of which the following are examples (Earnshaw and Denett, 2003):
    - Constraints to satisfy usage limits
    - Constraints to satisfy demand
    - 'If-then' constraints
    - 'Either-or' constraints

An overview of the different components of an LP problem can be seen in Figure 6.

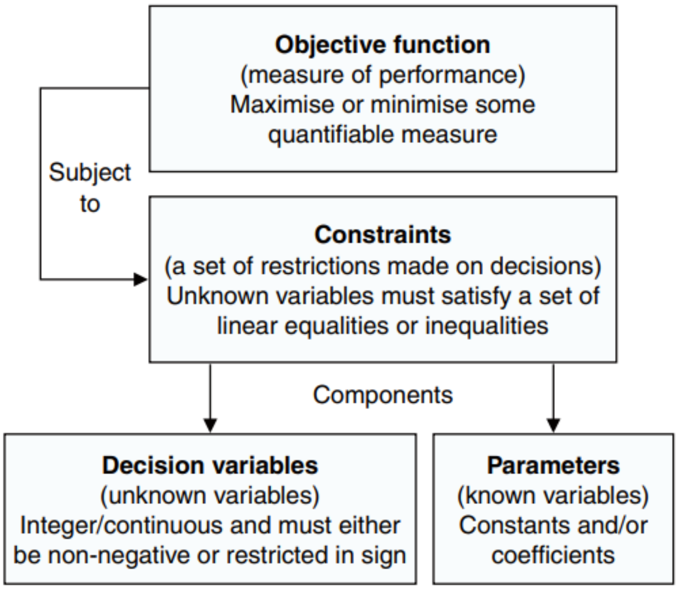

Figure 6: Components of Linear Programming models (Earnshaw and Denett, 2003)

For an LP to be an appropriate representation of a real-life situation, the decision variables must satisfy at least the following 4 assumptions (Winston, 2009):

- **The Proportionality assumption:** This assumption in an LP-model implies that the contribution of every decision variable is proportional to the value of that specific variable.
- **The Additivitiy assumption:** The additivity assumption implies that the value of the objective function is the sum of the contributions from individual decision variables.
- **The Divisibility assumption:** This assumption requires that each decision variable be allowed to assume fractional values. Whenever this assumption is not met for some decision variable, the model could still be useful but cannot be called an linear programming model. Some decision variables might have to attain integer values for example. In this case, the model is an *integer linear programming model*. These models are still useful in certain situations and can still be solved by computer software. However, the computation time is longer than for linear programming models.
- **The Certainty assumption:** The last assumption which has to be met is the certainty assumption. This assumption states that the value of every parameter is known with certainty.

Whenever these assumptions are not satisfied, the model does not represent the real-life situation closely. Therefore, whenever these assumptions are not met, some credibility of the model is lost (Winston, 2009). However, when these assumptions are met, it does not necessarily mean the model is credible. The assumptions are necessary for the model to represent the real-life situation closely, but are not sufficient.

As already stated, some mathematical optimization models contain variables that have to be integers. These problems are so called *integer linear programming problems*. Within these cases a differentiation is made between *pure integer programming problems* and *mixed integer programming problems*. In pure integer programming problems, all variables are required to be integers. For mixed integer programming problems, only some variables require to be integers (Winston, 2009).

3.2.2 Nonlinear programming problems

According to Boyd and Vandenberghe (2011), whenever the condition of linearity for the objective and constraint functions is not met, one deals with a nonlinear programming problem. Moreover, they state there are no efficient methods for solving the general nonlinear programming problem. Therefore, methods that aim to solve such problems have several different approaches, where compromises are made. Two examples of methods that aim to solve the problem are *global optimization* and *heuristic techniques*. In global optimization, the best values for the decision variables is found (Boyd and Vandenberghe, 2011). However, computation time is often extremely long, which causes this method to be of bad use in most situations. Heuristic techniques can be used to decrease the computation time needed for finding a solution. In general, heuristic techniques try to find a good solution for the problem, that does not have to be optimal. Local optimization is an example of such a heuristic technique. In local optimization, the compromise is to give up seeking the optimal value for the decision variables, which minimises the objective over all feasible solutions Boyd and Vandenberghe (2011). Moreover, decreases in the computational time computers need when applying heuristic algorithms causes heuristics to be a suitable method for solving complex nonlinear optimization problems.

3.3 Demand forecasting

In this section, different forecasting methods are described. According to Chopra and Meindl (2016), there are four different types of forecasting methods which can be used, namely:

1. **Qualitative:** Qualitative forecasting methods primarily rely on human judgement. They are appropriate when experts have market intelligence that may affect the forecast.
2. **Time series:** Time series forecasting methods use historical demand to make a forecast of future demand. These methods are applicable when the basic demand pattern does not vary significantly from one year to the next. This method serves as a good starting point for a demand forecast.
3. **Causal:** Causal forecasting methods assume demand is highly correlated with environmental factors. The relationship between environmental factors and demand is investigated and estimates for future environmental factors can be used to estimate future demand.
4. **Simulation:** Simulation methods for forecasting imitate the customer choices that give rise to demand to arrive at a forecast.

Chopra and Meindl (2016) state several studies have shown that using multiple forecasting methods to create a combined forecast is more effective than using anyone method alone. For example, combining the time series and qualitative forecasting methods can lead to a more accurate forecast, since both historical demand and market intelligence are used for creating the forecast.

When one makes a forecast based on historical data, 3 different variables are used to create the demand forecast (Chopra and Meindl, 2016):

- Level: This parameter provides the deseasonalised demand estimate during the initial period
- Trend: This parameter shows the increase or decrease in demand per period
- Seasonal factor: This parameter provides the impact of the seasonality for different periods.

Within time series forecasting, a distinction can be made between different methods which are applicable in different situations (Chopra and Meindl, 2016):

- Moving average: No trend or seasonality. This method calculates the new level for every period by dropping the oldest observation from a total of n observations and adding the newest.
- Simple exponential smoothing: No trend or seasonality. This method calculates the new level by using a smoothing constant, where more recent observations have a higher impact on the new level than older observations.
- Holt's model: Trend but no seasonality
- Winter's model: Trend and seasonality

We will try to make the variables: level, trend and seasonality clear by the following example: A company sells sunglasses to its customers. In the last few years, the demand from the customers has increased. This suggests that the demand shows a positive trend. Moreover, demand for sunglasses is always the highest during the period around summer, since the sun is shining the most. This suggest the demand shows seasonality: During summer the seasonal factor is higher than during the winter. In this specific example, Winter's model is most applicable to create a time series forecast, since the demand showed trend as well as seasonality.

3.4 Sensitivity analysis

This section reviews literature on performing sensitivity analyses in linear programming. Winston (2009) state that sensitivity analysis is concerned with how changes in an LP's parameters affect the LP's optimal solution. When data on input on a specific parameter is uncertain, a sensitivity analysis provides an outcome. In a sensitivity analysis, values of the parameters are examined to see whether the optimal solution for the decision variable changes if the parameters change. Parameters from the real world are often an estimation and the true value might differ. In these cases, analysing for what values of the established parameters the decisions variables change is interesting. Lieberman and Gerald (2020) state that the work of an operations research team is usually not even nearly done when the simplex method has been successfully applied to identify an optimal solution for the model. They state that one assumption of linear programming is that all the parameters of a model are *known constants*. Moreover, Lieberman and Gerald (2020) state that parameter values used in the model are often *estimates* based on a prediction of future conditions of a system.

Lieberman and Gerald (2020) claim the successful manager and operations research staff will maintain a healthy skepticism about the original numbers coming out of the computer and will view them in many cases as only a starting point for further analysis of the problem. An "optimal" solution is optimal only with respect to the specific model being used to represent the real problem, and such a solution becomes a reliable guide for action only after it has been verified as performing well for other reasonable representations of the problem. Parameters can be divided into two catagories:

- Sensitive parameters: Changing these parameters only slightly will change the optimal value of the decision variables.
- Non-sensitive parameters: Parameters for which changes will not affect the optimal solution quickly. Lieberman and Gerald (2020) state performing a sensitivity analysis on these parameters can also be interesting. It can be helpful to determine the *range of values* for which the optimal solution will not change. This is called the *allowable range to stay optimal*

Software packages which solve LP problems often offer the user information about sensitivity analysis of a solution (Lieberman and Gerald, 2020). For example, the *Excel Solver* enables the user to look for the allowable increase and decrease of parameters, for which the values of the decision variables remain optimal. According to Lieberman and Gerald (2020), the general objectives of a sensitivity analysis are to identify the sensitive parameters that affect the optimal solution, to try to estimate these sensitive parameters more closely, and then to select a solution that remains good over the range of likely values of the sensitive parameters.

3.5 Conclusion

From the literature that has been reviewed, we can conclude that optimisation methodologies like TOC and Lean Manufacturing focus on improving a production process. Moreover, we have found that there are different techniques for solving an optimization problems, like linear programming. Linear programming problems specifically can be solved with the help of computer software. Next we have seen that literature describes different demand forecasting methods and that using a mixture of these methods is effective. Lastly, literature showed that parameters used in linear programming problems are often uncertain. In order to draw good conclusions from an LP-model, sensitivity analysis can be used on sensitive parameters or parameters for which estimates are used.

4 The optimisation model

This chapter formulates an optimization model used to analyse the production facility of Company X. The following research question is thus answered in this chapter:

"What optimisation method is used for modelling the production system?"

This question is answered by making use of the following sections:

- 4.1 Research methodology
- 4.2 Model selection
- 4.3 Decision variables
- 4.4 Model notation
- 4.5 Objective function
- 4.6 Constraints
- 4.7 Simplified optimisation model
- 4.8 Model assumptions
- 4.9 Parameter input data
- 4.10 Conclusion

4.1 Research methodology

From Chapter 2 it became clear the current production facility is hardly able to keep up with the current demand and the employees have to work a lot of overtime. In the future, for which the demand is expected to increase, this is not a desired situation. Literature about increasing the production output of a manufacturing facility has been reviewed. Literature provided two well known optimisation methodologies to increase the production output of an operation: Theory of constraints and lean manufacturing. These are applicable to Company X.

Lean manufacturing focuses on eliminating waste and standardising processes. Methods based on lean manufacturing are 5s and SMED, since they aim to reduce waste and improve productivity. Although these methodologies are promising for improving production processes, these will not be used in this research. 5s is not used since the operations manager within the company is currently busy with implementing 5s already. SMED is not used since this will not increase the production capacity enough to solve the problem this research aims to solve. Calculations have been made to see how much changeover time there is at the facility. Production employees and the quality manager within the company state that on average there are about 2 mould changes per week, which take around 4 hours per change. If SMED reduces this time to 2 hours, the active production time at the production facility increases by 4 hours per week. The cumulative production time per week of all the production lines is 1200 hours when a 3-shift roster is used. Improving the active production time by 4 hours per week will increase the production output by less than 1%. This will not increase the output enough to meet future demand expectations and sales goals.

Theory of constraints focuses on the bottleneck of the system, the so-called constraint, and works on removing this constraint and then looking for the next constraint. In this way, the operation is always focusing on the part that critically determines the pace of output. The drum-buffer-rope theory is based on the TOC. For the specific case Company X is dealing with, this method is not applicable. Currently there is always raw material available for the bottleneck, the injection moulding machine, which means extra buffering is not needed. Although the drum-buffer-rope theory is not applicable to the situation of Company X, the general five steps of the TOC are applied:

Application of TOC on Company X

1. Step 1: *Identify the system constraint.* At Company X, the bottleneck are the different injection moulding machines in the production process.
2. Step 2: *Decide how to exploit the constraint.* This step focuses on obtaining as much capacity as possible, without expensive changes. For Company X, this could be done by reducing any non-productive time at the bottleneck. The operations manager within the company is already busy with this, through 5s. Without expensive changes, future demand expectations cannot be met.

3. Step 3: *Subordinate everything to the constraint.* This is currently the case at Company X, since steps in the production process before and after the injection moulding process are adjusted to the speed of the injection moulding machines.

4. Step 4: *Elevate the constraint.* 'Elevating' the constraint means eliminating it. Possible changes to the production policy have to be analysed and changes can be made when a desired future situation arises, where the future demand can be met. In this research, we focus on this step by analysing possible changes to the existing system.

5. Step 5: *Start again from step 1.* This step cannot be performed, since step 4 is not implemented within this research.

From the TOC, Step 4 is applied in this research.

4.2 Model selection

Section 4.1 motivates and explains the use of TOC in this research. Analysing possible changes to the production facility have to be analysed to see what possible changes can eliminate the production constraints and future demand can thus be met. In this research an LP-model is used to analyse possible changes. Based on this model, the best way to elevate the constraint can be selected. Afterwards Step 5 of the TOC can be applied. Motivation for using an LP-model is provided in the next paragraph.

The company aims to increase production output by 10% per year. The last few years, this goal has been achieved, which shows a good perspective for the future. Moreover, the commercial director of the company states the market still shows a lot of potential for more growth. In order to increase the production output, additional input for the production process is needed. Possible changes Company X is interested in are:

1. Implementing a 5-shift roster, where production also takes place during the weekend.

2. Investing in an additional injection moulding machine for buckets.

3. A combination of a 5-shift roster and an additional injection moulding machine for buckets.

Analysing possible changes can be done via different optimization techniques. Literature claimed there were 3 different types of optimization techniques, namely mathematical optimization, heuristic techniques and evolutionary algorithms.

In this research, we propose to analyse these scenarios with a linear programming model, which is a mathematical optimization technique. Winston (2009) state that linear programming can be used for financing problems. In these problems, investment possibilities are reviewed. Moreover, they provide an example where a multi period financial model is created for analysing investment possibilities and this was found to be effective. In addition, high quality software is available to assist LP-based investigations in building models, solving problems, and analysing output. This is helpful when drawing valid conclusions for investment possibilities. The mathematical model has been formulated via the steps described by the Simplex method, which are explained in Section 3.2.1.

4.3 Decision variables

According to Winston (2009), the first step in the formulation of a programming model of the problem is choosing the decision variables. The following decision variables have been selected for this research. Since some variables have to attain integer values, the formulated model is a *Mixed Integer Linear Programming Model* (MILP):

1. The first decision variable (N_{xit}) displays how many products x should be manufactured on every production line i during period t.

2. The second decision variable (W_t) displays whether weekend production takes place during period t.

3. The third decision variable (M_t) displays the number of new injection moulding machines invested in during period t.

4.4 Model notation

Since the model contains a lot of variables which are difficult to remember at first sight, an overview of the model is created. The following notations are used in the model:

Indices:

- x: Product type
- i: Production line
- t: Period

Parameters:

- OEE_{it}: Overall Equipment effectiveness for production line i in period t
- C_{xit}: Cycle time per product x on production line i in period t
- V_{xit}: The value created per product x on production line i in period t
- F_{xt}: Demand per product x in period t
- T_t: Production time available from Monday up until Friday in period t
- A_t: Production time available on Saturdays and Sundays in period t
- I_t: Investment costs for period t
- E_t: Additional employee costs for weekend production in period t
- D_t: Additional depreciation costs for an injection moulding machine during period t

4.5 Objective function

The model aims to solve the following objective function:

$$max \sum_{t=1}^{T} \Big(\sum_{x=1}^{X} \sum_{i=1}^{I} \left(N_{xit} \cdot V_{xit} \right) - I_t \Big)$$

The objective of the model is to maximise the value created at the production facility, which is the primary objective of the manufacturing plant of Company X.

4.6 Constraints

In order for the model to represent reality closely, several constraints have to be met.

$$I_t = D_t \cdot M_t + E_t \cdot W_t \tag{1}$$

Equation (1) shows how the *Investment costs* are made up. These costs are made up of depreciation costs for an additional injection moulding machine and additional employee costs. These costs are only incurred when an investment in the corresponding decision variables are made.

$$\sum_{x=1}^{X} \frac{N_{xit} \cdot C_{xit}}{OEE_{it}} \leq T_t + A_t \cdot W_t \quad \forall\, i,t \tag{2}$$

The constraint shown in equation (2) can be classified as a *constraint to satisfy usage limits.* The constraint makes sure the number of products manufactured at every production line does not exceed the production time available. This limits the amount of products that can be manufactured per period.

$$N_{xit} \leq F_{xt} \cdot M_t \quad \forall\, x,t \;;\; i \;=\; 14 \tag{3}$$

The constraint shown by equation (3) can be classified as a *constraint to satisfy usage limits.* This constraint makes sure products are only manufactured at machine 14 if an investment in this machine is made.

$$\sum_{i=1}^{I} N_{xit} \leq F_{xt} \quad \forall\, x,t \tag{4}$$

The constraint formulated in equation (4) can be classified as a *demand constraints.* This constraints makes sure the number of products manufactured per period does not exceed the product demand during the period.

$$M_t \leq M_{t+1} \; for \; t \; = \; 1, \; ... \; , \; T-1 \tag{5}$$

Once production takes place with an extra machine, the model cannot manufacture without an additional machine in the future. Equation (5) shows this constraint.

The following *sign restrictions* are also in place for the decision variables:

$$N_{xit} \geq 0 \tag{6}$$

$$W_t \in 0, 1 \tag{7}$$

$$M_t \in 0, 1 \tag{8}$$

The sign restriction of equation (6) makes sure the number of products manufactured at a machine during a period cannot be negative. In reality, the number of products manufactured is an integer as well, since an injection moulding machine is unable to manufacture half a bucket for example. Adding this sign restriction would increase the computation time to solve the model exceptionally however. Winston (2009) suggests not adding this sign restriction in these situations and rounding off the values of the decision variables to integers ones the solution is found. Since we want the model to solve with low computation time, we have not restricted N_{xit} to attain integer values.

On top of this, equations (7) nad (8) show the restrictions for the remaining two decision variables. When $W_t = 1$, weekend production takes place. When $W_t = 0$ this is not the case. When $M_t = 1$, production takes place with an additional injection moulding machine.

4.7 Simplified optimisation model

The model created in Sections 4.4 up until 4.6 is an MILP model. The data gathered for the model parameters is prone to errors in the future. Using this data for production scenarios in the far future is prone to larger errors than scenarios in the near future. Therefore, we propose to only analyse production scenarios that are in the near future, namely the yeas 2021 and 2022. Due to this short time period for which we propose to run the model, the model is changed to a single-period instead of multi-period model. Thus, the model will maximise the value created at the facility per year instead of multiple years. On top of this change, the model is changed to only consist of one decision variable: N_{xi}. The additional decision variables have been removed and are analysed separately in every experiment. In this way, all possible production scenarios for the decision variables M_t and W_t can be analysed, which makes the model easier to use for the company.

$$max \sum_{x=1}^{X} \sum_{i=1}^{I} \left(N_{xi} \cdot V_{xi} \right) - I \tag{9}$$

Equation (9) shows the objective function for the simplified model which is used in Chapter 5. The value of I depends on the value of the removed decision variables M_t and W_t.

Different constraints are also in place for the simplified optimisation model. The constrains shown in equation (3), (6), (7) and (8) are not used for the simplified model. The constrains from equation (2) and (4) are simplified. These can be seen in equation (10) and (11).

$$\sum_{x=1}^{X} \frac{N_{xi} \cdot C_{xi}}{OEE_i} \leq T + A \quad \forall \; i \tag{10}$$

$$\sum_{i=1}^{I} N_{xi} \leq F_x \quad \forall \; x \tag{11}$$

4.8 Model assumptions

Winston (2009) states that for an LP to be an appropriate representation of a real-life situation, the decision variables must satisfy at least the Proportionality, Additivity, Divisibility and Certainty Assumptions. In Subsections 4.8.1 up until 4.8.4, the mentioned assumptions are elaborated on for the simplified optimisation model of Section 4.7.

4.8.1 Proportionality

The proportionality assumption in an LP-model implies that the contribution of every decision variable is proportional to the value of that specific variable. In this research, this assumption is met since N_{xi} in the simplified objective function is multiplied by the corresponding value of V_{xi}.

4.8.2 Additivity

The additivity assumption implies that the value of the objective function is the sum of the contributions from individual variables. This is the case in our research, since the value of the objective function is dependent on the summation of the value of the individual variables. The summation signs in the objective function show this statement is true.

4.8.3 Divisibility

The divisibility assumption requires that each decision variable is allowed to assume fractional values. In our research this is the case since N_{xi} can attain fractional values. In the real life situation, it is impossible to manufacture 0,3 products for example. However, Winston (2009) suggests the results are still useful even though the real life system does not match this assumption.

4.8.4 Certainty

The last assumption which has to be met is the certainty assumption. This assumption states that the value of every parameter is known with certainty. This assumption is not met in this research. On top of this, some parameters are assumed to be constant, although they are not constant in the real life situation. According to Winston (2009), all assumptions have to hold in order for the model to be an accurate representation of reality. Since this assumption does not hold in our research, credibility of the formulated LP-model is limited. The validity of the parameter input data is discussed in Section 4.9. Moreover, a sensitivity analyses is performed in Section 3.4 to increase the credibility of the model, by analysing likely values for the input parameters.

4.9 Parameter input data

In this section, values for the parameters within simplified optimization model are collected. In this way, the model can be solved for the production facility of Company X. The data has been gathered by making use of stored data in the ERP-system and interviews when necessary data was not present. On top of this, the validity of this data is discussed. The following subsections are covered in this section:

- 4.9.1 Demand constraints
- 4.9.2 Additional production costs
- 4.9.3 Cycle times
- 4.9.4 Value created per product
- 4.9.5 Overall Equipment Effectiveness
- 4.9.6 Available production time

4.9.1 Demand constraints

The demand constraints (F_x) which are used in the model for the different products are found with the help of a demand forecast. For the demand forecast that is created in this research, two forecasting methods are used to arrive at the demand forecast, namely: a time series forecasting method and qualitative forecasting method. From the initial investigation from the sales numbers 2017 up until 2020, it became clear that demand patterns do not vary significantly from one year to the next. Therefore, time series forecasting is a good starting point to forecast demand (Chopra and Meindl, 2016). After this initial forecast, changes are made with the help of the financial director of Company X. This can be seen as a qualitative forecasting method, since we relied on human judgement to make changes to the initial forecast. Two forecasting methods are used in this research since Chopra and Meindl (2016) states this is more effective than using a single forecasting method.

Initial demand forecast
The initial demand forecast is made with the help of past sales numbers. These are found in the ERP system of the company, where sales data of 2017 up until 2020 are stored. In this research, we used Holt's demand forecasting model to analyse future demand, since Chopra and Meindl (2016) state that this method is appropriate to use when demand is assumed to have a level and a trend, but no seasonality. Since a forecast is made on a yearly basis, there is no seasonality. Before showing the yearly sales, it is important to mention some validity issues with the data that is analysed. First of all, the forecast is only based on data of a 4 year period. The forecast would be more accurate when data of a larger period is used. However, the data in the ERP system is limited to a 4 year period. Second, for some sales, data about the specific product that was sold is missing. For example, for some products it was not mentioned whether it was Product T4A or Product T4B. Assumptions were made on the product type with the help of the production planner within the company, since he is responsible for filling in these details in the ERP system. The number of sales for which this data was lacking was extremely small and the actual product types that were manufactured are thus good estimates to use. Lastly, Product T1B has been introduced in 2020. Hence, the aggregated forecast of this product only contains sales numbers of 2020 for this product.

The sales numbers for the different product types can be seen in Table 3.

Table 3: Sales numbers different product types 2017 up until 2020

Product	2017	2018	2019	2020
Buckets				
Product B1A.1	208,568	187,901	141,290	197,462
Product B1A.2	369,542	288,793	197,328	178,338
Product B1B	896,876	1,162,731	1,074,139	1,097,053
Product B2A	134,253	133,141	131,133	144,765
Product B2B	470,367	545,797	511,480	591,042
Tubs				
Product T1B	0	0	0	24,709
Product T2A	73,798	82,161	82,508	76,544
Product T3A	154,564	76,866	50,981	49,957
Product T3B	6,480	106,064	140,307	148,395
Product T4A	90,259	63,431	33,027	38,027
Product T4B	5,560	54,872	71,427	90,818
Rectangular Tubs				
Product R1A	2,427	2,799	2,873	7,585
Product R2A	22,536	24,242	36,620	38,854
Product R3A	73,960	51,567	27,272	29,989
Product R3B	2,660	51,499	74,236	100,647
Product R4A	79,092	57,050	24,547	26,060
Product R4B	6,510	68,517	89,828	127,544

The future demand for the different products has been analysed by aggregating the different products' sales numbers of 2017 up until 2020. Chopra and Meindl (2016) state that forecasting at the appropriate level of aggregation is more accurate. For the products we analysed, we aggregated all products with the same volume. This has been done since customers often switch from one bucket type to another. For example, when Product T3B was introduced to the market, the sales numbers of Product T3A declined, since customers switched to the newer version. Customers are still making this switch and this can be seen in Table 3. For tubs and rectangular tubs, an additional aggregation is made for products with the two lowest values. This aggregation has been performed since customers often chose to buy one of the two products with lowest volume, but not both.

Now that all products have been aggregated at the right level to create an accurate forecast, the demand forecast for 2021 and 2022 are calculated by using Holt's model. This is done with the use of a statistical method: linear regression. With linear regression, the level and trend is determined by drawing the best line through the data points. This method has been applied in *Microsoft Excel* with the use of the Data Analysis Toolpack that the software provides. The initial forecast can be seen in Table 4.

Table 4: Initial demand forecast using linear regression

Aggregated sales / year	2021	2022
Buckets		
Product B1	4,325,218	4,255,299
Product B2	2,264,413	2,371,585
Tubs		
Product T1 + T2	316,824	341,638
Product T3	640,419	676,503
Product T4	399,489	425,058
Rectangular tubs		
Product R1 + R2	161,110	184,174
Product R3	429,239	477,386
Product R4	503,973	561,818

Continued demand forecast

Now that we made a start on the demand forecasting with Holt's time forecasting method using historic sales data, we continued to create the forecast using a qualitative forecasting method. This is done with the help of the financial director of the company. According to Chopra and Meindl (2016) qualitative forecasting methods are primarily subjective on human judgement and can be useful when experts have market intelligence.

An important remark made by Van der Heijden (2019) on using historical sales data to forecast future demand is that historical data does not necessarily reflect the customer demand. During the discussion with the financial director, a market expert, it became clear that this is indeed the case. After conducting an interview with the financial director, the following conclusions could be drawn:

- The actual trend of the forecast is expected to be higher for the future. In 2019, a large customer of Company X switched to another supplier, which decreased the sales. This can be seen when looking at the cumulative yearly sales numbers in Figure 7.

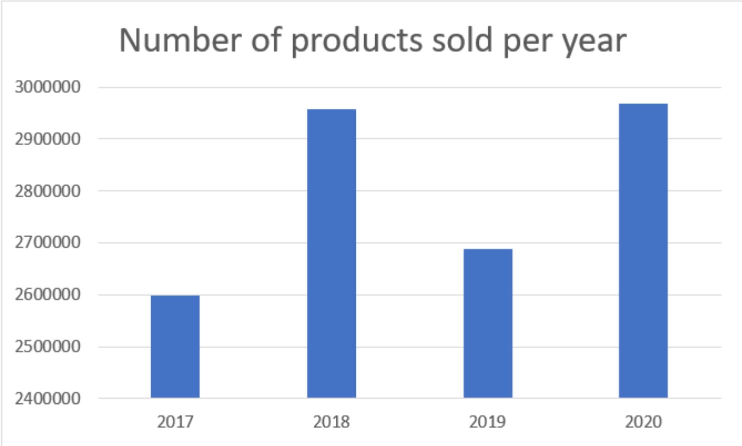

Figure 7: Cumulative yearly sales numbers

- The market shows a lot of potential for new customers and an increase in sales numbers.
- Company X can decide whether they want to acquire additional customers or not and thus increase the sales numbers.
- The goal for the upcoming years is an increase in sales numbers of 10% per year. The market shows enough potential/demand to reach these goals.
- When products have an older and newer version (depicted by the third variable of the product name), the sales numbers of newer versions are expected to increase around 20% per year and the sales numbers of the older versions are expected to decrease 10% to 15% per year.

Based on this information and the initial forecast, the final forecast has been made for the different product types. Whenever the aggregated demand values of the initial and final forecast differed a lot, the values of the final forecast were slightly adjusted. In this way, the two forecasting methods are combined into a final forecast. The final demand forecast can be seen in Table 5. The yearly sales increase around 10% per year, which is the goal of the company.

Table 5: Final demand forecast

Product / year	2021	aggregated	2022	aggregated
Bucket				
Product B1A.1	167,843		142,666	
Product B1A.2	151,588		128,850	
Product B1B	1,286,107	1,605,538	1,404,093	1,675,609
Product B2A	126,670		110,836	
Product B2B	709,251	835,921	851,101	961,937
Tubs				
Product T1B	37,063		48,183	
Product T2A	68,890	105,953	62,001	110,183
Product T3A	43,712		38,248	
Product T3B	178,074	221,786	213,689	251,937
Product T4A	34,225		30,802	
Product T4B	108,982	143,206	130,778	161,580
Rectangular Tubs				
Product R1A	9,102		10,922	
Product R2A	44,682	53,783	51,384	62,306
Product R3A	26,240		22,960	
Product R3B	120,777	147,017	144,932	167,892
Product R4A	22,803		19,952	
Product R4B	153,053	175,856	183,664	203,616

In Appendix B, the aggregated sales of the initial forecast and the final forecast are compared. The figure shows that for most products, the final forecast expects the sales to be higher. This is the result of a customer leaving Company X in 2019. This resulted in lower trend levels, which have been calculated using linear regression in *Microsoft Excel*. The only products for which this is not the case is for Product T1B and Product T2A. This is caused by the newly introduced Product T1B in 2020, which caused a spike in sales for this aggregated group in 2020.

4.9.2 Additional production costs

When production during the weekend and/or with an extra injection moulding machines takes place, additional costs arise. These costs are presented by the parameter I in the simplified model. For production during the weekend, the extra costs depend on additional staff. Some extra production employees and an additional technical staff member are necessary. The salary for the additional staff is discussed with the operations manager at the facility. Moreover, when production happens during the weekend, shift work allowance increases from 21% to 28%. This is also taken into consideration for the parameter input data. On top of this, electricity costs rise when production takes place during the weekend. However, these costs are taken into account in Section 4.9.4.

For production with an additional injection moulding machine, machinery depreciation is an additional cost. The depreciation costs of investing in an additional machinery also depend on what specific injection moulding machine is necessary. From interviews with several staff members, it became clear that buckets are under the most pressure for an increase in production output. Therefore, the additional machine analyzed in our research can only manufacture buckets. In (12), the costs are shown for production with 3 shifts or 5 shifts. Since machine depreciation is taken into account in Section 4.9.4, it is not taken into account in the equation.

$$Costs = \begin{cases} €606,000 & \text{if production takes place with 3 shifts} \\ €912,500 & \text{if production takes place with 5 shifts} \end{cases} \tag{12}$$

4.9.3 Cycle times

In the model, the variable C_{xi} represents the cycle time of product x on machine i. In the real life situation, improvements can be made to the cycle times and hence the cycle times in the future might be different. In the real life situation of the production facility, cycle times of the product show some variability around the mean. For example, the cycle time of Product B1B on machine 7 might be 13.9 seconds and change to 14.2 seconds the next week, due to changes in the machine configuration. The cycle times can be seen in Figure 8. They have been established with the help of experts within the company. An important remark is that the values used for the cycle times are the most recent values. These values can still be improved according to multiple employees within the company. Improvements can be made by improving the cleaning policy and optimising the machine settings. The boxes are left empty when machines are unable/not allowed to be used for the production of that specific product type.

Product \ production line	4	5	6	7	8	9	10	11	12	13
Bucket										
Product B1A.1		15,5								
Product B1A.2		16,8								
Product B1B	20		14	14						
Product B2A	21,7									
Product B2B					18	18				
Tubs										
Product T1B							20	21		21
Product T2A									40,4	
Product T3A								40,1	46,4	40,1
Product T3B							27,7	33		33
Product T4A								45	52,5	45
Product T4B							29	29,9		29,9
Rectangular Tubs										
Product R1A									40,7	
Product R2A							40,7	40,7		40,7
Product R3A								43,3	37,3	43,3
Product R3B							34,3	41	32,8	41
Product R4A									34,7	
Product R4B								28,7		28,7

Figure 8: Cycle times on the different machines (seconds)

4.9.4 Value created per product

In the model, values are assigned for V_{xi}, which represents the value that is created when one product of type x is manufactured at production line i. The value depends on the *Costs of goods sold* and *Sales price*. The sales prices have been found in the ERP system of the company, where standard sales prices are stored. Some customers would like their products to have a print on them instead of the ordinary product colour. These sales prices are not taken into account for the calculation of the sales price, since this would increase the average sales price. This is also not taken into account for the *Costs of goods sold*.

The *Costs of goods sold*, which is also reffered to as *production costs*, are calculated for the different products. The production costs itself depends on several costs, which have been mapped by the staff of the company: depreciation of machinery, electricity costs, raw material costs, cleaning costs, direct staff costs and indirect staff costs. In the model, direct staff costs are not used for the cost price calculation, since this is already taken into account in Section 4.9.2. Some variables that influence the *costs of goods sold* are not fixed in the real life situation. These variables are the production line used, cycle time and product weight.

For product weight, the latest value that is registered for the different products by the company is used. In real life, the product weight shows some fluctuation. For the two other variables, no assumptions are made, since they can be differentiated in the model and the corresponding *Costs of goods sold* value will change according to the value of these variables. When the cycle times are changed in the model, the accompanying cost price also changes.

4.9.5 Overall equipment effectiveness

The variable OEE_i represents the *Overall equipment effectiveness* of production line i. It represents the fraction of time the production line is actually manufacturing products good for sale. In practice, the production lines are not always active and do not always manufacture products that are good for sale. The *OEE* of Company X can be categorised based on three different factors:

1. **The actual run time:** The different production lines are not active 24 hours a day. Ever day, the machines are shut down a few minutes for cleaning purposes. Some production lines are also inactive due to mould changes.

2. **Performance loss:** At different steps in the production process, malfunctions can occur, which need to be fixed before production can carry on. This is often referred to as breakdown time.

3. **Quality loss:** Some products which are produced do not meet quality standards and can thus not be sold to customers. This often happens when a new mould is placed in an injection moulding machine and the settings of the machine are not optimised.

Data about these factors is stored by Company X. We used data from 4 weeks to estimate the value of the *OEE*. We proposed to only use data of the 4 recent weeks, since processing the data into *OEE* values is a time costly process. Data about the quality loss is also stored, but these values are unreliable according to the quality manager. The values are still used in the calculations for *OEE*, but have been refined when the percentage of quality loss was expected to be unreliable according to the quality manager. In the calculations, planned downtime has not been taken into account. On top of this, major failures that took more than a day to fix have not been taken into account, due to the small number of weeks for which we calculated the *OEE*. Because of this choice, the values for *OEE* are quite optimistic and are expected to be lower in practice. On top of this, the values are prone to errors due to the estimation being based on unreliable data. Moreover, the values are only based on 4 weeks of data.

4.9.6 Available production time

In the model, the variable $T+A$ represents the time (in seconds) that the production facility is active. The value of A depends on whether production takes place during the weekend or not. Production during the weekend on top of the regular working week will increase the available time. The values for these parameters can be seen in equation(13):

$$T = 239 \quad and \quad A = 96 \tag{13}$$

The numbers 239 and 96 represent the number of days the facility is active during the week and during the weekend respectively. These numbers take into account the holidays the facility will not be opened and takes into account 3 weeks of construction holiday. Moreover, it assumes the facility is open between Christmas and New Years Eve.

4.10 Conclusion

This chapter answers the research question: What optimisation method is used for modelling the system? In Section 4.1, argumentation is provided for applying Theory of Constraints in this research. Afterwards, reasons for using linear programming to create a model are given in Section 4.2. In the remaining sections, the mathematical optimization model is formulated and simplified for practical use. The parameter input data is gathered and its validity is discussed. This showed that *Certainty assumption* in Section 4.8 is not met, due to uncertainty in the future.

5 Experiments

This chapter carries out experiments with a simplified version of the optimisation model. It provides an answer to the research question:

“What experiments have to be carried out with the optimization model?”

With the use of the optimization model, experiments can be carried out to analyse future production scenarios. The following sections are covered in this chapter:

- 5.1 Experimental design
- 5.2 Experiment results
- 5.3 Sensitivity analysis
- 5.4 Conclusion

5.1 Experimental design

In this section, the experimental design of the experiments carried out with the optimisation model is provided. The simplified optimisation model explained in Section 4.7 is created in *Microsoft Excel*. This software is well known by the company and allows Company X to use the model for future scenarios by themselves. Other software packages available for solving the model are not known by the company and would make it difficult for the company to use the model. *Microsoft Excel* is able to solve linear programming problems with the use of the *Data Analysis Toolpack*. This toolpack allows the user to solve problems with the Solver Add-in. Since Company X is not familiar with this toolpack, an instruction page has been added to the model. The page can be seen in Appendix D. This page describes how to add the Toolpack and describes what scenarios can be analysed with the model. Since Company X is a Dutch company, instructions are provided in Dutch.

In the Excel model, all data necessary for solving the model is stored. Next to the input data and expected demand for the different products, a matrix is created for the decision variables N_{xi}. This matrix is filled in when running the Solver Add-in. This can be seen in Appendix C.

It is important to understand the difference between the model objective and the aim of this research. The question this research aims to answer is: “What changes have to be made to increase the production capacity of the production facility, taking into account customer demand?”. The model objective is to maximise the value created at a production facility during a certain period. In order to give an answer to the research question of this research, the production capacities of the different production scenarios are analysed on top of the value of the objective function.

5.2 Experiment results

In this section, the results of the experiments carried out of the model are shown. These results can indicate what production scenario fits the production facility the best. The following experiments are carried out with the model:

- 5.2.1 Validation experiment: This experiment serves as a validation experiment and uses production data of 2020 as demand. On top of this, the number of days the facility was open in 2020 is used in the model for $T + A$. In this experiment, the OEE parameter values are changed to match the real life system more closely.
- 5.2.2 Production scenario 1: Production without additional shifts and without additional machinery. Currently, it has been stated the production facility is unable to manufacture the customer demand when employees do not work overtime during the weekend. This experiment is used to see whether the extra costs that arise from weekend production/production with an additional machine are worth the investment.
- 5.2.3 Production scenario 2: Production with additional shifts and without an additional machine. This experiment analyses whether production with 2 additional shifts is a desirable situation. In this scenario, production also takes place during the weekend. This causes the production facility to be available for a longer duration and an increase in demand can therefore be met.
- 5.2.4 Production scenario 3: Production with an additional machine and without additional shifts. According to multiple employees, the demand for buckets is hardest to be met. In this experiment, an additional machine for the production of buckets is used to look whether investing in an additional machine is desirable.

- 5.2.5 Production scenario 4: Production with additional shifts and an additional machine. When bucket demand is unable to be met in production scenario 2, Experiment 4 might show to be a more desirable situation, since additional bucket demand can be met.

Table 6 shows a clear overview of the differences between the production scenarios.

Table 6: Production scenarios analysed

Experiment	Production during the weekend?	Production with an additional injection moulding machine?
Production scenario 1	No	No
Production scenario 2	Yes	No
Production scenario 3	No	Yes
Production scenario 4	Yes	Yes

The results of the experiments provide information on three aspects: (1) Value created at the production facility, (2) Machine utilization and (3) Fraction of demand met. Although the objective of the model is to maximise the value created at the production facility, an analysis on (2) and (3) are needed for answering the research question this research aims to answer.

5.2.1 Validation experiment

In this experiment, the production facility of 2020 is analysed. The total production output achieved in 2020 is used for the demand constraint in 2020. Moreover, the number of days the facility was active in 2020 is used as input data for $T + A$. By using these input parameters, the model output will show whether the model is able to perform similar to the real life system.

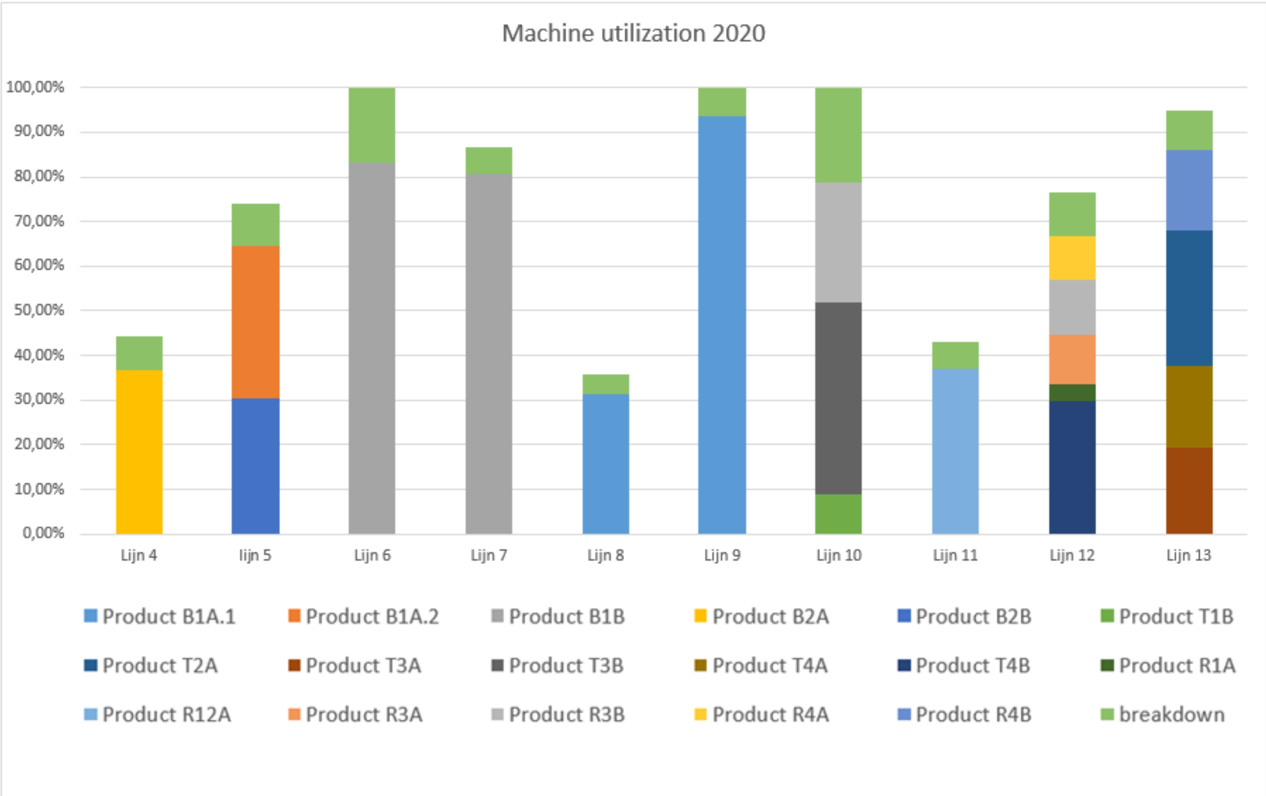

Figure 9: Machine utilization 2020 of the validation experiment

Figure 9 shows the machine utilization when running the model. The model shows that most machines are not fully utilised to achieve the production output that was achieved in 2020. In the real life system, this was the case in 2020. There could be several reasons for this mismatch:

- The cycle times used in the model are too optimistic.
- The *OEE* is an overestimate and is lower in the real life system.
- The number of days the facility is open is used as input data. The model assumes the facility is open 24 hours every day. In reality, some days are not open all day or only part of the production lines were active.

The cycle times have been discussed with employees in the company, who suggest the cycle times are similar to those in the real life system and could therefore not create the mismatch. Moreover, the number of days the facility was open in 2020 could not cause such a big mismatch, since the number of days the facility was open is stored in the ERP system. The mismatch between the model and the real life system is therefore expected to be caused by an overestimate of the *OEE* for the most part. This is the result from the lack of data analysed for generating the input values. An additional experiment is carried out where the *OEE* is changed to better match the real life system.

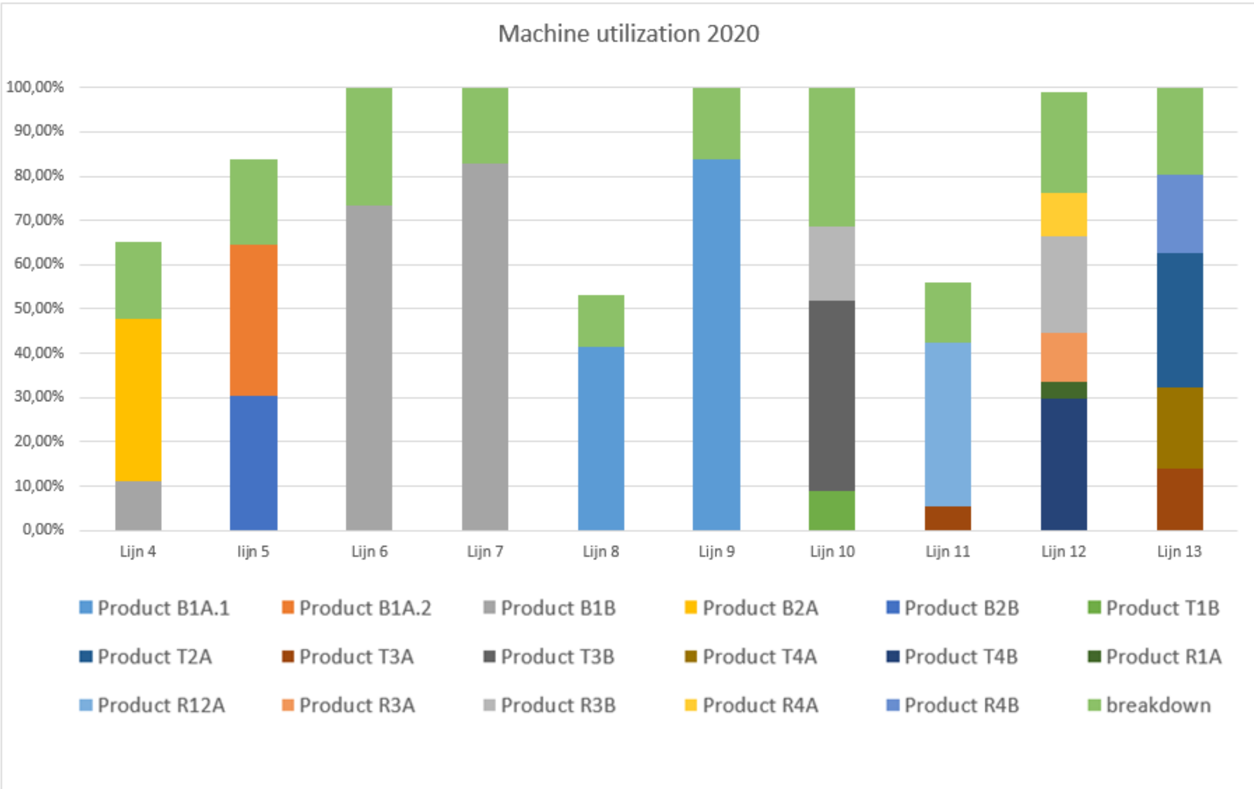

Figure 10: Machine utilization 2020 (adapted OEE values)

In Figure 10, the machine utilization can be seen for 2020 when the values of *OEE* are reduced by 10% for all production lines. This experiment yields results which represent the facility more closely. All demand is able to be met in these experiments and most machines are utilised most of the time. When machines are not utilised, it logically follows from the fact that during some shifts, only 2 production employees were present. When only 2 employees are present, not all machines are activated for production. This accounts for some unutilised time of production lines. For the remaining experiments, the *OEE* parameter stays decreased by 10% to yield results that represent the production facility more closely. The updated *OEE* values which are used for production scenario 1 up until 4 can be seen in Table 7.

Table 7: Updated *OEE* values

Production line	OEE
Line 4	73,26%
Line 5	76,92%
Line 6	73,28%
Line 7	82,93%
Line 8	77,91%
Line 9	83,65%
Line 10	68,69%
Line 11	75,65%
Line 12	76,83%
Line 13	80,45%

5.2.2 Production scenario 1

In this experiment, no investments have been made for weekend production or an additional injection moulding machine. This experiment is carried out to compare the value created at the facility when not all demand is able to be fulfilled, but staff and machine depreciation costs are lower.

In Figures 11 and 12 the machine utilization can be seen for the solution to the model in 2021 and 2022. All machines except for 5 are fully utilised which means the production output almost equals the production capacity of the facility. The value of the objective function in these experiments are €393,868 and €514,071 respectively. In the figures, all bars contain some breakdown time, which are calculated according to the *OEE* values for the different production lines.

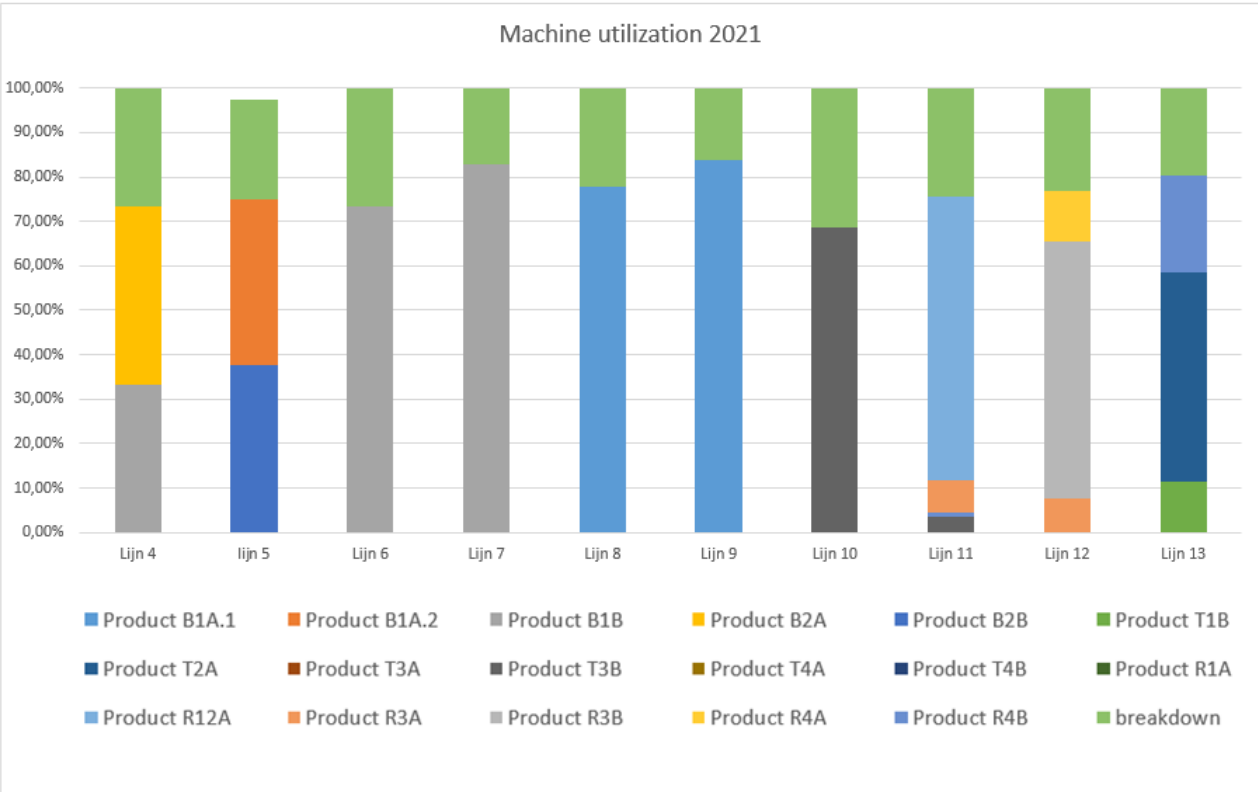

Figure 11: Machine utilization 2021 (Production scenario 1)

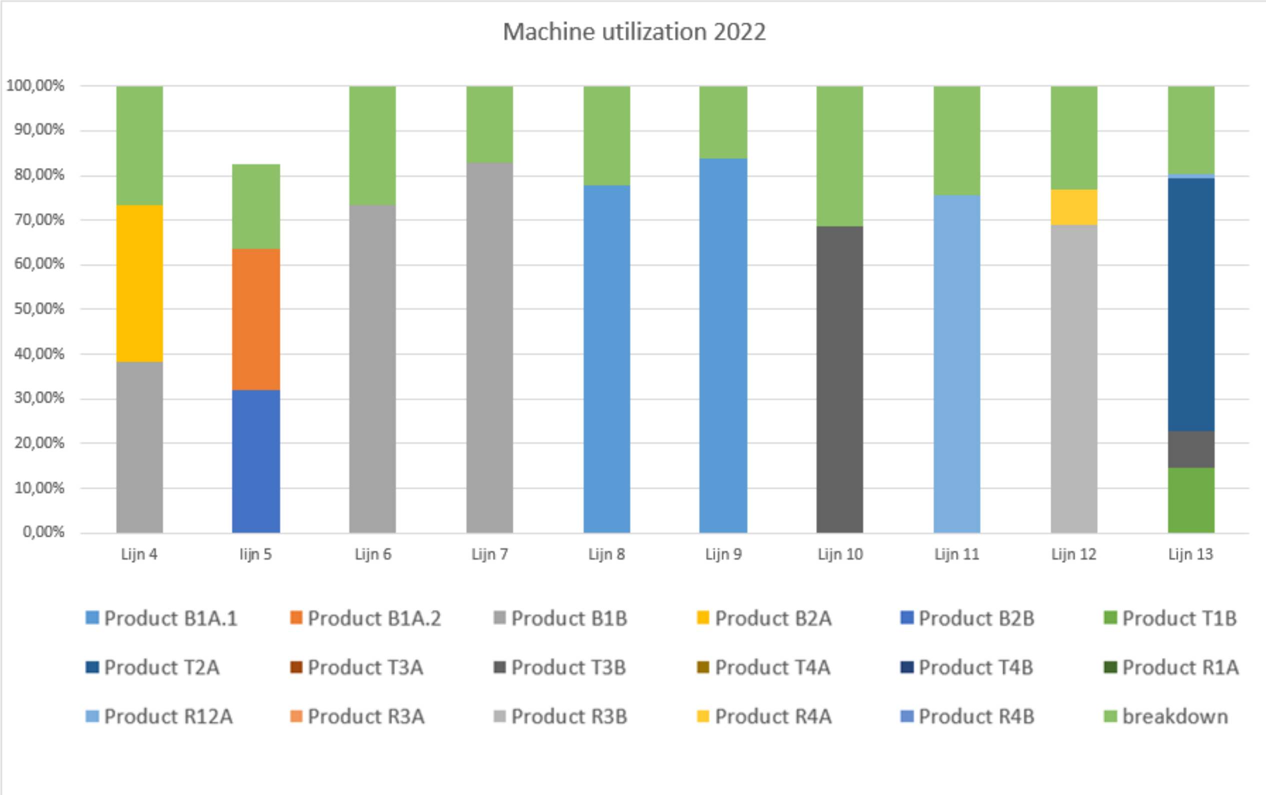

Figure 12: Machine utilization 2022 (Production scenario 1)

Demand
One of the downsides of manufacturing without an additional machine or during the weekend is the percentage of demand which is able to be met. Figure 13 and 14 show that the expected demand for the future is unable to be met in this way.

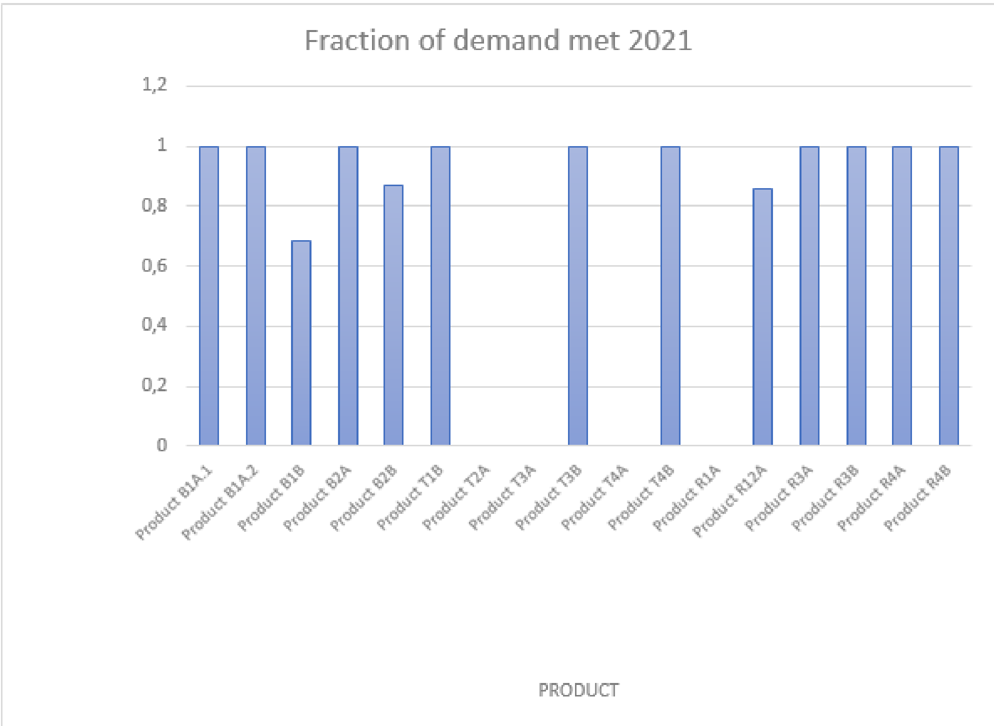

Figure 13: Demand able to be met in 2021

In 2021, 4 products are not manufactured at all when production does not take place with additional input. Moreover, 3 products are not able to meet all demand.

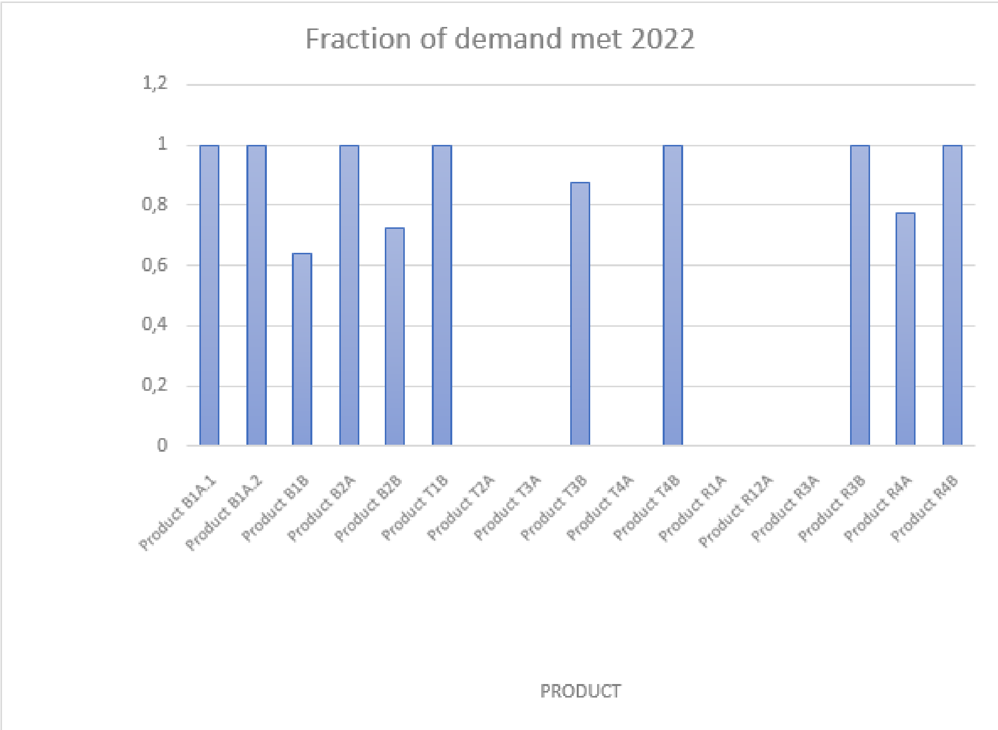

Figure 14: Demand able to be met in 2022

In 2022, 6 products are not manufactured at all. Moreover, 3 products are not able to meet the expected demand.

5.2.3 Production scenario 2

In this experiment, the scenario where production takes place during the weekend has been analysed. This scenario involved extra costs due to the additional shifts and extra employees needed. However, extra production time is available at the production facility. This causes the production capacity of the facility to increase and thus more demand can be met than in the first experiment.

In Figures 15 and 16, the machine utilization can be seen for the years 2021 and 2022 respectively. The value of the objective function in these experiments are €437,503 and €795,718.

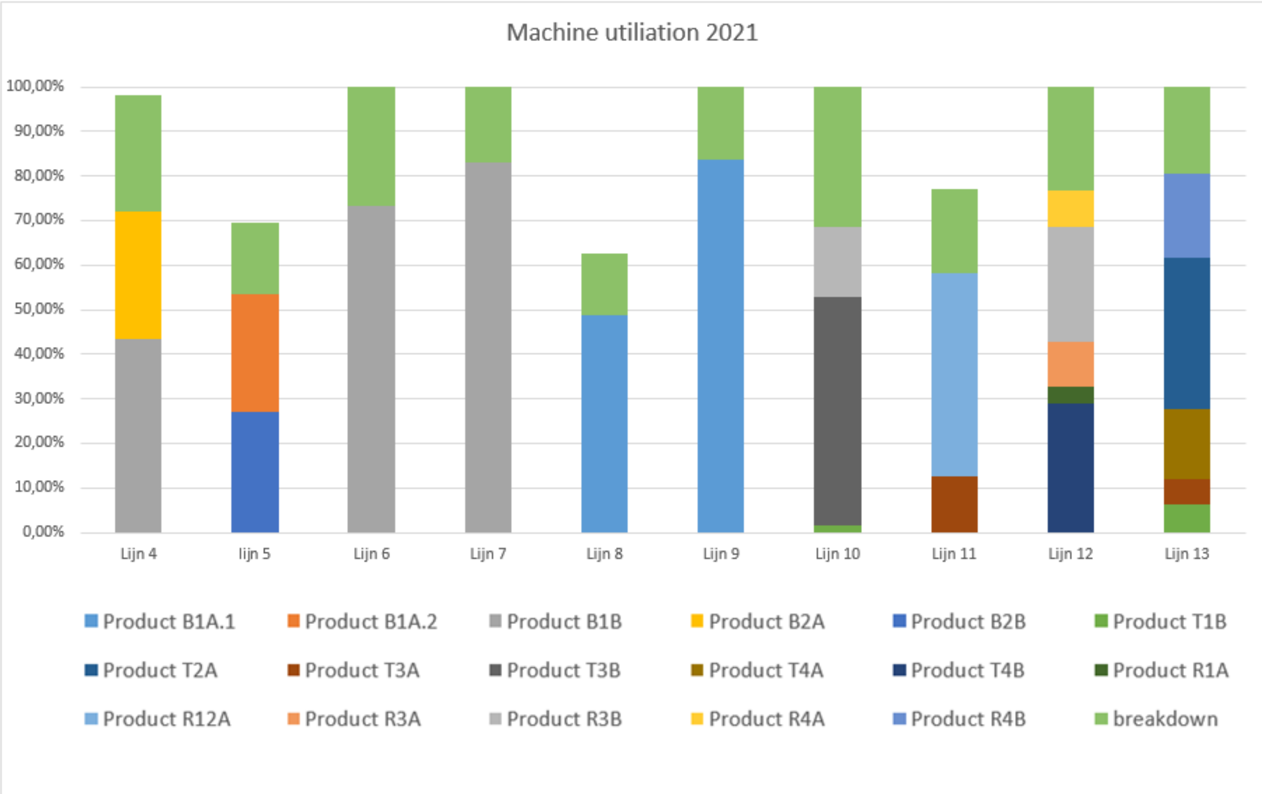

Figure 15: Machine utilization 2021 (Production scenario 2)

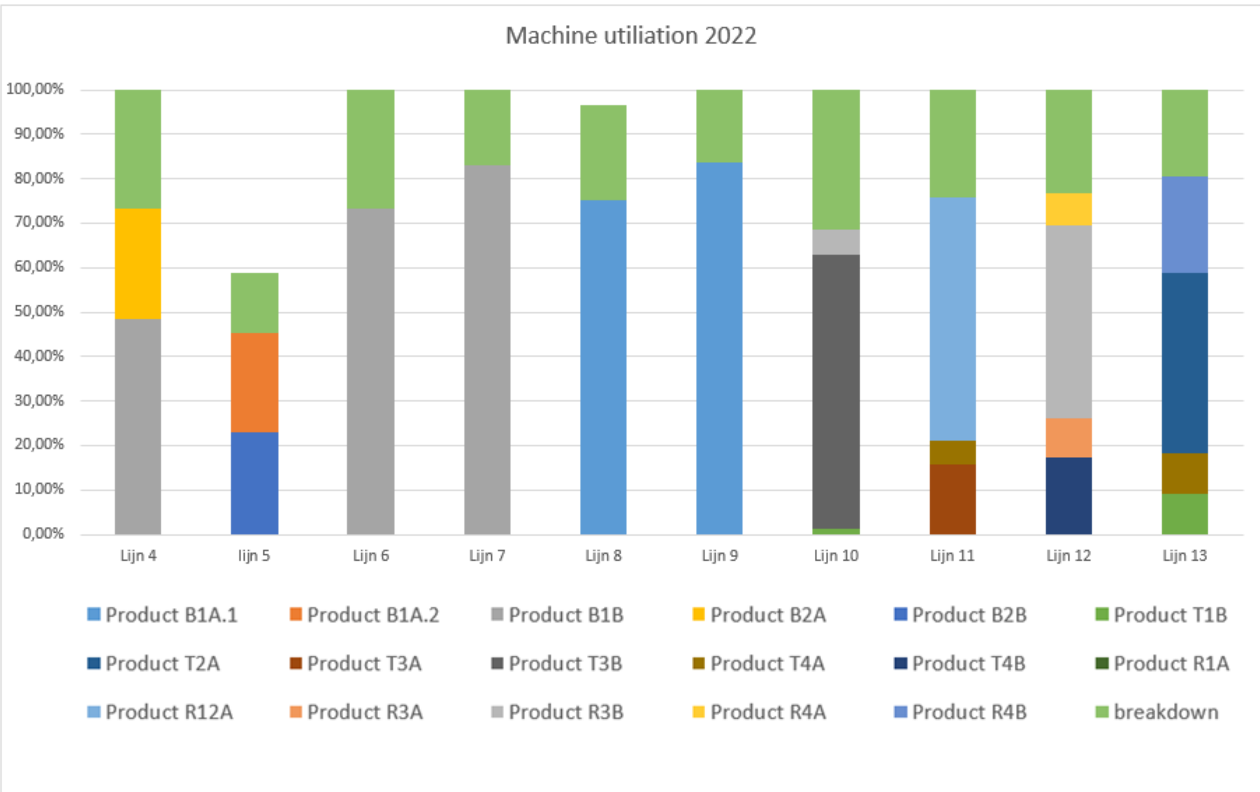

Figure 16: Machine utilization 2022 (Production scenario 2)

Demand

An important aspect of this experiment is that the expected demand in 2021 can be met. For 2022, this is not the case.

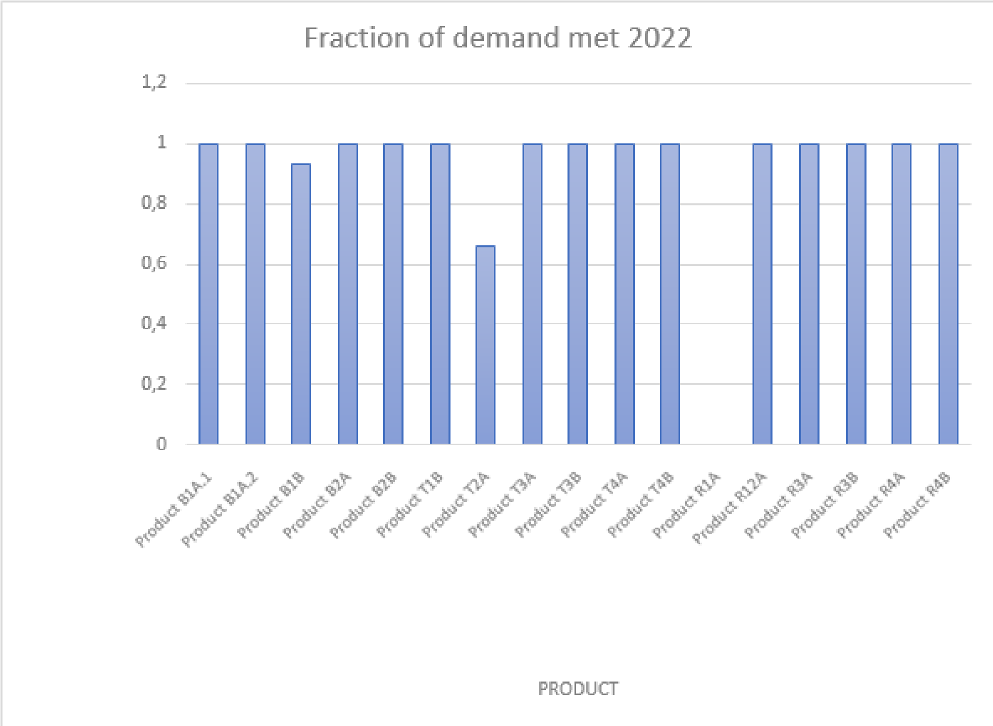

Figure 17: Demand able to be met in 2022

Figure 17 shows that 1 product is not manufactured at all and 2 are not able to fully meet the demand in 2022.

5.2.4 Production scenario 3

In the third experiment, the scenario where production takes place with an additional production machine is analysed. This additional production machine is only able to manufacture buckets. Since no data about this machine is available with regards to cycle times and cost prices, we used the values of the best performing production line 4 up until 9 for this.

In Figures 18 and 19 the machine utilization can be seen for the years 2021 and 2022 respectively. The figures show the machine utilization for tubs and rectangular tubs is 100%. The utilization for the production lines that manufacture buckets is lower due to the additional production line, which manufactures Product B1B and Product B2B in the model. The value for the objective function is €446,533 in 2021 and €566,736 in 2022.

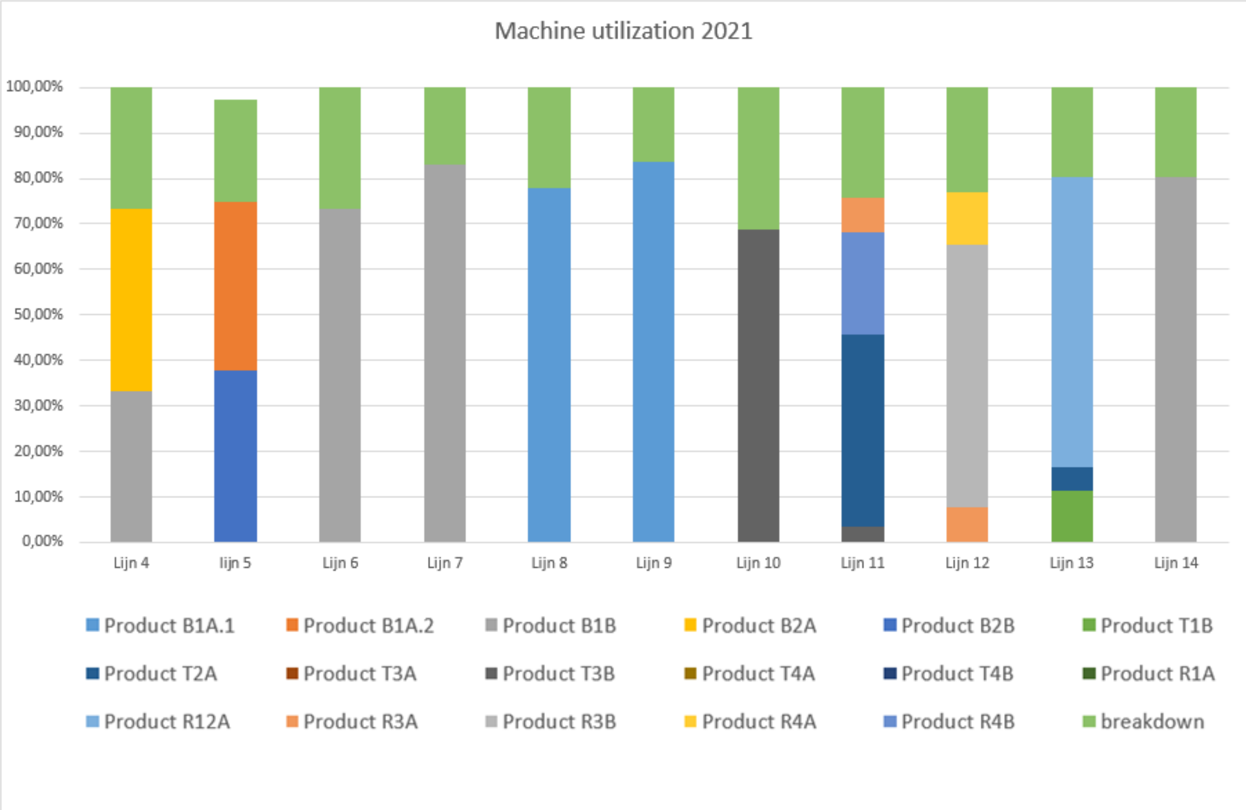

Figure 18: Machine utilization 2021 (Production scenario 3)

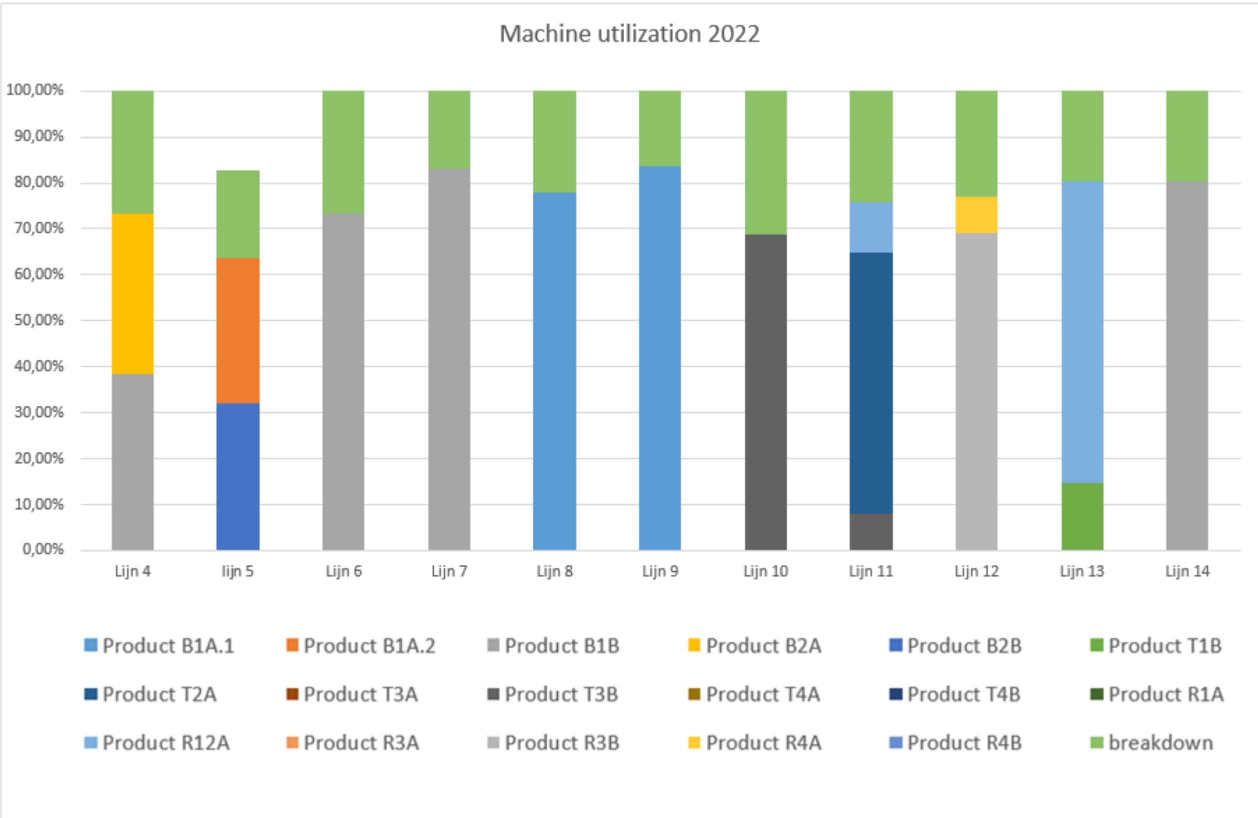

Figure 19: Machine utilization 2022 (Production scenario 3)

Demand
Just like in production scenario 1, the expected demand is not able to be fully met in production scenario 1. This can be seen in Figures 20 and 21.

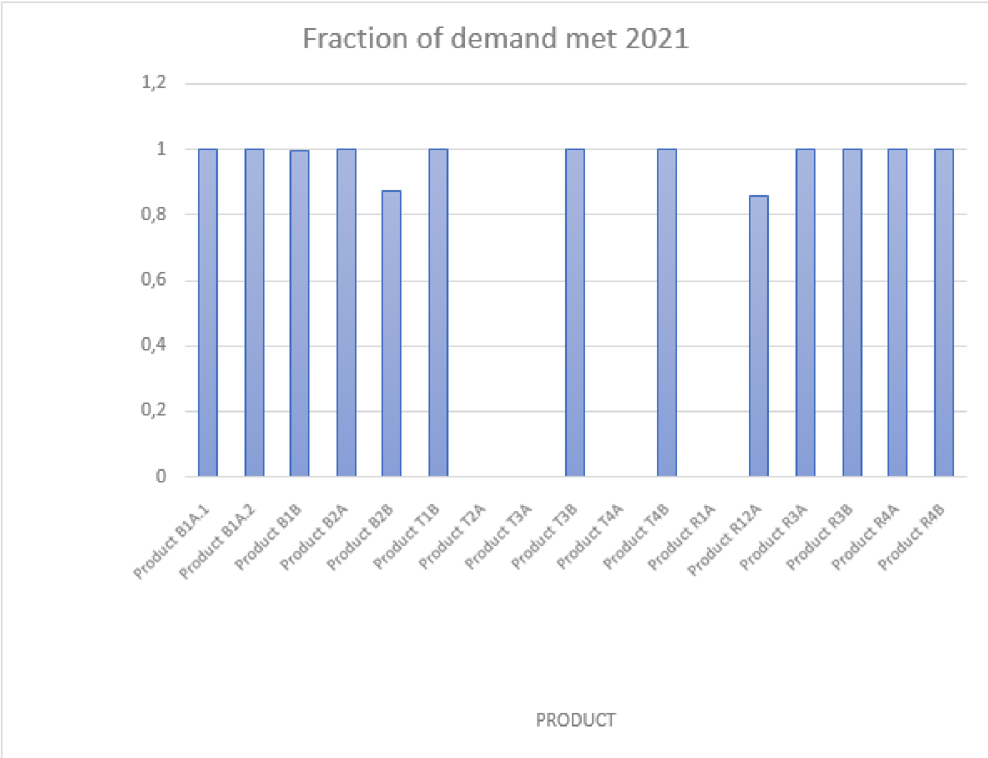

Figure 20: Demand able to be met in 2021

In 2021, 1 product is not manufactured at all in the model and 2 are not able to fully meet the expected demand. The fraction of fulfilled demand of tubs and rectangular tubs is the same as in Production scenario 1. The buckets are able to meet all demand in this experiment, due to the additional production line.

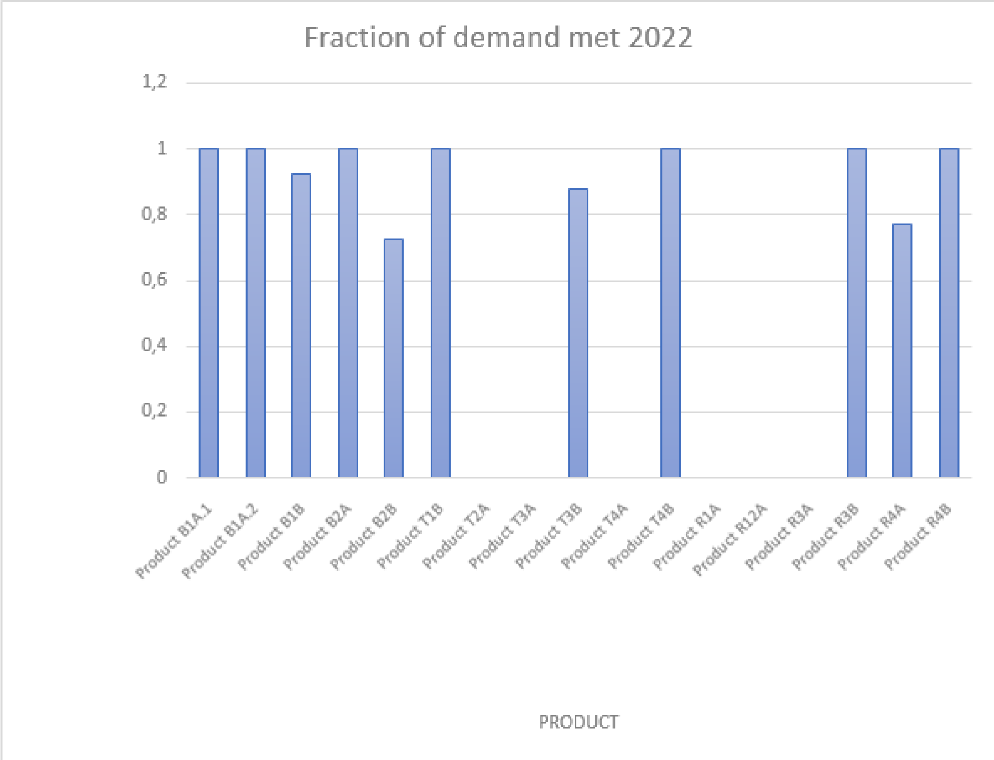

Figure 21: Demand able to be met in 2022

In 2022, 4 products are not manufactured at all. Moreover, 1 product is not able to meet the expected demand. All buckets are able to be manufactured in 2022.

5.2.5 Production scenario 4

In this experiment, the production scenario with a 5-shift roster and an additional injection moulding machine for 2022 is analysed. In this experiment, we do not show the results for the production scenario in 2021, since all demand is met for this year when production takes place with a 5-shift roster and without an additional injection moulding machine. Analysing the results of 2021 would thus only result in extra costs.

Figure 22 shows the machine utilization for this production scenario. The value created at the facility is €778,224 for 2022, which is lower than the value created in 2022 in Experiment 2. Hence, the additional bucket demand that is able to be met with an additional machine does not weigh up against the machine depreciation costs.

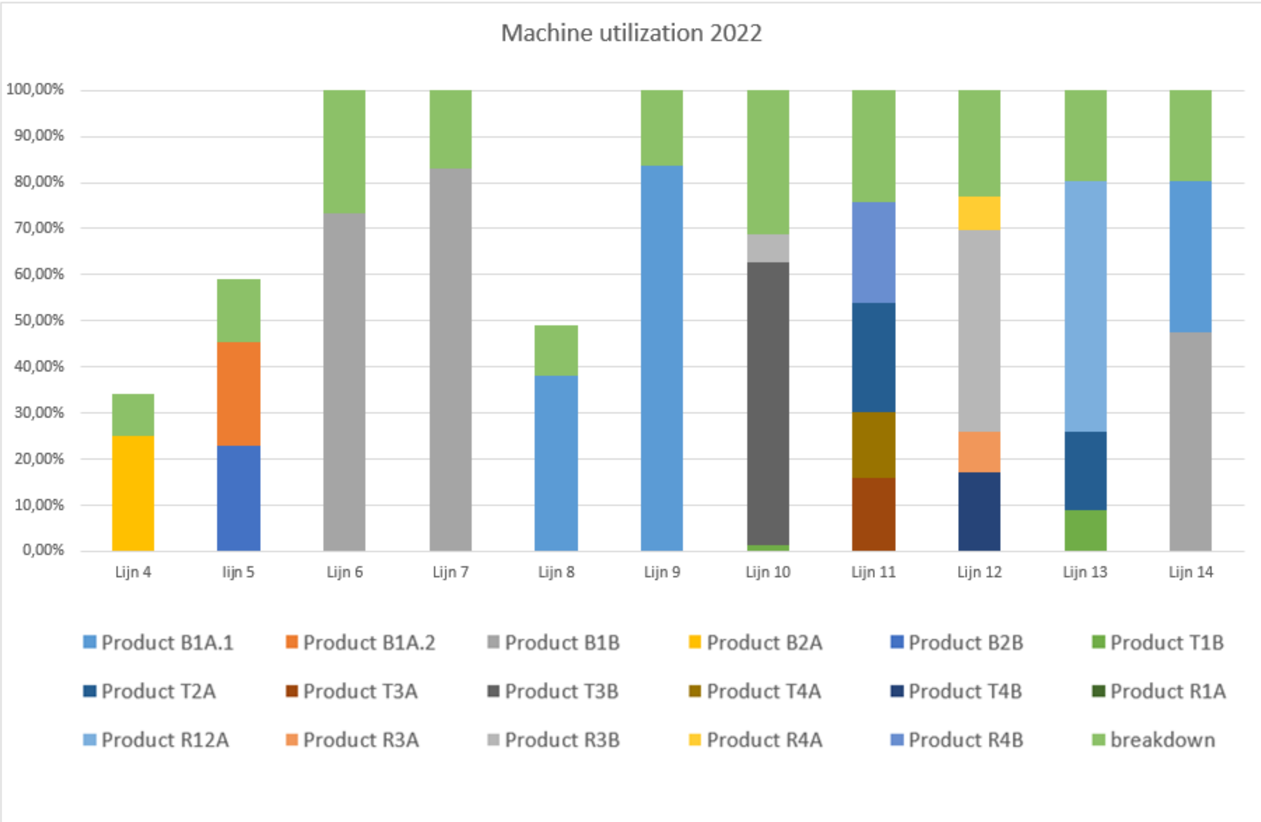

Figure 22: Machine utilization 2022 (Production scenario 4)

Demand

Just like in production scenario 2, the expected demand is not able to be fully met in production scenario 4. Figure 23 shows that all demand for buckets is able to be met, but for tubs and rectangular tubs this is not the case.

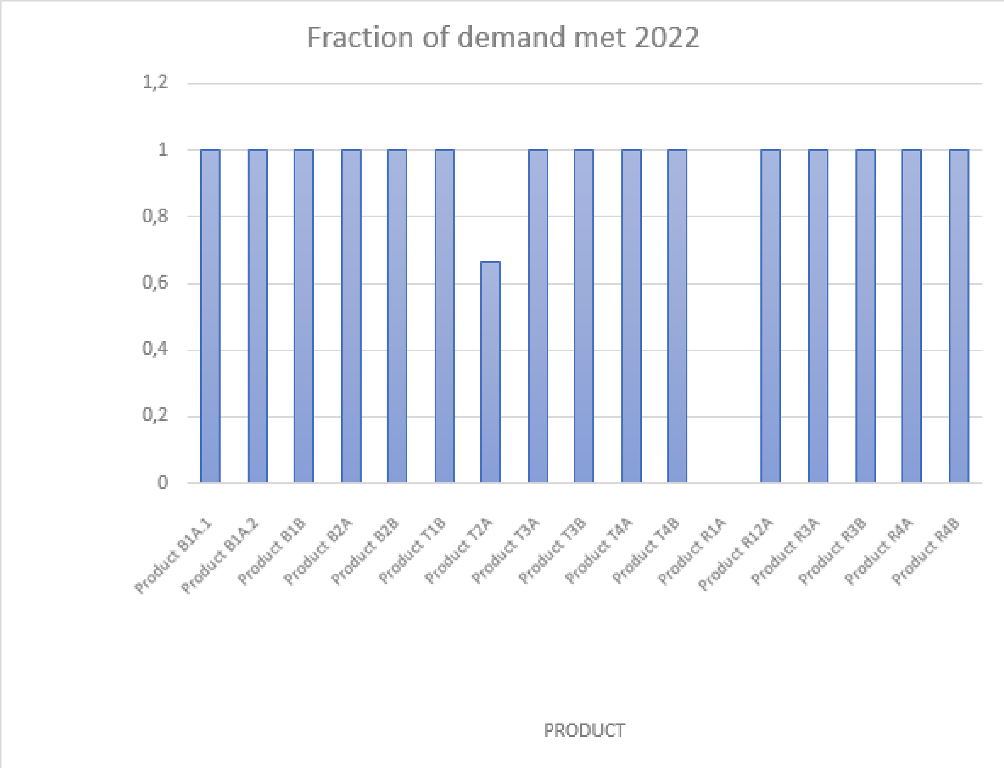

Figure 23: Demand able to be met in 2022

In 2022, 1 product is not manufactured at all in the model and 1 is not able to fully meet the expected demand. The fraction of fulfilled demand of tubs and rectangular tubs is the same as in Production scenario 2. The buckets are able to meet all demand in this experiment, due to the additional production line in this production scenario.

Table 8 shows a summary of facilities performance for the different production scenarios. During the years 2021 and 2022, scenario 2 generates the most combined value and is able to meet all demand in 2021. It is illogical to implement scenario 3 during 2021, since the machine depreciation is not taken into account for the years 2022 up until 2025 for this scenario. Moreover, not all demand is able to be met, which dissatisfies customers.

Table 8: Summary of the facilities performance for the different production scenarios

Production scenario	Value created (€)	Value created (€)	All demand met?	All demand met?
	2021	2022	2021	2022
1	398,688	514,071	No	No
2	437,503	795,718	Yes	No
3	446,533	566,736	No	No
4	-	778,224	-	No

5.3 Sensitivity analysis

In this section, a sensitivity analysis is performed on the optimization model. Chapter 4 describes that not all parameter data used for the model is known with certainty. This causes the model to lose credibility. Chapter 3 describes that performing a sensitivity analysis provides a solution to this problem. This section consists of the following subsections:

- 5.3.1 Initial analysis
- 5.3.2 Changes in expected demand
- 5.3.3 Changes in *OEE*
- 5.3.4 Changes in cycle times

The final part of this section shows an overview from the results of the sensitivity analysis.

5.3.1 Initial analysis

Before making changes to input data and analysing the changes to the decision variables, we decide what changes had to be analysed. Therefore, an initial analysis is performed. In this analysis, we reflect on the difference between how literature describes to carry out a sensitivity analysis and the way we performed the sensitivity analysis.

Lieberman and Gerald (2020) and Winston (2009) both state a sensitivity analysis should be carried out for sensitive parameters for which the optimal decision variables might change when the parameter input changes. This is done to see whether the optimal solution, with regards to the decision variables, changes. In this research, the decision variable the model aims to optimise (N_{xi}) displays how many products x should be manufactured on every production line i. However, the reason for conducting the experiments is not to see how many units of each product should be manufactured on each machine, but to see to what extend the expected demand can be met in different production scenarios and how much value is created at the production facility in these scenarios. Therefore, we did not analyse what changes with regards to decision variables when parameter input data is changed, but what happens to the output section that is created in the model. This section provides information with regards to: (1) production value created at the facility, (2) fraction of demand able to be met and (3) machine utilization. Based on this output, a decision can be made which production scenario is optimal to use by the company.

In Section 4.9, the way the input data for the model was gathered and the data validity of this data is discussed. Since the experiments analyse future production scenarios, all input data is an estimate to some extend. However, some input data is more likely to be different in the future. 3 Parameters that carry significantly more uncertainty are analysed: Demand, OEE and Cycle times. Experiments are carried out with different values of the parameters that are realistic for the real life situation in 2021.

5.3.2 Expected demand

The expected demand is calculated based on historic sales data and a qualitative meeting with the financial director. Although an extensive forecast has been made for 2021 and 2022, the expected values are subject to forecast errors and can largely be impacted by Company X. For example, a big customer might leave the company or a new customer might be acquired.

For this parameter, 3 experiments are carried out. Production scenarios 1, 2 and 4 are analysed in these experiments. The expected demand for 2021 has been changed in these experiments. The following demand changes are made, since these are likely values for the real life system in 2021:

- The expected demand decreases with 10% for all products.
- The expected demand increases with 10% for all products.
- The expected demand increases with 20% for all products.

The aim of these experiments is to find out whether all demand is still able to be met, or whether it exceeds the capacity of the production facility. Moreover, a look has been taken whether the best performing production scenario (with regards to the value created) changes.

Demand decrease of 10%
When all product demand decreases by 10%, the value created at the facility is reduced to €196,933. This is a decrease of €240,570 in comparison to production scenario 2. All demand is able to be met for this scenario.

When this experiment is run for the production scenario of Experiment 1, the facility creates €334.764 value. In this scenario, not all demand is able to be met.

Demand increase of 10%
When all product demand increases by 10%, the value created at the facility increases to €652,999, which is an increase of €215,496. However, not all demand is fulfilled for production scenario 2 when demand increases by 10%.

When this experiment is run for the production scenario of Experiment 4, the value created at the facility is €640.970,13, which is slightly lower than the scenario of Experiment 2. Contrary to this however, all bucket demand is able to be met and the machine utilization for buckets is lower.

Demand increase of 20%
When demand increases by 20%, the value created at the facility increases to €836,016, which is an increase of €398,513.

When this Experiment is run for the production scenario of Experiment 4, the value created at the facility is €868.713, which is higher than for the production scenario of Experiment 2. In this scenario, all bucket demand is still able to be met due to the additional injection moulding machine.

Figure 28 in Appendix E shows that the fraction of demand that is met decreases when demand is increased, for production scenario 2. When demand is not able to be met, customer satisfaction decreases.

5.3.3 Overall equipment effectiveness

The values for *OEE* used in the model are only based on 4 weeks of production data. After the validation experiment, the values were all lowered by an additional 10%. Due to the little amount of data the OEE is based on and the positive impact an improvement in the *OEE* can create, experiments are carried out where the values of the *OEE* are increased.

For this parameter, 2 experiments are carried out using a 5 shift roster without additional machinery. For these experiments, the production scenario of Experiment 2 is analysed. The following changes have been made to the parameter in this experiment, since these changes are expected to be possible improvements:

- The OEE for the different production lines are increased with 5%.
- The OEE for the different production lines are increased with 10%.

OEE increase of 5%
When the experiment is run for production scenario 2, the value created at the facility is €456,664 and all demand is met. When the experiment is run for production scenario 1, the value created at the facility is €522,724. Not all demand is able to be met in this scenario.

OEE increase of 10%
When the experiment is run for production scenario 2, the value created at the facility is €475,539 which is only a slight increase compared to an increase of 5% of the OEE. For production scenario 1, the increase is more significant, namely €92,740. The increase is way bigger since additional demand is able to be met for this production scenario.

Figure 29 in Appendix E shows that when improvements to the *OEE* are made at the production facility for production scenario 2. The machine utilization decreases. Thus, more demand can be met when the *OEE* values improve.

5.3.4 Cycle times

The cycle times which are used in the experiments are constant. In the real life situation, these show variation and can still be improved. Analysing to what extend this will improve the production facility is interesting, since it shows what can be gained by improving the cycle time.

The experiments carried out for this analysis are based on a decrease in cycle time. Only decreases are used since there are a lot of improvement possibilities for the cycle time. Moreover, 1 experiment is carried out where demand is increased by $\frac{1}{9}$, to keep machine utilization the same. The experiments are run for production scenario 2 and 1. The following decreases are used:

- A decrease of 5% for all cycle times.
- A decrease of 10% for all cycle times.
- A decrease of 10% for all cycle times and a demand increase of $\frac{1}{9}$.

Cycle time reduction of 5%
When the cycle time is reduced by 5% for all products on all production lines, the value created at the production facility increases to €525,277 for production scenario 2. This is an increase of €87,774. For production scenario 1, this increases to €533,099, which is an increase of €140,823. The increase for this production scenario is higher since additional demand is able to be met.

Cycle time reduction of 10%
When the cycle time is further reduced by 10%, the value created at the facility increases to €612,745 for production scenario 2. This is an increase of €175,242. For production scenario 1, this is increased to €837,975

Cycle time reduction of 10% and a demand increase of $\frac{1}{9}$
When the demand is increased on top of the cycle time reduction, machine utilization is exactly the same as in Production scenario 2. The value created at the facility increases to €899,537. This is an increase of €462,034 during the year 2021. For Production scenario 1, the value created at the facility increases to €783,004, which is an increase of €389,136.

In Figure 30, which can be found in Appendix E, the machine utilization can be seen and compared for production scenario 2. Due to the decrease in cycle times, the production capacity increases and the machine utilization decreases. For the last bar chart, the utilization is the same as when demand is normal and cycle time is normal. The results are similar to these of the experiments carried out in Section 5.3.3.

The performance differences for the different analyses carried out in Section 5.3 can be seen in Table 9. This table shows that making improvements to the *OEE* and Cycle time at the facility significantly improves the value created at the facility per year. On top of this, other production scenarios outperform scenario 2. It should be noted that when production scenario 1 outperforms scenario 2 with regards to the value created at the facility, this scenario is not able to meet demand. Since not being able to meet customer demand dissatisfies customers, scenario 2 is still the best performing production scenario to our belief, since the additional value scenario 1 creates does not weigh up against the customer dissatisfaction.

Table 9: Summary of the facilities performance for the different changes in input data

Change in input data	Additional value created (€)	All demand met?	Other experiment with higher created value?
Demand			
Decrease 10%	-240,570	Yes	Yes (scenario 1)
Increase 10%	215,496	No	No
Increase 20%	398,513	No	Yes (scenario 4)
OEE			
Increase 5%	19,161	Yes	Yes (scenario 1)
Increase 10%	38,036	Yes	Yes (scenario 1)
Cycle time			
Decrease 5%	87,774	Yes	Yes (scenario 1)
Decrease 10%	175,242	Yes	Yes (scenario 1)
Decrease 10%, Demand increase 11.1%	462,034	Yes	No

5.4 Conclusion

This chapter carried out experiments with the simplified optimization model. The initial *OEE* values are changed since the validation experiment showed the system performance to be too optimistic. When analysing different scenarios for the upcoming 2 years, production scenario 2 performed best overall. In 2021, the value created is higher in Experiment 3, but not all demand is able to be met, which dissatisfies customers. After the experiments for the production scenarios have been carried out, a sensitivity analysis is performed. This analysis showed that the value created at the production facility can be improved drastically when improvements to the *OEE* and Cycle times are made. On top of the additional value created, extra production demand can be met due to the increase in production capacity. In several Experiments, scenario 1 outperformed scenario 2 with respect to the value created at the production facility. However, since demand is unable to be met for this scenario, production scenario 2 is still the choice of preference.

6 Conclusions, recommendations and discussion

This chapter concludes on the results of the experiments carried out with the optimization model and the research as a whole. This chapter is structured as follows:

- 6.1 Conclusions
- 6.2 Recommendations
- 6.3 Discussion

First, conclusions are drawn on the main research question this research addresses. Second, recommendations are given based on the experiment results from Chapter 5.2 and overall findings at Company X. Lastly, the discussion provides a critical reflection, where the model limitations are discussed.

6.1 Conclusions

This section answers the main research question this research addresses. The answer to the research question is based on the answer to the sub-research questions. These have been answered in Chapters 2 up until 5.

From the context analysis, we concluded that the bottleneck of the production facility are the injection moulding machines. These machines have restrictions on what products are able to be manufactured on them. Moreover, the facility is unable to manufacture the desired production output with the 3 shift-roster that is currently in place. During some parts of the year, a 5 shift-roster is used where employees work overtime to manufacture the desired output.

From the theoretical framework, we concluded that optimisation methodologies like TOC and Lean Manufacturing are applicable to the production facility of Company X. These methodologies focuses on improving production processes. Subsequently, literature showed different techniques for solving optimization problems, like linear programming. These problems can be solved with the help of computer software. On top of these findings, literature argued to conduct a sensitivity analysis when solving a linear programming problem.

In Chapter 4, we argued to use a mathematical programming model for this research. The model is formulated according to the Simplex method. In order to solve the model, data of the model's parameters is gathered and the validity of this data is discussed. After simplifying the formulated model, experiments are carried out with the linear programming model in Excel. The validation experiment showed that the initial input data used for the model was incorrect. Based on these findings, input data was changed to make the model match the performance of the real life system. From additional experiments carried out with the adjusted input data, it became clear the production facility performs best when production takes place with a 5-shift roster during 2021 and 2022, since the value created at the facility is the highest value in this situation. For 2021 specifically, implementing a 3-shift roster with an additional injection moulding machine created slightly more value. However, investing in an injection moulding machine means depreciation has to be paid for 5 years and since 2022 in Experiment 2 outperforms 2022 in Experiment 3, the company should introduce a 5 shift roster at the production facility. On top of this, not all demand is met when the company invests in an additional injection moulding machine, which dissatisfies customers.

Based on the findings of the sub-research questions, the research question of this research can be answered. The research question this research addresses is:

"What changes have to be made to increase the production capacity of the production facility, taking into account customer demand?"

Based on the experiment results and its interpretation, Company X should start implementing a 5-shift production roster, where production also takes place during the weekend. In this situation, the value created at the production facility is maximised for the upcoming two years and the expected future demand for these years is able to be met.

6.2 Recommendations

In this section, recommendations are given based on the experimental results and overall findings during the research.

- First of all, we recommend the company to start implementing a 5-shift roster for the production employees. The extra time the production facility is active results in future demand expectations to be met, where most machines are not even utilised for 100%. In practice, this would mean that not every machine needs to be active all the time and machines need some planned downtime. This can be done by deactivating some machines in certain shifts. Whenever 2 employees are present during a shift instead of 3, some machines can be turned off. In this way, planned downtime can be used effectively with the use of less employees during some shifts.

- Second, we advice the company to start implementing a good cleaning policy for the moulds of the injection moulding machines. The research showed that the OEE of the production lines was lower than expected by the staff. According to several employees, the breakdowns at the machines are mainly caused by bad cleaning. Hence, implementing a good cleaning policy reduces breakdown time at the machines. On top of this, product quality increases and the cycle times for the different products can be lowered, since clean moulds can manufacture at lower cycle times than dirty moulds.
- Third, the company should focus on reducing and standardising cycle times. Currently, there is a lot of variation in cycle times and there is no clear standard of what the cycle time should be. Due to this fact and the bad cleaning policy, cycle times at the injection moulding machines are often higher than they could be. Reducing the cycle time reduces the average *Costs of goods sold* and thus increase the profit margin. Moreover, the production capacity is increased when cycle times are lowered. When cycle times are reduced by 5%, the value created at the production facility increases with €87,774. On top of this improvement, additional demand can be fulfilled.
- Lastly, we recommend the company to use the optimisation model for future production scenarios. This allows the company an indication to see whether the demand can still be met when they want to acquire an additional customer, for example. Moreover, the model can be used to see to what extend the facility is able to manufacture the expected sales for a certain period. It is important to note that data used in the model should be checked and changed when outdated. Whenever this is not done, the credibility of the model decreases significantly and it is hard to draw valid conclusions from the model results.

6.3 Discussion

In this section, a discussion is provided on the limitations of the research and to what extend the conclusions that can be drawn from the research are valid. It should be noted that any model of a real life system has limitations, since a model can never represent the real life system exactly as it is. Thus, implementing a production scenario from the model in the real life system might yield different results.

First of all, some parameters used in the optimisation model are uncertain and based on estimates. Examples of these are the cycle times and Overall Equipment Effectiveness. For the cycle times, a sensitivity analysis has been carried out to see what the impact on the model output is when changes are made to the cycle times of the different products. Due to the limited amount of time of 10 weeks of this research and the time consuming process needed for calculating the OEE, the *Overall Equipment Effectiveness* of the production lines is based on data from 4 different weeks. This causes the OEE of the model to be based on limited data and might show inaccuracies. The absence of data limits the credibility and accuracy of the model, since the real life results might differ due to different inputs. Thus the model should be used as a supportive tool for decision making and is all-telling.

Second, it is important to understand the optimisation model does not take into account all aspects of a production scenario. Although experiment 2 performs best and is recommended to be implemented at the facility, the experiment does not take into some practical/qualitative aspects. The model does not take into account whether production employees are willing to work during the weekends, for example.

Third, not all costs of the production facility are taken into account in the optimization model. The costs include: direct staff, electricity, raw material, machine depreciation and indirect staff costs. Additional costs that can arise in the real life system, like tools and office supplies.

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A Facility layout

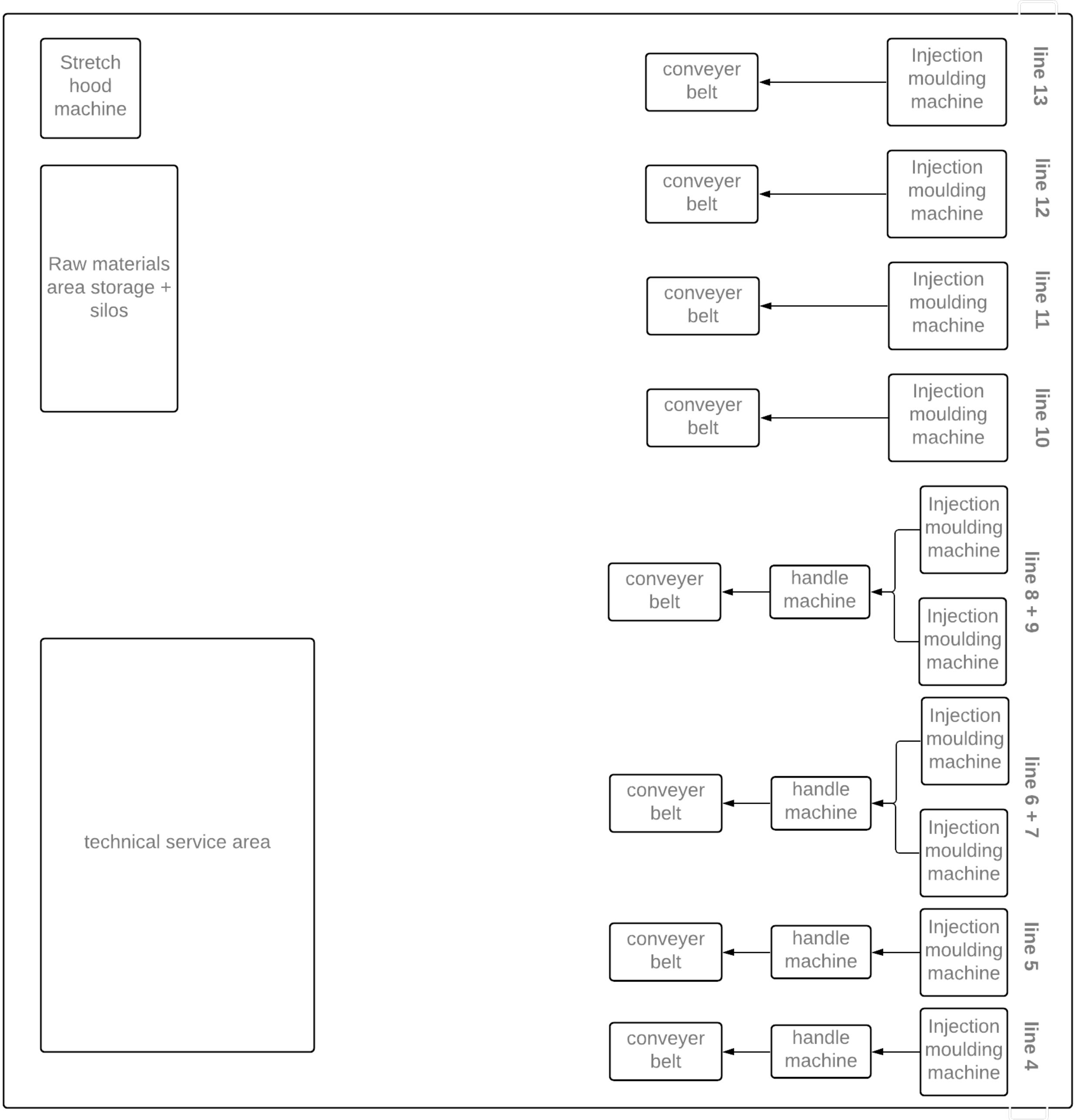

Figure 24: Simplified layout of the production facility

B Demand comparison

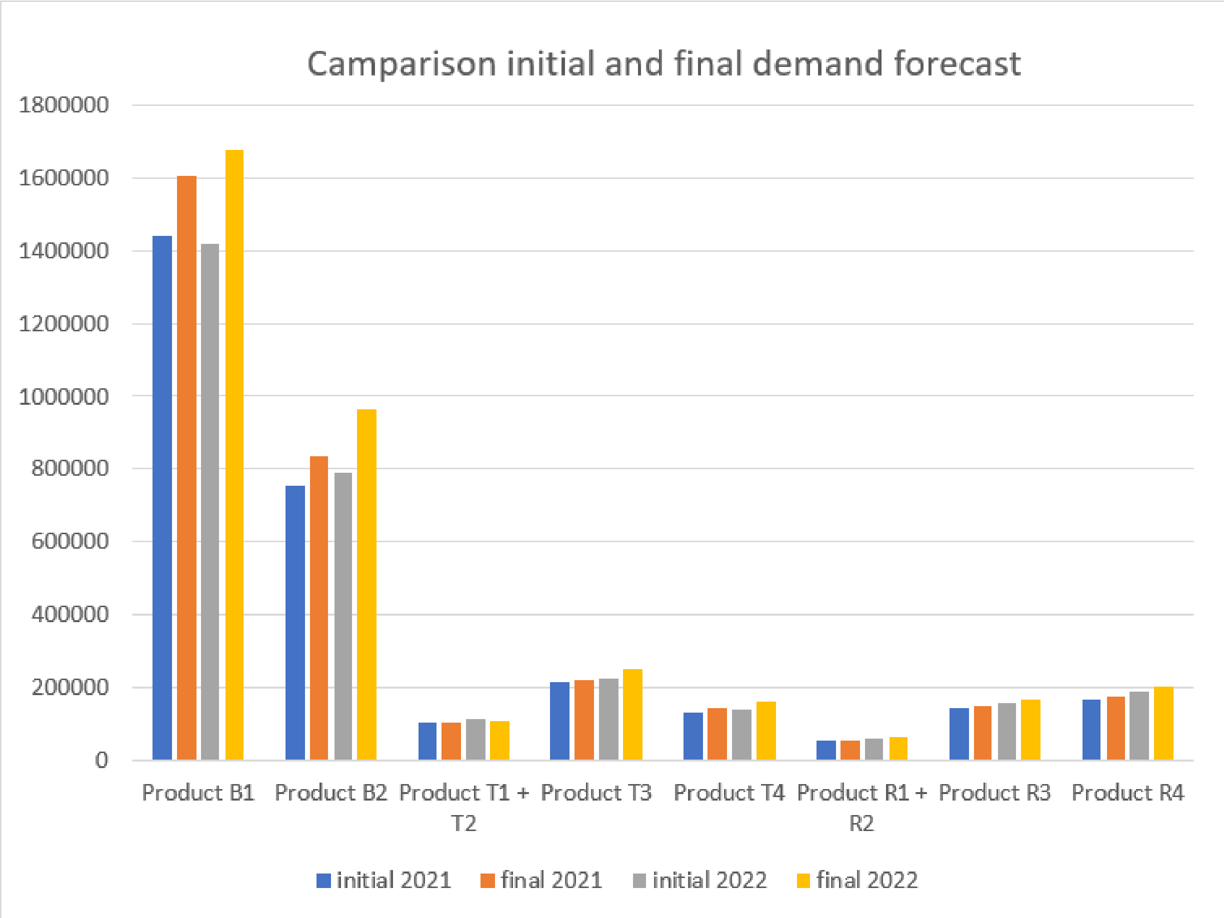

Figure 25: Comparison between the initial and final demand forecast

C Decision variables

1. Decision variable												
Product	Lijn 4	lijn 5	Lijn 6	Lijn 7	Lijn 8	Lijn 9	Lijn 10	Lijn 11	Lijn 12	Lijn 13	Lijn 14	**Totaal**
Product B1A.1		167843									0	167843
Product B1A.2		151587,6667									0	151588
Product B1B	0		1286107	0							0	1286107
Product B2A	126669,6667										0	126670
Product B2B					0	709250,6667					0	709251
Product T1B							37063,33333	0		0		37063
Product T2A									68889,66667			68890
Product T3A								0	0	43712		43712
Product T3B							178073,6667	0	0	0		178074
Product T4A								0	0	34224,66667		34225
Product T4B								0	0	108982		108982
Product R1A									9101,666667			9102
Product R12A							44681,66667	0	0	0		44682
Product R3A								0	26240	0		26240
Product R3B							120776,6667	0	0	0		120777
Product R4A									22803			22803
Product R4B								153053		0		153053

Figure 26: Decision variables in the optimisation model

D Instructions

Gebruik optimalisatiemodel

Met behulp van dit Excel bestand kan het optimalisatievraagstuk voor productie opgelost worden.
Vanwege de complexiteit van het model en een software-extensie die toegevoegd moet worden
om het model te kunnen gebruiken is er een gebruiksaanwijzing voor het model.

Toevoegen software-extensie

1. Ga in Excel 2010 of later naar **Bestand > Opties**
2. Klik op **Invoegtoepassingen** en selecteer vervolgens **Excel-invoegtoepassingen** in het vak **Beheren**.
3. Klik op **Start**.
4. Schakel in het vak **Beschikbare invoegtoepassingen** het selectievakje **Oplosser-invoegtoepassing** in en klik vervolgens op **OK**.
5. Nadat u Oplosser hebt geladen, is de opdracht **Oplosser** beschikbaar in de groep **Analyse** op het tabblad **Gegevens**.

Scenario's die geanalyseerd kunnen worden

Met behulp van dit Excel bestand kunnen 4 scenario's geanalyseerd worden. Bij deze analyses wordt gekeken naar de productiecapaciteit per machine, productvraag en winst van de productiehal.

1. Productie met 3 shifts gedurende de normale werkweek. Als u dit scenario wil analyseren gaat u naar de sheet: *3 shifts*
2. Productie met 5 shifts, waarbij productie ook in het weekend plaats vindt. Als u dit scenario wil analyseren gaat u naar de sheet: *5 shifts*
3. Productie met 3 shifts gedurende de normale werkweek met een extra spuitgietmachine voor emmers. Als u dit scenario wil analyseren gaat u naar de sheet: *3 shifts, extra machine*
4. Productie met 5 shifts, waarbij productie ook in het weekend plaats vindt. Bovendien vindt productie plaats met een extra spuitgietmachine voor emmers.
   Als u dit scenario wil analyseren gaat u naar de sheet: 5 shifts, extra machine

In het model kunnen de volgende cellen aangepast worden:

Figure 27: This Excel sheet provides instruction on how to use the optimisation model in Excel (in Dutch)

E Sensitivity analysis

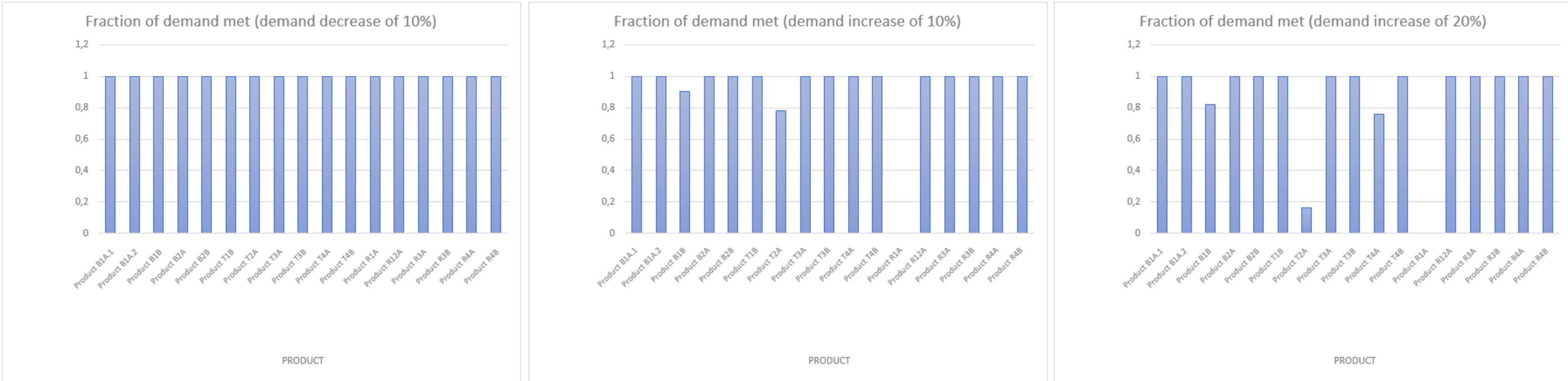

Figure 28: Fraction demand met when demand is decreases/increased

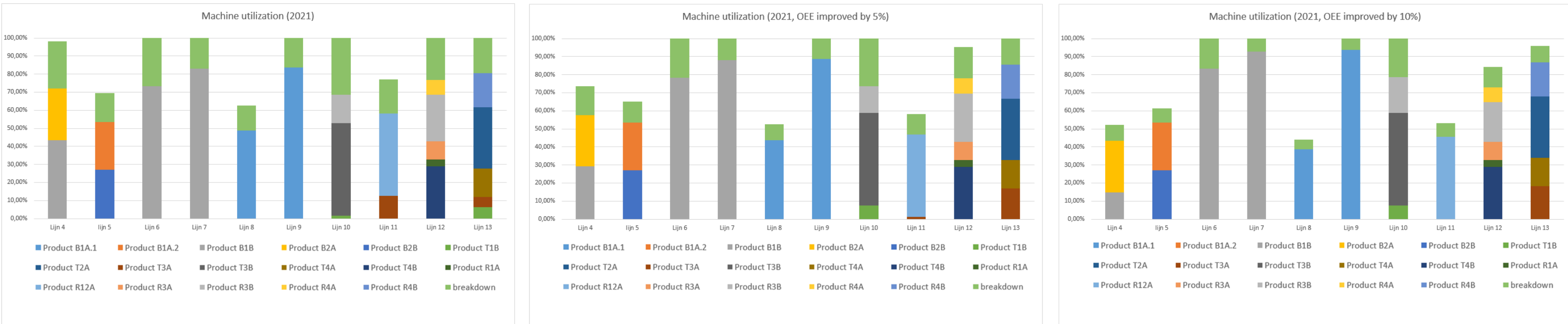

Figure 29: Production line utilization for different OEE values

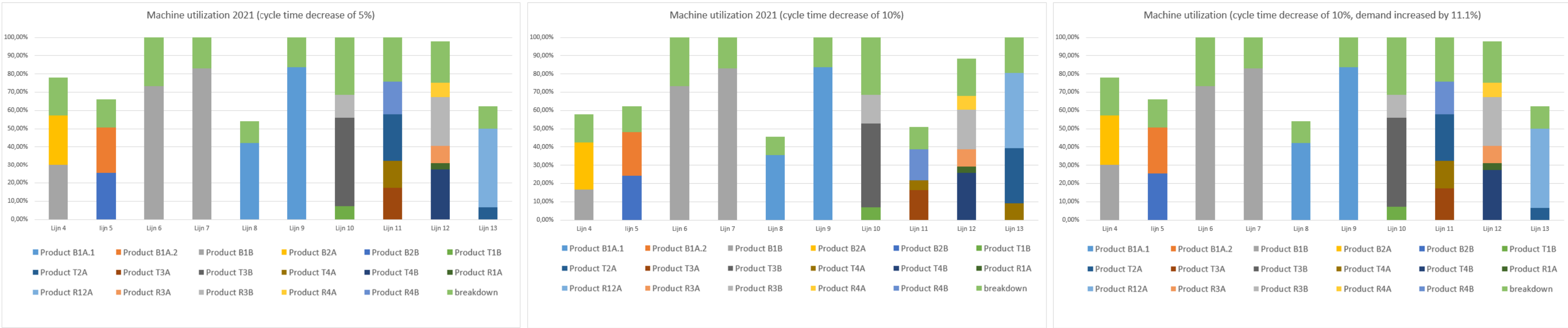

Figure 30: Production line utilization for improved cycle times