MASTER THESIS INDUSTRIAL ENGINEERING & MANAGEMENT

Improving the production planning of a producer of plastic packaging

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PREFACE

In front of you lies a report that is the result of my graduation project to acquire my master's degree in Industrial Engineering and Management, with the specialisation in Production and Logistics Management. This preface is used to thank everyone that made it possible to realise this thesis.

For this master thesis, which has been executed at Hordijk Verpakkingsindustrie Zaandam BV, I entered the world of mass production of plastic packaging. I really enjoyed working at the company and I learnt a lot. Especially the transition from an ”old” to a new factory opened up my eyes. I want to thank Hordijk for giving me the opportunity to graduate here and for all the lessons I learnt. Next to that, I want to thank everyone at the company for helping me when needed and really taking the time for this. In particularly, I want to thank my supervisor Jeroen. He has been a great help during the entire period of my graduation.

Furthermore, I want to thank my UT supervisor Peter Schuur. I really enjoyed the meetings we had, even though they were all online. The meetings were a perfect mix between humour and seriousness. And that made it a pleasure to work with you.

Graduating for my master means that my student time in Enschede and at the University of Twente is about to end. I enjoyed the five years of studying, although unfortunately, the last year was hindered by Covid-19. But still, the four years before were amazing. I want to thank everyone that helped me during my studies, and specifically Jesper, with whom I did almost all projects during the master. All of you made my student time to such a success.

For now, all that remains for me to say is: enjoy reading this report.

Martijn Korver
July 2021

MANAGEMENT SUMMARY

This thesis is written for Hordijk Verpakkingsindustrie Zaandam BV. Hordijk is a producer of plastic packaging for the food industry. Millions of plastic cups and lids leave the factories per year. In Zaandam there are currently three factories, however, only two of them are being used. One of them is namely a brand new factory which made the use of the third factory not needed anymore.

This research is conducted with the aim to answer the following research question:

What can Hordijk do to improve their planning process and thus reduce their production and inventory costs, without affecting the demand restrictions?

The problem which the company encounters is that they lack insight into their production planning. Out of experience it is known that the company encounters a seasonal demand. Therefore the company decides to produce extra products in non-busy months to cover up the seasonal pattern. However, the company does not know what product is best to produce earlier and how much to produce earlier.

Currently the company uses two simple rules to determine which products to produce earlier and how much of the product. The product to produce earlier is selected at random. This means that any product could be produced earlier. The amount to produce earlier is equal to a quarter of its yearly demand. This method has worked for many years, but in all those years it was never known whether the decisions made were the least costly. Therefore the company wants to see the data behind the schedule and wants to use that data to determine how much to produce earlier and of which products.

Literature has been searched to find models, which can solve this problem. Different models are found that can solve planning and scheduling problems. The results of the models are schedules in which the lot size and the timing of production are determined for the entire time horizon. This means that the result of the model is an optimal schedule and that the planners should use that schedule instead of their own schedule. For the company this was not what they were looking for. The company is not yet ready to incorporate a whole schedule made by software. Therefore the aim of this research is to create ”new” monthly demands. With ”new” is meant that they are different from the actual monthly demand and incorporate earlier production. These forecasts can then be used by the planners.

Since the goal of the research has changed, the models found in the literature must be adapted. The Capacitated Lot Sizing Problem (CLSP) found in the literature has been adapted for this purpose. In the literature it is stated that the CLSP is NP-hard, which means that it is unlikely to solve optimally in polynomial time. This claim has been tested by solving the whole problem for eight consecutive hours. After the run, no optimal solution had been found. Therefore, the problem has been divided into subproblems. These subproblems have been solved optimally and by combining them, the optimal solution for the whole problem has been found.

The subproblems made it possible to determine the optimal solution for the company. However, this method is very time consuming, since all the input data has to be separated and inserted into the solver one by one. Next to that, it is not possible to use the method for the whole problem, as this did not solve optimally in time. This means that whenever the company wants to see both factories combined, it is not possible. To cope with this problem, a simulated annealing framework has been created. With this framework, the whole problem can be solved. Next to that, additional constraints, such as a total number of employees over both locations can be added.

There are three different type of results. One fully based on the demand forecasts, one which is the result of the mathematical model and one solution created by the simulated annealing framework. These results are explained one by one.

The demand forecasts are expressed in production hours and put into a dashboard. On that dashboard it can be seen which months are busy and which months are not. Next to that, it can be determined for which months production has to be scheduled earlier. Not only the capacity can be checked, also KPIs as the average number of employees needed on a day and the total tonnes of plastic foil needed can be determined. All these data gives the company a good idea of what is expected in the upcoming year. Next to the KPIs, the objective function has been determined, which is equal to 1.5 million euros.

Looking at the optimal solution, many things have been changed in comparison with the forecasted demand. All these difference have resulted in a decrease in costs of 700 thousand euros. The main difference is that the number of setups is decreased. By increasing inventory for some products, less setups were needed and costs decreased. With regard to the capacity, it can be seen that no capacity is exceeded anymore and thus the solution is feasible.

In comparison with the optimal solution, the simulated annealing framework did not create good results. The results of the framework had an optimality gap of at least 24%. This means that the costs were 200 thousand euros higher. Unfortunately this means that the simulated annealing framework cannot be used in this state. Extra research has to be done to check whether there is a possibility to improve it.

In the end, the result of this research is a dashboard which shows the expected forecasted demand as well as the optimal solution. KPIs are calculated based on both inputs. The dashboard is able to show the company what will happen in the upcoming months and how to produce the least costly.

To be able to use the dashboard for a longer time, a Python tool has been created which can generate the inputs for the dashboards. To use the dashboards effectively, it is recommended to update the dashboard based on the forecasts once every month. By updating it every month, the company can foresee problems already 12 months before they are happening. This means that the company can react in time. Next to that, it is advised to determine the optimal solution every three months. It is not advised to do this every month as creating the input sheets is a lot of work. Furthermore, the tool is mainly used to determine when to produce earlier and which products to produce earlier and this is mainly the case in months December, January, and February. So updating every three months is enough to capture these months together and in time.

GLOSSARY

Extrusion Extrusion is a process in which plastic shreds are heated until it is a fluid. The fluid is pressed through a die and cooled down again, so that it keeps the given form. In this case the form is a plastic foil.. 5

Moulds A mould is an hollowed-out block that is used during the production of the plastic products. The plastic is pressed into the hollowed-out parts, which causes them to get into a specific form (the product shape). 6

Shredder The shredder is a machine that grinds the unused plastic foil. All the foil is added to the machine and made into plastic shreds. These shreds can later be used again as input for the production process.. 6

Thermoforming Thermoforming is a process in which material is heated and formed into a shape (the form). If the material cools down, the form is fixed. 6

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1 INTRODUCTION

This research is conducted as graduation project for the master Industrial Engineering and Management at the University of Twente. This research is done for Hordijk Verpakkingsindustrie Zaandam BV, which is part of the Hordijk Groep. This report aims on improving the planning and scheduling process at the factories in Zaandam.

In this chapter a short introduction of the company Hordijk is given in section 1.1. In section 1.2 the production process of thermoforming is generally explained. Section 1.3 states the encountered problem of the company and in section 1.4 the research question of this paper is stated.

1.1 Introduction of the company Hordijk

Hordijk Groep was founded in 1922 in Berkel en Rodenrijs by G. Hordijk. Hordijk Group is a family business that includes several subsidiaries which are active in the manufacturing industry. Approximately 400 employees work for the Hordijk Groep and a turnover of €100 million is achieved. Each subsidiary of Hordijk Groep is highly skilled in the design and production of plastic packaging.

1.2 Production process at Hordijk

The focus of this research is on the planning and scheduling of the machines at the factories in Zaandam. The factories in Zaandam produce thermoformed packaging. In this chapter, the production process of the factories is globally explained. For a more detailed explanation of the process, I refer to Section 2.1.

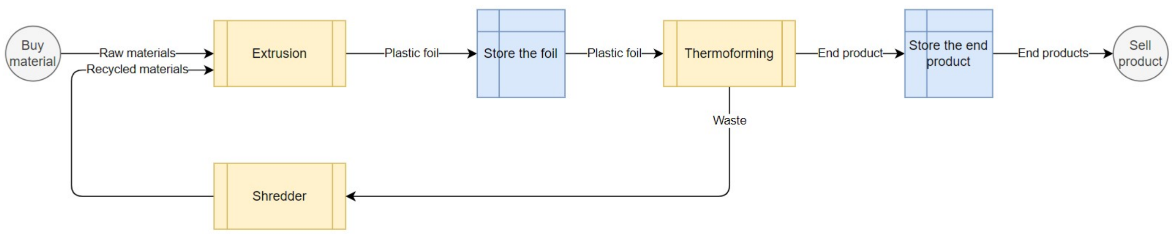

Figure 1.1: Global production process at Hordijk

In Figure 1.1 a simplified version of the production process can be found. The process starts with the purchasing of raw material. By doing extrusion, plastic foil is created. After the extrusion, the plastic foil is stored in a small warehouse. When a thermoform machine is ready to produce, the plastic foil is attached to the machine. The foil is then heated and formed into the correct shape. The end products (see figure 1.2) are stored into boxes or cages and put into another warehouse. From there the products are sold to customers. The waste (parts of the foil that are not used) is collected and put in the shredder. This can be added to the raw material. In this way, there is no waste (apart from some lost shreds).

Figure 1.2: End products of the company

1.3 Description of the problem

The company has a lack of insight into their planning and scheduling process. Currently, the planning is made by the planners based on their knowledge, experience and intuition. The planners make use of demand forecasts for the upcoming weeks made by a forecasting software. Whenever the inventory position drops below 0, actions are taken to make sure the product is produced and the stock does not run out. The production amount is equal to a fixed lot size. The company produces many different products, which have different machine requirements, but also fluctuating demand. The combination of all these factors makes it hard for the company to see the effect of parts of the planning on the whole scheduling process. Do they have a good inventory level or can the inventory be decreased/increased, is it beneficial to combine multiple production orders such that the set-up times decrease, are the lot sizes good or do they need to produce smaller batches? All those questions are unanswered. Therefore the company wants to research what the impact is of the planning, on all factors mentioned above, to further improve their planning and scheduling process.

The key question in this problem is: When do we need to produce, on which machine do we need to produce and how much do we need to produce?

To come up with an optimal planning, a good balance must be found between batch size and inventory level as well as a good balance between the batch size and the set-up times. The research problem that is addressed in this thesis can be described as:

The planning and scheduling process of Hordijk is currently non-optimal. The planning does not find the optimal balance between production and inventory costs.

1.4 Research questions

To be able to solve the research problem, many things should be investigated. But first of all, the research question has to be determined. In Section 1.3 the research problem is determined. Out of this problem, the following research question can be made:

What can Hordijk do to improve their planning process and thus reduce their production and inventory costs, without affecting the demand restrictions?

To solve the research question, multiple sub-questions are stated. The sub-questions themselves also have sub-questions. For every question the necessity is explained as well as the approach to solve it.

1. What is the current planning and production system at Hordijk?
   (a) How is the timing of production determined?
   (b) What is the lot size and how is it determined?
   (c) How is decided on which machine the production is started?
   (d) How is the switch from planning to actual production schedule made?
   (e) What are the objectives and restrictions on the planning/production?

Chapter 2 focuses on answering the above questions. The current situation of the production process is explained in detail. Employees are asked on how and why they are doing the things as they are doing it right now. It is important to know the starting point of the research. Only when everything is fully clear, I am able to come up with improvements.

2. How can the planning system be quantified?
   (a) What KPIs are kept track of?
   (b) What are the target values of those KPIs?
   (c) Which KPIs are most important to the company?
   (d) How can the KPIs be determined?

Chapter 2 also addresses the quantification of the planning and production system. What indicators should be calculated to determine the performance of the current scenario and the solution alternatives found. If it is fully clear what KPIs are used, different alternatives can be compared on performance.

3. What is stated in the literature about the problem Hordijk encounters?
   (a) How can lot sizes be determined best?
   (b) Which models can be used to determine the start time of production?
   (c) How to combine lot size and the timing into one model?
   (d) How to evaluate the model? What KPIs can be used?

Chapter 3 describes a literature review to find methods useful for solving the research question. Next to that, models are described which can determine optimal lot sizes as well as models that can generate the perfect moment to start with production. It is checked if they can be combined, or if other methods need to be found that can combine lot size and start-time optimization. Lastly, articles are checked on the KPIs they use, why they use them and whether it is good for this research to use them as well.

4. What solutions can be thought of for Hordijk?
   (a) What does the literature suggest?
   (b) What requirement does Hordijk have for the solution?
   (c) What solution alternatives can be distinguished?
   (d) What are their pros and cons?
   (e) What choice is recommended?

Chapter 4 describes the used approach to solve the problem of the company. This approach is based upon the literature stated in chapter 3 as well as on current knowledge. The mathematical model used is described as well as an optimazation method to solve the problem, using subproblems, optimally. Lastly a metaheuristic is described, which is created to solve the whole problem at once.

5. What is the best solution for Hordijk and how can it be implemented?

Chapter 5 explains the input data and the settings of the Simulated Annealing framework used. This means that the variables, objectives, penalty costs and the temperature are explained. It will check the capabilities of the alternatives, the computation time, the outcome and many more factors and will choose the one that suits Hordijk the best.

Chapter 6 gives the results of the dashboard and tools created. The results are separated into three sections. The first section explains the current scenario and what can be seen from the dashboard. The second section explains the optimal solution and what is different compared to the current scenario. The third section describes the results of the simulated annealing method.

Chapter 7, which is the last chapter of this report, describes the conclusions of the research. These conclusions are translated into recommendations for the company. Next to that, it is discussed what assumptions have been made and what their effect is on the research. Lastly, it is explained what future research could be done at the company.

1.5 Deliverables

After conducting this research, the following will be delivered to the company.

1. A dashboard created with Excel that gives insight in the demand of the upcoming year. Next to that, the dashboard shows the optimal production planning for the upcoming month.
2. A tool created with Python that creates the inputs for the dashboard. By inserting the forecasts and article data, a production list is created, which is used in the dashboard.
3. A manual on what, why and how to use the tool. Furthermore all the steps used in the analysis are described in detail.
4. This report which states how the research is conducted, what conclusions have been drawn, which recommendations are given to the company and which future research can be conducted.

1.6 Scope

This research focuses on optimizing the production planning of Hordijk. The purpose is to create new insights in what the effect is of planning on the inventory as well as to create a planning technique/tool that minimizes the costs of production and inventory.

2 CURRENT PROCESS

In this chapter, the current planning and scheduling process is analyzed. First of all a detailed description of the thermoforming process is given in section 2.1. Section 2.2 explains the focus of this research. Section 2.3 describes how the current schedule is made. The weekly production schedule is explained in section 2.4. The KPIs that Hordijk keeps track of are explained in section 2.5. Section 2.6 describes how the problem is tackled. The conclusion of this chapter is explained in section 2.7.

2.1 Thermoforming process

In this section, the whole process of creating the products is described. This includes parts of the process which are not treated in the research, however it is good to have a bigger picture of which part of the process is researched and what will be the impacts on the total process. Which specific part is treated in this research is stated in section 2.2.
In Figure 1.1, the global process has been explained, and this chapter explains all the steps of the process in more detail.

The first step in the process is the purchasing of raw materials. These materials are needed to create the plastic foil. Once the raw material is purchased, the actual process within the factory can start. The steps of the process are explained in separate sections. First, the extrusion is explained, then the thermoforming and lastly the shredder. Next to that, information is given on the moulds.

2.1.1 Extrusion

Extrusion can be explained as creating a roll of plastic foil from shreds. In Figure 2.1 the process of extrusion can be seen.

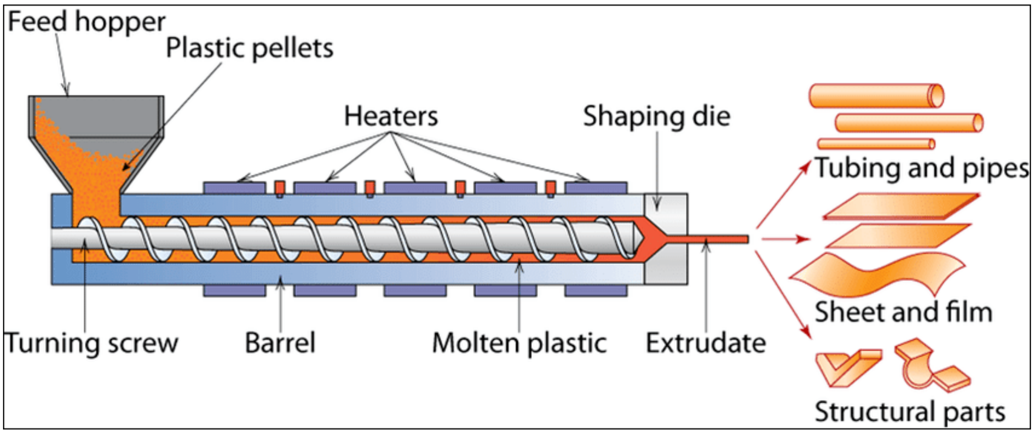

Figure 2.1: Working of an extruder (Bacalhau et al., 2017)

The process starts with raw materials, which are plastic shreds. A mixture of granulate and other plastic shreds is made and put in the Feed hopper. This mixture will fall into the Turning screw, in which it is heated, mixed and ground. The air is pushed out and the material is filtered from contaminants. When the material is fluid, the molten plastic is pushed through a die, which creates a foil. This foil then moves onto two rolls, causing the material to cool down as well as adjusting it to the right thickness. When the material is cold, it is rolled up. When the roll is finished, this roll moves towards the storage.

2.1.2 Thermoforming

When the plastic foil is ready, the foil is put on the thermoforming machine (see Figure 2.2). The foil is unrolled and heated so that it can be formed. It is formed by pressing the foil into a mould. If the form is created, the plastic cools down such that it cannot form back to its original form. After that, the products are stacked and put into boxes or cages, ready to be sold.

Figure 2.2: Thermoform machine

2.1.3 Shredder

A disadvantage of thermoforming is that part of the foil cannot be used. Hordijk uses a shredder to solve the problem. The unused plastic is collected and moved towards the shredder. The plastic is broken into shreds. These shreds can be used in the extruder. This means that there is almost no waste.

2.1.4 Moulds

The moulds are used to create the product out of the plastic foil. Before production can start, a mould has to be installed on the machines. After production they are removed for maintenance. This means that whenever a new batch starts, there is always a set-up time needed to install the moulds.

2.2 Focus of this research

This research focuses on the thermoforming process (so section 2.1.2). This means that extrusion and shredding is not taken into account. It is assumed that the production of plastic foil is always on time, or in other words, the inventory of the plastic foil is infinite. In the remainder of this chapter, the given information is all about the thermoforming process and specifically the planning of the thermoforming process.

Before continuing with the thermoforming process, it is good to know that Hordijk has two factories in Zaandam and both of them work separately from each other on their pool of products. This means that the factories have their own planning of the thermoforming process. Both factories are treated in this research, as in general they can be seen as two identical factories only with different numbers of machines and different moulds.

In the following sections, it is explained how the planning is made, what is done on weekly basis to the planning, what the planning is based on and which KPIs are kept track of. Furthermore, it is explained how the problem is tackled.

2.3 How is the planning actually made?

As said in the last section, the company has two factories. Both factories function separately of each other and therefore there are two different plannings made, one for each factory. Each factory has its own planner, but both planners work according to the same methods. The most important factors are: when to schedule, how much to schedule and on which machine to schedule. In the following sections this is explained.

2.3.1 Batch start time

The start of a production batch of a product is planned when the inventory position becomes 0 or in other words, the future moment at which the cumulative demand forecast is equal to the inventory position. So the start time is equal to the t for which $F^0 + F^1 + \cdots + F^t - I^0 \leq 0$, with F^i = forecast of time period i.

It can occur that at some point in time, there is no room to produce the article at the exact t calculated. Then the planner uses his intuition and knowledge to shift the products in a way that is best according to him.

2.3.2 Lot sizing

The lot sizing or batch sizing at Hordijk is done once for every new product. The first time the product is produced, the forecast for that year is determined. After that forecast is known, the lot size is determined with the following formula:

$$Lot\ size = \frac{Forecasted\ demand\ first\ year}{4} \tag{2.1}$$

The lot size is determined in a way that there are 4 expected production batches per year. Currently, the planners handle an average inventory of 6 weeks, which is in line with the formula. The factory is active for around 47 to 48 weeks a year. To get an average inventory of 6 weeks (assume linear demand), 12 weeks should be produced in one go. That is a quarter of 48 weeks, which is the same as dividing by 4.

2.3.3 Determination of the machine to produce on

The company has multiple types of machines. In Table 2.1 a list of the machines, can be found. Next to that the number of those type of machines can be found per location. It is not important to know the exact differences between the machine. However, what is important, is that all machine use different moulds. The moulds are specifically made for one type of machine. That means that one machine type can only make the products for which a mould is available.

Since most of the products only have one mould, they are obligated to be produced on a certain machine type.

Table 2.1: Thermoform machines at Hordijk

Machine group	Factory 1 (old)	Factory 2 (new)
1	A	I
2	B	J
3	C	K
4	D	L
5	E	M
6	F	N
7	G	O
Total	**H**	**P**

2.4 Weekly production schedule

At the beginning of every week, the planners meet with the production workers to talk about the production schedule for the upcoming week. The intention is to produce according to the planning. However, almost every week there are circumstances that need a switch in the schedule. Some possible causes for deviation in the schedule are:

- Emergencies that need to be produced quickly
- Adaptation of the production sequence
- Machine failures or damaged moulds
- No raw materials in stock, no foil in stock etc.

The major reason for changing the schedule is emergencies. It can occur that some products have to be produced as quickly as possible. Think of administration errors causing the wrong product to be produced. These errors can happen, but they have to be solved quickly and thus the schedule has to be changed.
Another reason is a change in production sequence. Sometimes the production workers prefer a different order in which the products are made. The schedule is adapted to these preferences. The last two reasons are more common reasons. Of course, when production material is missing or the machine is broken, there cannot be produced. Then the schedule has to be changed. In all other cases the schedule is the same as the planning.

2.5 What KPIs are kept track of?

The company keeps track of multiple KPIs to determine the performance of the production schedule. Many of them are directly connected to the planning, but there are also some that affect the planning in a later stadium. The KPIs are first summed up, after which all of them are explained.

- Inventory position
- Man hours
- Production yield

- Used machine capacity
- Usage of pallets and cages

Inventory position

The inventory position (IP) is kept track of every day. The IP is checked on separate products as well as on all products combined. The inventory position is the major factor that decides whether to produce a product or not. The current target of the average inventory position is six weeks.

Man hours

The total number of man hours needed per day is important since there is only a certain number of man hours available. Therefore, the planning cannot exceed the man hours constraint. The man hours constraint can differ per week, since the company uses a flexible pool of employees. The number of employees needed per machine can differ from 0.5 to 1 employee. This value is called the man factor. The man hours needed is the summation of the man factor times the production time over all machines.

Production yield

The production yield is a KPI that does not directly affect the planning. However, if the production yield is too low, too little products are made and thus there is a chance that the planning has to be changed to be able to meet demand. The production yield is calculated by dividing the total hours of output by the total hours the machine has produced. The target yield is 75%. This target might seem low, but in the case of Hordijk, it is a fair target. At the start of every batch the quality of the products is not high enough and therefore a lot of those products are thrown away. This means that the yield at the start is close to 0%. After a certain time, when the machine is running correctly, only some of the products are thrown away and thus the yield is increasing. Over a total batch, this means that 75% yield is a very good result and thus a good target.

Used machine capacity

The machine capacity used is the KPI that is mainly determining whether there has to be produced earlier than needed. It is determined by dividing the total hours of machine production through the hours of machine production available. If the machine capacity needed is higher than 100%, the production cannot meet the demand for that period. That is an indication to produce some products earlier than actually needed.

Usage of pallets and cages

The company uses pallets and cages to store the finished products in. There is a fixed amount of those resources and therefore it cannot exceed those values. This affects the planning since the planner has to adjust the planning if not enough cages or pallets are available.

2.6 How to tackle the problem?

The aim of this research is to look for a better production planning, or at least, give insight in when it is best to produce the products and why. As stated in chapter 1 it is currently not known via data when to produce products on forehand. Intuitively some products are planned earlier than needed by the planner as he knows that in the spring and summer the production capacity is smaller than the production demand for some of the machine groups. However, it is not known whether that is the most cost-effective way. The problem arises since the demand in some months is higher than the production capacity. Figure 2.3 shows the current demand for one of the factories in production hours plus the setup times in hours (assumed that every product can only be produced once per month). If the total production hours needed is compared to the capacity, it can be seen that in some months it is not possible to produce every product needed in that month. Especially the machine group 2 (upper right) encounters months in which capacity is exceeded.

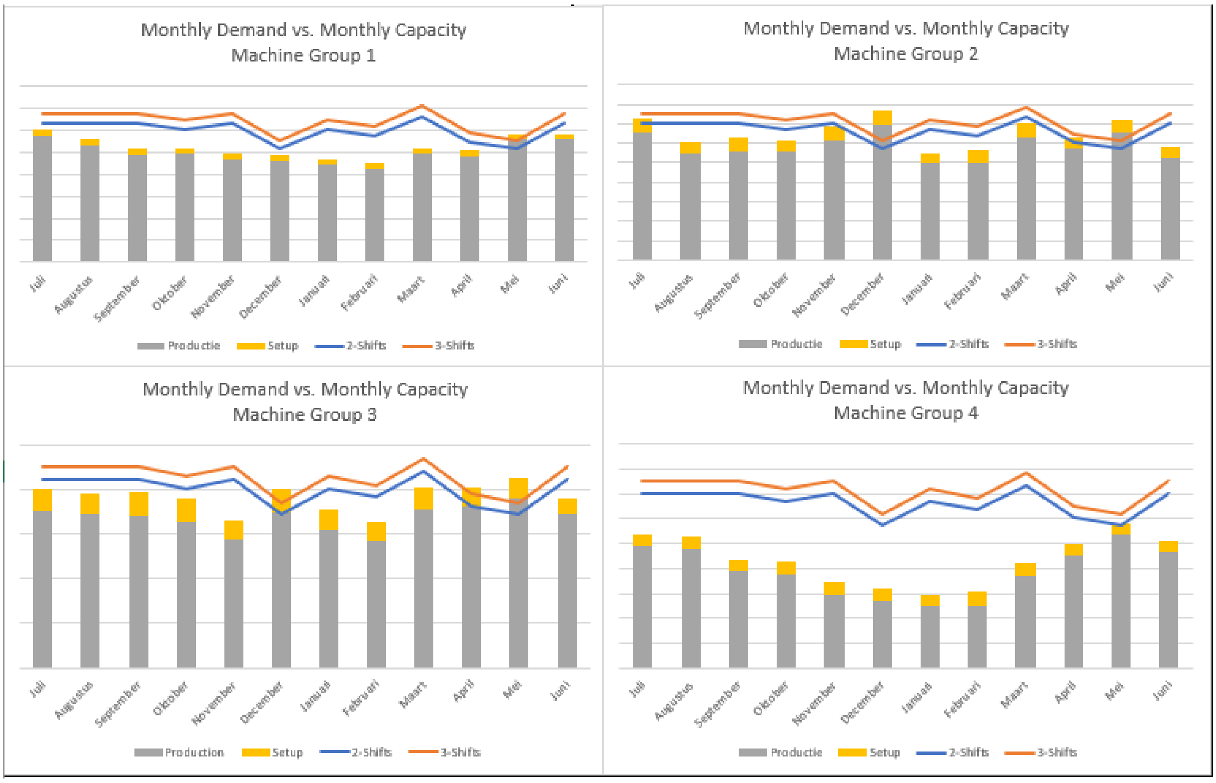

Figure 2.3: Production & Setup times vs Capacity

2.7 Conclusion

This research focuses on the thermoforming process of the company. The company has two factories and both factories have their own separate process and planning. As shown in figure 2.3, the production demand exceeds the capacity for some months. Therefore products have to be produced to stock in the months before. Currently the planning is made by the planners in such a way that a product is planned, whenever the inventory position is close to zero. The amount to produce is close to a quarter of the yearly demand and the machine to produce on is fixed for every product. This research uses data to determine when it is best to produce products. **What is important to know is that the planners are always in the lead and the model built during this research is a supportive model, not a decisive model.**

3 LITERATURE REVIEW

This chapter answers the second sub-question, namely: ***"What is stated in the literature about the problem Hordijk encounters?"*** *Literature will be reviewed to find relevant topics that can help to solve the research question. Chapter 3.1 explains the general production planning problem. Characteristics of the lot sizing problem are explained in chapter 3.2. Chapter 3.3 states the general mathematical model of lot-sizing problems. Methods to solve lot-sizing problems are given in chapter 3.4. A conclusion on all the findings in literature is given in chapter 3.5. In the last chapter, chapter 3.6, the impacts of the literature on the rest of the research are explained.*

3.1 Production planning

Planning production comes down to determining the best use of production resources to satisfy demand for a certain period, the planning horizon (Karimi et al., 2003). Typically the planning process is separated in three time ranges, namely long-term planning, medium-term planning and short-term planning. Long-term planning consists of all strategic decisions, such as the number of machines or the number and size of production facilities. Medium-term planning is the planning that decides upon needed materials for production, determining the production amounts in such a way that demand is met, without breaking capacity restrictions. Short-term planning is the day or weekly planning. This planning decides the sequence in which the products are placed upon the machine and adapt schedules when needed (Karimi et al., 2003).

In this research, the focus is on medium-term planning and especially on the timing of production and the lot-size of production. Before diving into the literature stating how to solve such a problem, it is good to know what characteristics are important for a lot sizing model. Knowing these characteristics makes it easier to find detailed literature on comparable problems.

3.2 Lot sizing problem characteristics

This section describes the eight most important characteristics of lot sizing problems. Every characteristic is explained in a separate section. The characteristics and explanations are based on the book of Ramya et al. (2019) and the article by Karimi et al. (2003).

3.2.1 Number of levels

The number of levels is explained as the number of operations that need to be done to create the final product from the raw materials. Single-level means that there is one operation needed to create the product. This means that the product demand is directly assessed from market forecasts. This is called independent demand. The other option is multi-level. This means that more than one operation is needed to create the product, meaning there is some sort of parent-component relation. In such a parent-component relationship, the demand can be dependent on the parent and therefore this is called dependent demand. In the case of this research there is only one operation needed to create the product, so therefore this is a single-level model.

3.2.2 Number of products

The number of different end products created is important. The more products, the more complex the model is and the harder it is to improve the planning. Again this can be divided in single- and multi-item plannings. In this case there are many different end products, so the model is multi-item.

3.2.3 Capacity constraints

In a lot sizing problem there are multiple capacities to note, think of manpower, machines, storage room, etc. If there is a restriction on at least one of the capacities, the problem is capacitated. If there is no restriction at all, it is an uncapacitated problem. In this case there is a restriction on machine capacity as well as on manpower, therefore this problem is capacitated.

3.2.4 Planning horizon

The planning horizon is the period up ahead which the production plan covers. This period can be finite or infinite. A finite planning horizon is mostly connected to dynamic demand and an infinite horizon to stationary demand. In this case a finite horizon is used, since the demand is dynamic. The planning horizon is separated in small or big buckets. A small bucket is a bucket in which only one product can be produced. Big buckets are buckets in which multiple items can be produced.

3.2.5 Deterioration

Deterioration can happen when products lay too long in storage. In this case there is no need to worry, since the plastic will not deteriorate. Every product can be stored for years and will still be in good condition after.

3.2.6 Inventory shortage

For a lot sizing model it is important to know whether backlogging or lost sales is allowed or if all the demand must be met in time. For this research there is no shortage allowed. This means that at certain times in the planning horizon, the demand should always be met.

3.2.7 Setup times

The setup time is an important characteristic. There are two options for setup times. It can be that for any product, no matter what product was produced before it, a known setup time occurs. In that case the setup time structure is simple. Another option is that a certain sequence of products does not need setup times, whereas another sequence does need them. In that case the structure is complex. In the case of this research, the setup time is always the same for a product, meaning that it is a simple setup time structure.

3.2.8 Demand

Lastly the demand is important. There are two types of demand, static and dynamic. Static demand means that every period the demand is the same. Dynamic demand differs per time period. If the demand is known on forehand, it is deterministic, if not, it is stochastic. In this case the demand is assumed to be known, so therefore it is a known dynamic demand.

3.2.9 What is the type of problem for this research?

According to the characteristics of a lot size model, the problem encountered in this research can be described as: **A single-level capacitated lot sizing problem (CLSP), with a finite planning horizon and known dynamic demand without backlogs. The setup time structure is simple and there is no deterioration of the end products.**

3.3 Model for CLSP

In the last section, the problem has been formulated in the correct terminology. The next step is to address the problem in parameters, indices and variables. This makes it possible to describe the problem in a mathematical model. There are many different models to describe the problem, all with a slightly different approach to the problem. All the models can be seen in figure 3.1. One of those models is the capacitated lot sizing problem. There is thus a model specifically made for the CLSP.

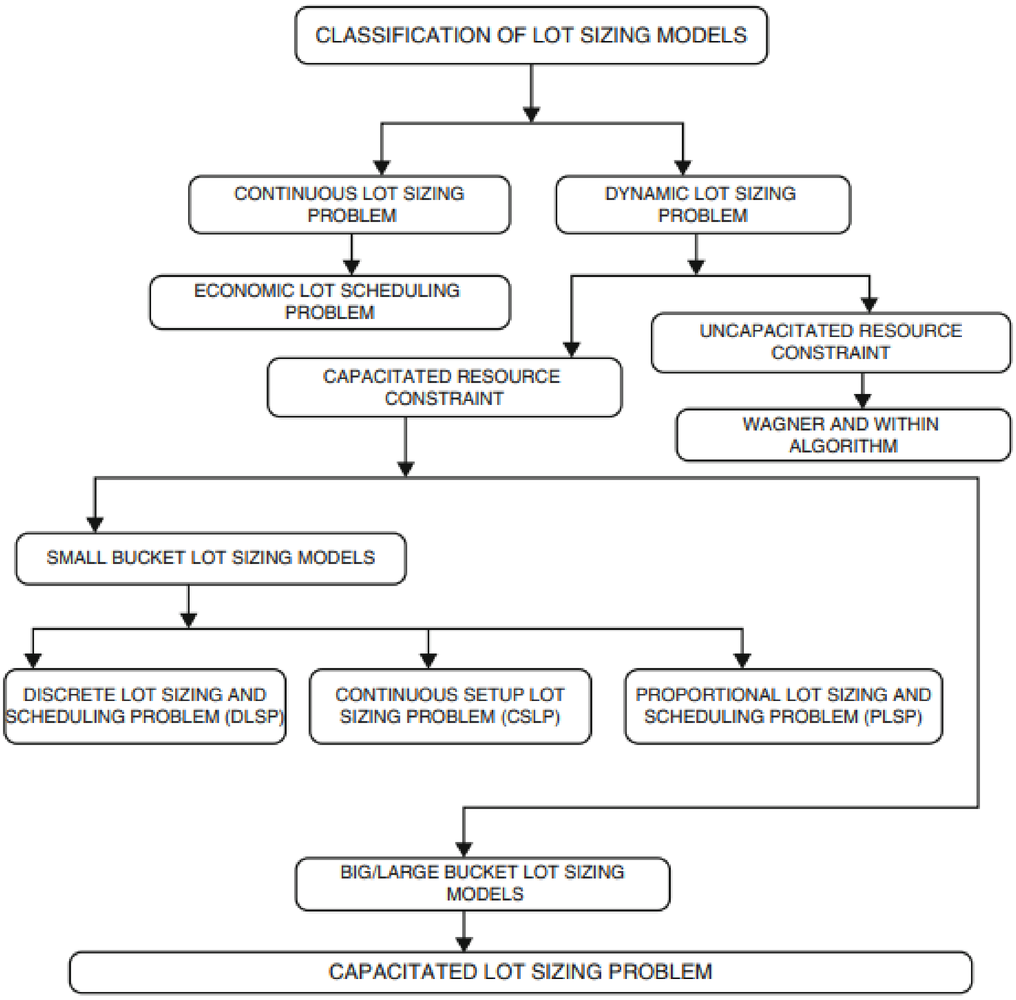

Figure 3.1: Lot-sizing models in literature (Ramya et al., 2019)

The general mathematical formulation for the CLSP model is written below. The CLSP has time slots in which multiple products can be planned. The model assumes independent setup times and a finite planning horizon. The demand in each period is known and the demand is met at the beginning of a time period. No shortages are allowed and setup costs are constant over time (Karimi et al., 2003).

Indices

i	a product, with i = (1,...,N)
t	a time period, with t = (1,...,T)

Parameters

T	the number of periods in the planning horizon
R_t	available machine capacity in period t
d_{it}	demand forecast for item i in period t
h_{it}	holding costs for item i at the end of period t
a_i	unit resource consumption for item i
S_{it}	setup costs for item i in period t
N	the number of products

Variables

X_{it}	number of products i produced in period t
I_{it}	inventory level of product i at the end of period t
Y_{it}	binary variable that is 1 if product i is produced in period t, 0 otherwise

CLSP model

$$\text{Minimize} \quad Z = \sum_i \sum_t S_{it}Y_{it} + h_{it}I_{it}$$

subject to:

$$\sum_i a_i X_{it} \leq R_t \qquad (t = 1, ..., T) \tag{3.1}$$

$$X_{it} + I_{i,t-1} - d_{it} = I_{it} \qquad (i = 1, ..., N; t = 1, ..., T) \tag{3.2}$$

$$X_{it} \leq M_{it}Y_{it} \qquad (i = 1, ..., N; t = 1, ..., T) \tag{3.3}$$

$$Y_{it} \in \{0, 1\} \qquad (i = 1, ..., N; t = 1, ..., T) \tag{3.4}$$

$$X_{it} \geq 0 \qquad (i = 1, ..., N; t = 1, ..., T) \tag{3.5}$$

$$I_{it} \geq 0 \qquad (i = 1, ..., N; t = 1, ..., T) \tag{3.6}$$

The objective is to minimize the sum of the holding and setup costs over all products and every time period. Constraint (3.1) states that the sum of all production time in period t, should be smaller than or equal to the maximum resource capacity. Constraint (3.2) is the calculation of the inventory in period t for product i. The inventory is equal to the old inventory plus the number produced minus the demand. Constraint (3.3) makes sure that whenever a product is produced, the setup variable Y is set to 1. Y is set as binary variable in constraint (3.4). Constraints (3.5) and (3.6) make sure that the production amount and the inventory position are always larger than or equal to 0. This means that no lost sales or back-orders are allowed.

There are several alternatives (see figure 3.1 which differ in small parts from the CLSP. For example the discrete lot-sizing problem (DLSP). The DLSP uses small-buckets instead of large-buckets. This means that every time slot only one product can be produced. Therefore the X_{it} is changed into a binary variable which indicates whether the product is produced in that period or not. If a product is produced in a period, the product is produced for the entire duration of that time period, so it is more or less all-or-nothing. The continuous setup lot sizing problem (CSLP, not to be confused with CLSP) removes this all-or-nothing restriction, by stating that the amount to be produced in that period can be less. However, still only one product can be produced per period (Gicquel et al., 2008). The proportional lot sizing and scheduling problem (PLSP) is an adaptation of the CSLP, and now two products can be produced in one period.

3.4 Solving methods

The single-item CLSP is known to be NP-hard (Florian et al., 1980). This means that it is unlikely to solve within polynomial time. The multi-item CLSP is even strongly NP-hard (Chen and Thizy, 1990). Therefore it is even more unlikely to solve the problem optimally using a mathematical model within polynomial time. Other solving methods have to be found, which give good results. In literature there are only few attempts that use an exact algorithm, while there are many heuristic approaches. According to the review of Karimi et al. (2003), the heuristic approaches can be divided in common-sense approaches and mathematical programming based heuristics. Common-sense approaches consist of three steps, the lot-sizing step, the feasibility step and the improvement step. The lot-sizing step comes down to creating a production schedule without restrictions on capacity. The feasibility step checks if the solution made in the lot-sizing step is feasible. If not, the schedule is made feasible. The improvement step looks for improvements in the schedule by changing the sequence of production, or by changing the lot size. This step makes sure that the solution remains feasible (Karimi et al., 2003). For the lot-sizing and improvement step there are multiple methods proposed in literature. In the following sections, the most important methods are explained.

3.4.1 Lot-sizing step

As said in the last section, one of the steps in using common-sense heuristics is the lot sizing step. This step does not look into feasibility, which means that the optimal balance between inventory and setup costs can be found. In this case useful techniques are: the economic production quantity (EPQ), the Wagner-Whitin algorithm and the Silver-Meal heuristic.

Economic production quantity

The EPQ is a method used to determine the optimal relation between order costs and inventory costs. The EPQ is derived from the Economic order quantity (EOQ). The difference between the EOQ and the EPQ lies within the addition of the produced stock. In the case of the EOQ, the produced stock is fully added at one point in time, whereas the EPQ adds the stock over time. The EPQ takes into account that during production already products are made, and thus that the stock already increases over time. In this case of a production company, the EPQ is the best out of the two, since during production the inventory is slightly increased, but not immediately as with the EOQ. The EPQ assumes that the demand is constant over the year. In cases with fluctuating demand or seasonal demand, the EPQ will not give the best result. Therefore there are several algorithms and heuristics that can be used, such as the Wagner-Whitin algorithm and the Silver-Meal heuristic (Finance Management, 2020).

Wagner-Whitin algorithm

The Wagner-Whitin algorithm (WW) is, according to Saydam and Evans (1990), a dynamic programming lot sizing algorithm. It determines the optimal lot-sizes over the given demand period. It assumes that a full period is produced in one go. The algorithm uses dynamic programming for this. Dynamic programming means that the problem is divided into subproblems. These subproblems are solved optimally and by combining these subproblems, the eventual problem can be solved. This means that the WW calculates over the full time horizon the optimal lot sizes (Gonzalez and Antonio, 2004).

Silver-Meal heuristic

The Silver-Meal heuristic (SM) is closely related to the WW algorithm. SM only looks at what is the best amount to produce right now and does not look at future consequences of that decision. As with WW, SM assumes that a full period has to be produced at once. Therefore the aim is to find the best number of periods to produce in one go, such that the average cost per period is lowest. The method keeps adding a period to the production size until the average costs per period increase. If the costs increase that means that the last period is not added and the production size is equal to all the periods that have been added before.

Conclusion lot-sizing

The options to choose from are EOQ, Silver-Meal or Wagner-Whitin. The benefit of EOQ is that it is an easy formula. Next to that, the EOQ formula is available in the software of the planners, so it is easy to implement. However, the major disadvantage of the EOQ is that it is only applicable to products with a stable demand. For the unstable demand products it is better to use SM or WW. If the number of products with unstable demand is little, the WW algorithm can be used, since the computation time will still be low. However, if the amount of products is large, it is better to use SM. The solution will be a bit more costly, however, the computation time is way lower.

3.4.2 Improvement step

For the improvement step metaheuristics can be used. Metaheuristics are high-level problem independent frameworks that provide guidelines to develop heuristic optimization algorithms (Sörensen and Glover, 2013). This means that metaheuristics can be used on different problems, not specifically this problem. In this section, three of the most used metaheuristics are explained, namely variable neighbourhood search (VNS), simulated annealing (SA) and Tabu-search.

Metaheuristics

Variable neighbourhood search
VNS is proposed by Mladenović and Hansen (1997) as a metaheuristic. VNS is a method that searches multiple neighbourhoods during optimization. This means that it cannot get stuck in a local optimum of one neighbourhood. Whenever the heuristic cannot find a better solution in one neighbourhood, another neighbourhood is searched. If a better solution is found, the first neighbourhood is searched again. This continues until there is no better solution anymore. This results in a solution that is the best out of all neighbourhood structures searched.

Simulated annealing
SA was introduced by Kirkpatrick et al. (1983) to solve combinatorial optimization problems. SA can be seen as an improved version of local search heuristics (Dowsland and Thompson, 2012). In local search heuristics an initial solution is gradually improved by considering small changes, such as swapping the order of production on a machine. If the new solution is better, it is accepted, otherwise it is denied. If there is no improvement anymore, the heuristic stops and the optimum is found. This termination point is a local optimum. In the case of simulation annealing, the procedure of local search heuristics is slightly adapted. Simulated annealing uses a so-called acceptance probability. This probability gives the chance of accepting a solution

generated by adapting the initial solution. The value of the probability is 1 if the new solution is better than the old one. If the solution is worse, the probability is equal to $e^{\frac{\Delta c}{t}}$, in which t is the temperature which will decrease over time and Δc is the difference in objective value of the current solution and the candidate solution (Gnanachandran, 2016). What can be noticed is that simulated annealing will accept almost all new solutions when t is large, but when t decreases, the chance of accepting a worse solution is also decreasing. Using this technique, the heuristic is able to escape from local optima and thus the chance of finding good solutions is increased.

Tabu-search
Tabu search is a metaheuristic that is based on a local search heuristic. Just like the other metaheuristics mentioned in this chapter, TS is able to escape from local optima. TS searches the full neighbourhood for the best solution and it picks that solution. To overcome the problem of getting stuck in a loop of constantly choosing the same solutions, a tabu-list is created. This list consist of solutions that have been just visited. These solutions cannot be picked and thus the second best will be chosen. This continues until there is no better solution anymore.

Why a metaheuristic?

A metaheuristic has been chosen over a normal simple heuristic, since it offers more possibilities with regard to optimizing on different objective functions. If a simple heuristic would have been chosen, it uses strict rules which have to be followed. This can cause problems when using multiple different objective functions. Furthermore, all the rules have to be created from scratch, since in literature no simple heuristic have been found. For metaheuristics there are multiple examples in literature. Those examples can be used as a guideline to create the metaheuristic for this research.

3.5 Conclusion literature review

The problem can be described as a capacitated lot-sizing problem. This problem is strongly NP-hard and thus unlikely to solve optimally in polynomial time. Therefore multiple heuristics have been analyzed. The solving process consists of three steps: the lot-sizing, the feasibility and the improvement step. For the lot-sizing step a lot-sizing method has to be used. The Silver-Meal gives the best results in the combination of computation time and costs. The feasibility step can use any simple heuristic or algorithm to make it feasible. For the improvement step there are three metaheuristics to choose from, namely Variable Neighbourhood search, Tabu-search or Simulated Annealing. Simulated annealing has the preference, since it does not have to search the whole neighbourhood before determining a candidate solution. Since the neighbourhood is large and there are multiple neighbourhoods that have to be searched, it is better to use simulated annealing. Next to that, simulated annealing offers more possibilities to combine neighbourhoods. By running a lot of repetitions it is possible to search the whole neighbourhood in small steps, which means that it possibly takes little time to find a better solution, but to find the best solution, it can take a long time.

3.6 Impacts of literature on report

As stated in the last section, this chapter has given a mathematical model which can be used to solve the problem researched. However, since the problem instance can be too large to be able to solve optimally, a simulated annealing framework could be used to solve the problem. The simulated annealing creates candidate solutions by adapting the current solution. In the next chapter, the steps given in the literature are explained and adapted in a way that it is practically feasible. Furthermore, the assumptions needed to solve the problem as well as the adaptations to the mathematical model are explained.

4 RESEARCH DESIGN

In chapter 3 literature is stated which is related to the problem of the company. In this chapter this literature is used on the problem of the company. In section 4.1 the encountered problem is summarized. Section 4.2 describes the mathematical model used to solve the problem. Section 4.3 descirbes how the mathematical model is solved to optimality. Section 4.4 describes the solving method, based on the literature. In section 4.5, the simulated annealing framework is described. In the last section, section 4.6, a conclusion of the chapter is given.

4.1 The encountered problem

As explained in Chapter 2, the company encounters a lack of insight in their planning of the production process. It is unclear what the effect of the weekly planning is on the upcoming months. Out of experience, the planners know that the demand is unstable and there is a peak demand in the months May, June and July. Therefore, the planners decide to build up inventory in the months preceding to the peak months. However, it is not known whether this early production is done at the correct timing and with the correct production size, such that it is economically feasible. Next to that, it is not known which products are better of with producing earlier and which not.

A mathematical model has been found in literature which can be used to solve the problem optimally, if some small changes are added to the model. However, it is unknown if the problem can be solved optimally or whether the size of it is too big to solve in polynomial time. Therefore, in this chapter it is determined if the problem can be solved optimally and whether a metaheuristic should be used to solve the problem.

4.2 Mathematical model

The mathematical model that is used to solve the problem can be separated in a general model and additions. The general model consist of all indices, variables and constraints that are used in every scenario. The additions are extra constraints or rules that are added to the general model to change the purpose of the model or to adapt the model to certain other scenario's.
The general model is closely related to the CLSP model stated in Chapter 3.

Indices

i	a product, with i = (1,...,N)
t	a time period, with t = (1,...,T)
m	a machine group, with m = (1,...,M)
T	the number of periods in the planning horizon
N	the number of products
M	the number of machine groups
R_{mt}	available capacity (in units of time) for machine group m in period t
d_{it}	demand forecast for item i in period t
h_{it}	holding costs for item i at the end of period t
Q_i	number of hours needed for a setup of product i
S_{it}	setup costs per hour for item i in period t
O_{mi}	output per hour of article i on machine group m

Variables

X_{mit}	number of products i produced in period t on machine group m
I_{it}	inventory level of product i at the end of period t
Y_{mit}	number of setups of product i in period t on machine group m

General mathematical model

$$\text{Minimize} \quad Z = \sum_i \sum_t S_{it} Q_i Y_{mit} + h_{it} I_{it}$$

subject to:

$$\textstyle\sum_i X_{mit}/O_{mi} + Q_i Y_{mit} \leq R_{mt} \qquad (t = 1, ..., T; m = 1, ..., M) \tag{4.1}$$

$$\textstyle\sum_m X_{mit} + I_{i,t-1} - d_{it} = I_{it} \qquad (i = 1, ..., N; t = 1, ..., T) \tag{4.2}$$

$$B * Y_{mit} \geq X_{mit} \qquad (i = 1, ..., N; t = 1, ..., T; m = 1, ..., M) \tag{4.3}$$

$$X_{mit} \geq 0 \qquad (i = 1, ..., N; t = 1, ..., T; m = 1, ..., M) \tag{4.4}$$

$$I_{it} \geq 0 \qquad (i = 1, ..., N; t = 1, ..., T) \tag{4.5}$$

Constraint (4.1) makes sure that the machine capacity of a machine group cannot be exceeded. The inventory is calculated by constraint (4.2). Constraint (4.3) states that at least one setup has to be done if products are produced. Since Y is minimized, Y is always 0 if X is 0. Constraints (4.4) and (4.5) state that X and I cannot be negative.

This general model can be solved optimally using for example a Gurobi solver or a CPLEX solver. According to the literature, stated in chapter 3, this can only solve optimally for small instances. It is not known what the boundary is for a small instance. Therefore this is investigated. In the next section, the problem is solved optimally for multiple instances, to check whether it is possible to create an optimal solution.

4.3 Solve to optimality

As stated in the last section, this section focuses on solving the mathematical model optimally for different instances. First of all it is tried to solve the whole model, so both locations together at once. This option did not solve optimally within the given eight hour run time boundary. Therefore, the data has been separated over the two locations and solved independently of each other. The total run time of both combined should be at maximum eight hours. This is not possible with the given input data, however, after the run, it is concluded that again the duration of the runs is too long. Lastly, the input data has been separated again, over the different machine groups. This means that for factory 1 there are four machine groups and thus four different input data to solve. For factory 2 there are seven different machine groups and thus seven sets of input data that has to be solved.

The solutions for the subproblems can be solved optimally using a CPLEX solver. For the small subproblems an optimal result is found quickly. In almost all cases in less than one minute. Since every machine group and location has its own products, combining all the optimal results of the subproblems result in the optimal solution for the whole problem. Thus, by separating the input data into small subsets, the optimal solution can be found.

The results of all the runs can be found in Chapter 6. In that chapter the results of the current scenario, of the optimization and of a metaheuristic are stated. By combining all of the results in one chapter, the differences can be seen clearly, without having to swap from chapter to chapter.

One could think that using an heuristic is unnecessary as the problem can be solved optimally. However, there are certain issues that makes using the mathematical model problematic. The first issue arises with updating the input data. Since there are in total eleven subproblems, eleven input sheets have to be updated, to be able to load the data in the solver. This is time-consuming to do. Another issue that arises is that the problem cannot be solved in its whole. By combining the articles of both locations, new insights could be gained on changing the production location of some of the products. Therefore it is decided to create an alternative solving method. This method is capable of solving the whole problem at once. In the next section, this alternative solving method is explained.

4.3.1 Validation

Before diving into the alternative solving method, it should be known how the tool is validated. The validation of the optimal tool is the same as for the alternative solving method. Therefore, a reference is made towards the validation explanation of the alternative solving method. Everything regarding validation is explained in section 5.5.

4.4 Alternative solving method

According to the literature, to solve the whole problem there are three steps that have to be taken. These are the lot-sizing step, the feasibility step and the improvement step. For every step, there are numerous ways to perform them. The specific method used is explained in the upcoming three sections.

4.4.1 Lot-sizing step

In the lot-sizing step, the data is put into a working solution. It does not yet have to be feasible, but it should be workable. In this case the lot-sizing step creates a solution that is equal to the demand forecasts plus setup times.

The forecasts are known for the upcoming year. This means that the total production hours needed for the upcoming year are known as well. In the lot-sizing step, the forecasts are expressed in production hours and are summed per month. It is assumed that every product is produced in a maximum of one batch per month. This means that the setup time can be determined per month. Adding the setup time per month to the production time per month indicates the total machine demand per month. Graphing these information (see figure 2.3) shows in which months it is very busy and in which months the machine demand is lower. Next to that, it can be determined if the demand exceeds the capacity and thus if products have to be produced in an earlier month such that demand is met.

4.4.2 Feasibility step

The monthly machine demand is determined in the lot-sizing step. However, it can occur that this monthly machine demand is higher than the available machine capacity, so the schedule is infeasible. There are multiple restrictions which state whether a schedule is feasible or not. Restrictions 1 to 3 are hard constraints, which means that they always have to be met. Constraints 4 and 5 are soft constraints and can be violated. However, when those constraints are violated there is a cost penalty. In this way the model aims to meet those constraints as well.

1. The total monthly machine demand cannot exceed the available machine capacity (based on three shifts a day)
2. The monthly machine demand per article cannot exceed the available mould capacity
3. The inventory has to be larger than or equal to zero.
4. The total monthly machine demand preferably cannot exceed the available machine capacity (based on two shifts a day)
5. The total support equipment (cages, boxes, etc.) preferably cannot exceed a certain threshold.

The idea of the feasibility step is that it adapts the current solution in such a way that the first three constraints are met, and preferably all five. First it is checked which constraints are violated and for which articles. When that list is known, production demands are planned earlier to meet the restrictions. The reason that it is not planned later, is because the initial solution is already planned just-in-time (JIT). Therefore, when scheduling production later, the inventory constraint is always violated.

4.4.3 Improvement step

The improvement step aims to reduce the costs as much as possible keeping the schedule feasible. The general framework used to improve the schedule is simulated annealing (SA). This means that slight changes are done to the solution, and then the solution is accepted or denied. In the beginning of SA, worse solutions can also be accepted, which means that the chance of getting stuck in a local optimum is little, compared to other methods that only accept better solutions. The working of the improvement step is explained in Chapter 5.

4.5 The Simulated Annealing framework

The three step method to solve the problem works well, however, there could be a lot of lost information during the process of SA. Every iteration there is a chance of changing the solution into an infeasible one. With the current rules, the infeasible solution has to be declined and thus there is a loss of data. To avoid this loss of data, it is chosen to slightly adapt the method. The adaptation to the method is that a solution which is infeasible is no longer declined. It is penalized, which means that whenever it is infeasible, the objective function is increased with a number X. In the beginning of the SA, the temperature is high, which means that the extra penalty is not that big of a deal, since the penalty is divided through the temperature. This means that in the beginning of the SA, some infeasible solutions could occur. However, the lower the temperature, the more likely it is that the infeasible solutions are declined and only the feasible solutions remain. The detailed explanation of the SA and its neighbourhood structures are explained in chapter 5.

4.6 Conclusion

As explained in this chapter, this research focuses on creating insights in the planning process. The idea is not to create a schedule, but the idea is to distribute the forecasts over the months in such a way that the production is able to produce it and the costs are minimized. To come up with a better schedule, a mathematical model has been formulated which can be solved to gain a schedule. However, the problem instance is too big to solve optimally. Therefore a SA framework is made which can be solved to get a schedule. How the SA is used is explained in the next chapter.

5 SIMULATED ANNEALING

In this chapter the written approach described in chapter 4 is explained in detail. The input data is explained in section 5.1. The objectives and penalties are described in section 5.2. The neighbourhood structures are explained in section 5.3. Section 5.4 sums up the most important settings of the SA. The validation of the results is explained in section 5.5 and section 5.6 concludes this chapter.

5.1 Input data

In this section the input data for the SA is explained. It is explained how all the parameters are determined and why they are determined that way. If there are assumptions made on certain input data, these are stated at the corresponding input data. Lastly the values of the parameters are given if possible.

5.1.1 Production days

The number of production days per month can differ much. The production facilities are functional on workdays, however, in some months there are a lot of holidays. On those days, the facility is closed. This means that for example in December, due to Christmas, some production days are missing and the capacity is lower than for example October in which there are no holidays. Table 5.1 shows the number of production days per month. To calculate the monthly capacity, the number of days is multiplied with the amount of working hours a day.

Table 5.1: Number of production days per month

Month	Production days	Month	Production days
January	21	July	22
February	20	Augustus	22
March	23	September	22
April	19	October	21
May	18	November	22
June	22	December	18

5.1.2 Production hours per day

A production day consists of three shifts. Two shifts consist of eight working hours, whereas, the third shift consist of 7.5 hours. In normal conditions only two out of the three shifts are used. These are the so-called morning and evening shift (both 8 hours). The night shift, which is the 7.5 hour shift, is only used whenever it is really needed. This shift also costs more, since employees are paid more and the total production time is 0.5 hours less. For the research model this knowledge has some impacts. There need to be correct costs associated to the night shift. If these costs are too low, the model might give a result that uses too many night shifts. Too high and no night shifts are used at all.

5.1.3 Output of a product per hour

Every product has a certain output per hour that is assumed to be true. That means that if you run the machine for one hour, the output number is produced, so the inventory increases with the output. As earlier said, almost all products only have a mould for one type of machine. This means that the output of that product is 0 per hour for every other machine group. So if the output is equal to 0, it means that the product cannot be produced on that type of machine.
The output number is calculated by multiplying the pace of the machine per hour (so the number of times the mould is closed) with the number of products that are made with closing the mould once (multiplicity of the mould). The outcome is then multiplied with the production yield of 75%, resulting in the net outcome per hour of the product on a machine group.

5.1.4 Assigning products to machines

As said earlier, nearly every type of product has its own moulds which can only be put on one machine type. This means that it is clear on what machines the products are produced and that there is no possibility to change this.

5.1.5 Forecasts

As stated earlier in this paper, the forecast per article is determined by a software system. The software takes into account the historical demand and potential adaptations inserted by the planners. In that way it creates monthly demand forecasts, which can be used as input for the simulated annealing framework.

5.2 Objectives & Penalties

In this section the objectives and the penalties are explained. The two objectives are always used in the same way for every run. The height of the penalties can differ for every run, however, the idea is to find the best possible height for the penalty which thus results in the best solution possible. Other objectives which can be used are explained in section 5.2.3.

5.2.1 Objectives

Inventory costs

Perhaps the most important costs are the inventory costs. In the optimal scenario, which would be without capacity restrictions, you would not create inventory, since you could produce on order. However, in this case inventory is needed to fulfil demand. The inventory costs in this case are 11 cents per kilogram of finished products. This means that a cage with 10 kilogram of products costs 110 cents, or € 1,10. The weight of every finished product is known, so the costs can be calculated per single product.
In the simulated annealing, the inventory costs are calculated at the end of a period, which is at the end of a month. This means that only the end inventory costs money and what happens before that is not priced.

Setup costs

Setup costs are the costs associated with preparing the machine to produce a certain product. In this case the costs are equal to the hourly costs of a machine not running multiplied with the number of hours needed to setup the machine. The number of hours needed depends on the type of machine as well as the type of mould that has to go on the machine.

5.2.2 Penalties

Infeasibility penalty

Whenever a solution is infeasible, it cannot be chosen. However, as we do not want a loss of information, it is decided to give a very high penalty to an infeasible solution. It should be so high that only around the start temperature solutions which are infeasible can be selected, but when the SA gets closer to its end, all the infeasible solutions should be rejected.

Capacity penalty

The company can use three shifts. One of them is the night shift, which is preferably not used. However, this is only true to a certain extent. If for example, production of November has to be done in January already, because the rest of the months there is no capacity, then it is better to use some night shifts in November, since the inventory costs are very high. Therefore costs have to be associated to using part of the night shift. This is done by multiplying the extra capacity used in percentages by a number X. The height of number X has to be chosen in such a way that the division between extra capacity and earlier production is within the boundaries set by the company.

5.2.3 Advanced settings

The above mentioned objectives and penalties are used to determine the best solution taking into account capacity constraints and the fact that demand has to be met. There are certain other settings that can be added to the model to make sure the model reacts on other restrictions. Below a list is made of settings that can be added to the model.

Number of employees

The number of employees depends on the amount of work scheduled in the month. Every employee works five hours in a shift. So, if the total hours needed per week is divided by eight hours, we get the number of employees needed on a day. If we divide that number by two, we get the number of employees needed per shift.
If this number has to be stable, a penalty can be added for example to the standard deviation over all the months. This means that if the number of FTE needed differs a lot per month, a high penalty is added to the objective, making the solution unattractive.
Another option is a hard bound on the number of employees. This bound is used the same as the machine capacity constraint. If the capacity is exceeded, a massive penalty is given to the objective.

Number of cages/boxes

The number of cages or boxes available is very important. By calculating how many are used for the whole production, it can be checked if there is enough available or that more cages/boxes have to be bought.

5.3 Neighbourhood structures

In this section it is explained how the SA is searching the solution space. There are multiple neighbourhood structures searched which in combination make sure that the full solution space is taken into account. In this section these structures are explained one by one, followed by a conclusion why the full solution space can be touched.

5.3.1 Move a product to a month earlier/later

The first method is moving the monthly production of a product to a month earlier or a month later. If a product is already produced in the new month, the production amount is added to the amount already produced. This means that every production amount which is present can move to any month, but it is always added up until all the production is done in one month. Therefore this method cannot be used on its own, and thus the next structure is made.

5.3.2 Move a percentage of a product to a month earlier/later

This structure works the same as the previous, however, it does not move the whole production amount. It only moves a percentage of 50% - 100% of the amount planned in that month. The reason why it is at least 50% is because the move should have some impact, so there has to be a switch of at least 50% to see the impact. Eventually every percentage below the 50% can be touched if this method is performed multiple times. Combining this method with the previous one makes sure the whole solution space is touched.

5.3.3 Combine two production amounts if production time is too little

This third method is used to speed up the process of looking for better solutions. This method combines production amounts if the production time of a certain product in a certain month is smaller than 2 times the setup time. This is done because, out of experience, it is known that a production time of less than a day is not feasible and causes too many setups. So, by performing this method once in a time, it can save a lot of bad solutions in which there are too many setups and thus too many costs.

5.4 The parameter settings

The start temperature, end temperature, cooling down parameter and the Markov chain length all have to be determined to be able to run the SA. The start temperature makes sure that the acceptance ratio at the highest temperature is equal to 1. In this case a starting temperature of 1000 makes sure the first acceptance ratio is 1. The end temperature is set at a height such that the acceptance ratio is equal to 0, in this case the end temperature is 5. The cooling down parameter determines the speed with which the temperature decreases towards the end temperature. The cooling parameter is determined in such a way that the graph of the acceptance ratio per Markov chain is decreasing slowly in the beginning of the SA and decreases more rapidly towards the end of the SA. In this case a good decreasing factor is 0.95. The length of the Markov chain is dependent on the other settings and the running time. In this case, the other settings are fixed and the running time is at maximum eight hours (one working day). So, the maximum length of the Markov chain can be determined by calculating the run time per Markov length. The number of Markov chains that are finished during the run-time is equal to 104 runs. This means that every run can take at maximum 276.92 seconds (8 hours divided by 104). A Markov chain length of 1000 equals the maximum run length of 276.92 seconds. For clarity a list with all parameters below each other is shown.

Start temperature	1000
End temperature	5
Cooling down parameter	0.95
Markov chain length	1000

5.5 Validation of the results

Before and after the use of the simulated annealing method, it should be known whether the input data and the output data are valid and feasible. Therefore multiple validation approaches have been used. First the input data has been checked. This has been done by randomly selecting some products and check the input parameters with the ones in the software system of the company. If any mistakes had been found, all the articles were checked. If no error was found in the sample, it was assumed that the rest of the articles were correct as well.

When all the input had been checked, the analysis was done, and the output data was gathered. This output data again has been validated. The first check was on the total production amount. The total production amount of the output should be equal to the total amount of forecasted demand. If that holds, again a sample of products was taken and for those products the given inventory was recalculated by hand. If any inventory was incorrect, all inventories had to be checked.

Next to the inventories and the production amount, it should be checked if no capacity is exceeded. This means that the mould capacity should be checked as well as the machine group capacity. For the machine group capacity it can be checked by looking at the capacity graphs on the dashboard. If any column exceeds the 3-shifts line, it is infeasible. For the mould capacity a check has to be created. For every month the production amount per product is determined. This is then subtracted from the mould capacity per product. If any of the resulting numbers are negative, the solution is infeasible as that mould capacity is exceeded.

If everything above is checked and found to be correct, it can be said that the solution is feasible and all the numbers are correct and valid. This means that the calculation of the objective function uses all the correct parameters.

5.6 Conclusion

The simulated annealing takes into account objective and penalty costs. The objectives are minimizing the inventory and the setup costs. The penalty costs occur occasionally, dependent on the feasibility of the solution. There are penalty costs for infeasibility and the usage of a third shift (the night shift). Next to these objectives, advanced settings can be used. There can be extra costs associated with the number of employees needed or the number of cages and boxes used.
To cover the entire solution space, neighbourhood structures have been created. These structures swap the monthly production to other months, combine monthly demands or swap parts of the monthly production to other months. By setting the correct parameters for the simulated annealing framework, solutions with lower objective costs can be found within a working day.

6 RESULTS

In this chapter the results of the research are presented. This chapter is divided into five sections. Section 6.1 focuses on the insights that have been gained about the current situation and current planning process. The mathematical model results are explained in Section 6.2. Section 6.3 is focused on the results of the simulated annealing framework. In Section 6.4 the results are concluded and section 6.5 describe the tools used.

6.1 Graphing the current process

The first goal of this research is to gain insight in the current planning process and thus gaining insight in the current demand and production pattern. This has been done firstly by expressing the customer demand in production and setup hours, with an assumption that every product can only be produced once a month. By setting the number of hours needed against the available capacity in hours, the first insight is gained. In Figure 6.1 the capacity against the demand can be seen for one machine group. The other graphs can be found in Appendix A and Appendix B.

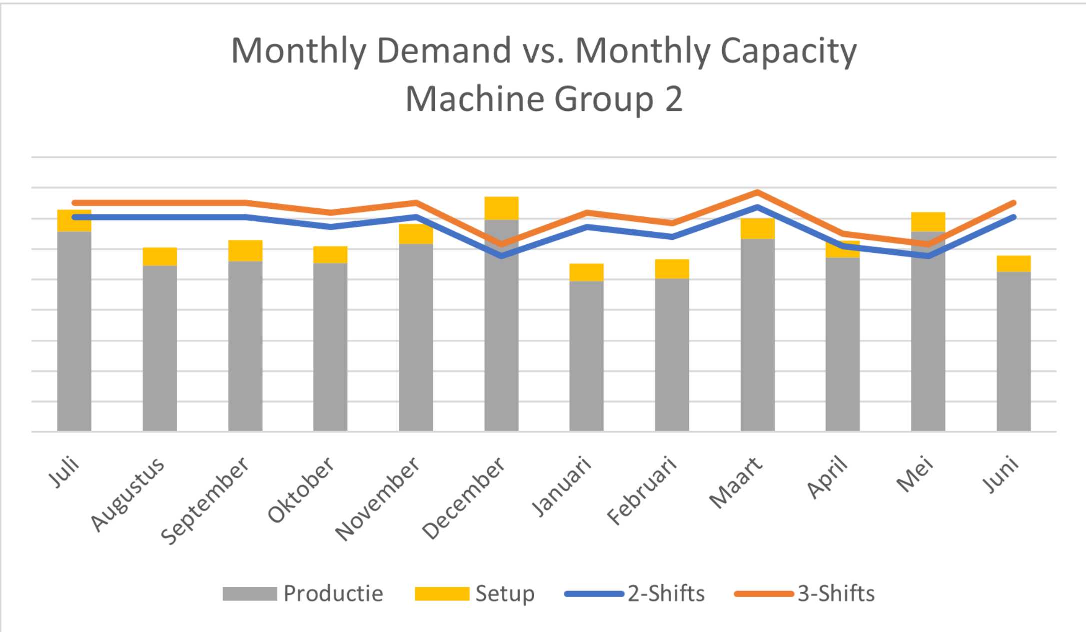

Figure 6.1: Capacity vs Production hours of machine group 2

Figure 6.1 shows that in some months the demand exceeds the capacity. In the case of machine group 2, it can be seen that the months December and May are exceeding the capacity at both the 2 and 3-Shifts configuration. Therefore production has to be scheduled in the months before December and May. When looking at the graph, it can be seen that the months August, September and October have enough space to cover up the exceeding demand of December and in January and February, the exceeding demand of May can be covered up.

6.1.1 KPI values

For the current situation, important KPIs have been put onto a dashboard. This dashboard can be used to see what is expected to happen in the upcoming months. In this section some of the graphs of the dashboard as well as some tables are shown. All of the tables contain important information for the company.

Objective function

The objective function for the current scenario is equal to € 1,509,895. As the inventory costs are € 0, the setup costs are equal to the objective function. This objective function can be used to compare other solutions with it and state the cost benefits of changing the schedule.

Number of employees needed

The number of employees needed on average per day is calculated for both factories. Table 6.1 shows the number of employees that work 8 hours on a day. This table can be interpreted as the average number of employees that work a shift on a day in a specific month. For both factories the month May is a busy month. This is because the number of working days in May is less than the other months due to the holidays. It can be seen that for both factories there is nearly always a fluctuation in the number of employees needed. This means that the flexible layer of employees can differ a lot in between months.

Table 6.1: Average number of FTE needed per day per factory

Month	**Factory 1 (old)**	**Factory 2 (new)**
July	23	35
August	22	33
September	20	33
October	21	35
November	19	34
December	24	45
January	18	33
February	19	34
March	20	36
April	25	40
May	29	46
June	22	35
Average	**22**	**37**

Kilograms of foil needed

To be able to produce the demand, plastic foil is needed. It is important to get an insight in how many kilograms of foil is needed and which type of foil is needed. As said earlier in this report, there are two types of plastic foil, namely PP and APET. For both factories the total number of tonnes needed is shown in the tables below. Table 6.2a shows the tonnes of foil needed for the older factory and table 6.2b shows the tonnes of foil needed for the new factory.

Table 6.2: Kilograms of APET & PP needed

(a) Kilograms of foil needed for factory 1 (old)

Month	APET (x1000 kg)	PP (x1000 kg)
July	A	N
August	B	O
September	C	P
October	D	Q
November	E	R
December	F	S
January	G	T
February	H	U
March	I	V
April	J	W
May	K	X
June	L	Y
Average	**M**	**Z**

(b) Kilograms of foil needed for factory 2 (new)

Month	APET (x1000 kg)	PP (x1000 kg)
July	A	N
August	B	O
September	C	P
October	D	Q
November	E	R
December	F	S
January	G	T
February	H	U
March	I	V
April	J	W
May	K	X
June	L	Y
Average	**M**	**Z**

It can be seen that in factory 1 (see table 6.2a) no PP plastic foil is used. Apparently, the company decided to produce PP plastic only at the new factory. This means that in case of a new product made with PP plastic, it can only be produced in factory 2.

With regard to the fluctuation in the number of kilograms of plastic foil, it is shown that the APET plastic foil consumption has the same pattern as the demand, namely an increase of kilograms needed in the summer months. For PP plastic foil the highest consumption is in the months August and September, which is some months later than the peak demand.
This table can be effectively used to check if there is enough capacity to create all the plastic foil needed. Furthermore, the values could be used to improve the plastic foil production planning. In section 7.4 it is explained what further research can be done on this subject.

Number of setups

The last KPI that is important to show on the dashboard is the number of setups per month. Since it is assumed that a product can only be setup once per month, and the data is currently based on the demand forecasts, the number of setups can be explained as the number of different products sold in a month. For both factories this number is determined.

Table 6.3: Number of setups needed per month

(a) Number of setups needed for factory 1 (old)

Month	# of Setups	Avg. per day	Setup hours
July	A	AA	N
August	B	BB	O
September	C	CC	P
October	D	DD	Q
November	E	EE	R
December	F	FF	S
January	G	GG	T
February	H	HH	U
March	I	II	V
April	J	JJ	W
May	K	KK	X
June	L	LL	Y
Average	**M**	**MM**	**Z**

(b) Number of setups needed for factory 2 (new)

Month	# of Setups	Avg. per day	Setup hours
July	A	AA	N
August	B	BB	O
September	C	CC	P
October	D	DD	Q
November	E	EE	R
December	F	FF	S
January	G	GG	T
February	H	HH	U
March	I	II	V
April	J	JJ	W
May	K	KK	X
June	L	LL	Y
Average	**M**	**MM**	**Z**

In tables 6.5a and 6.5b, it can be seen that every month there are a lot of setups and thus a very large amount of products that are sold. This means that a lot of hours are spent on setups. Therefore, combining monthly production demands decreases the number of setups and thus increases the percentage of time spent on production. Furthermore, less people are needed to do the setups, which decreases the employee costs.

6.1.2 Conclusion current scenario

In the current scenario it can be seen that there is enough capacity in the factories. The factories can manage all the demand with a 2-shift configuration. For a 2-shift configuration some adaptations have to be done to the schedule, for example, bring some production forward. The total kilograms of plastic foil that is needed for the upcoming 12 months is determined and could be compared with the foil production capacity. In that way it can be checked if all the plastic foil can be made in a year. The objective function is determined to compare other solutions to the current scenario and check whether they decrease costs or not.

6.2 Mathematical model results

This section shows the results of the mathematical model. The results have been created by solving many sub-problems. This section shows the combination of all those results of sub-problems. The same tables and graphs as for the current scenario are given in this section. In that way, the comparison can be done between the optimal solution and the current solution. Furthermore, the height of the inventory over the months is given as well as the difference in objective function between both solutions.

6.2.1 Monthly Demand vs Monthly Capacity

In figure 6.1 the capacity graph of machine group 2 has been shown. In that figure, there were months that exceeded capacity. In the optimal solution, these exceedances should be covered up in other months. As can be seen in figure 6.2, the exceedance indeed has been covered up by other months and the production hours do not exceed capacity anymore.

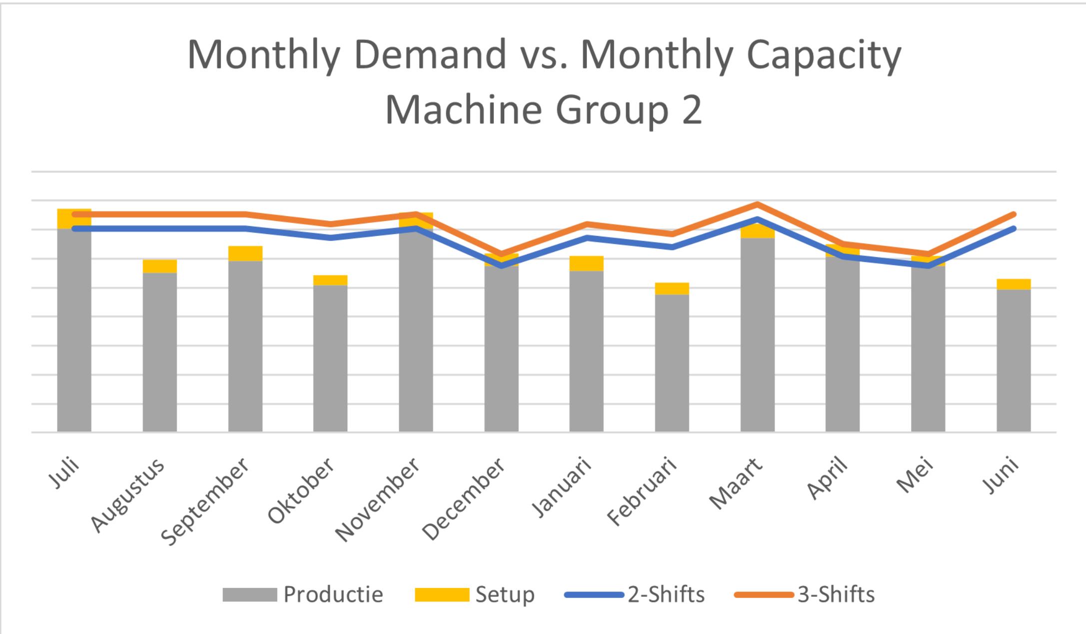

Figure 6.2: Capacity vs Production hours of machine group 2 after optimization

6.2.2 Objective function

The objective function of the optimized solution is in total € 801,842. The inventory costs are € 143,847 and the setup costs are equal to € 657,995. Looking at the current scenario, in which the objective function is equal to € 1,509,895, the total costs are nearly halved. Furthermore, the setup costs are drastically lowered, with a difference of around € 850,000.

6.2.3 Number of FTE needed per day

For the optimized solution, the FTE needed per day can be found in table 6.4. What can be seen is that for Factory 2, on average one person is needed less per day. Over a full year this is a large decrease in the number of shifts that has to be done. The difference is mainly due to the fact that the fluctuation in production amounts per month is decreased and thus the demand is more stable. On average this results in the decrease.

Table 6.4: Average number of FTE needed per day per factory after optimization

Month	**Factory 1 (old)**	**Factory 2 (new)**
July	26	39
August	21	31
September	20	34
October	21	33
November	19	38
December	23	41
January	19	34
February	18	34
March	21	37
April	25	41
May	27	43
June	21	33
Average	**22**	**36**

6.2.4 Number of setups

When looking at table 6.5 it can be seen that on average there are fifteen setups a day. In the optimized solution, the number of setups is decreased. In total the difference is decreased from 334 per month to 235 per month. Per day this means an decrease of 5 setups. What can be seen in both tables is that the first month has the highest amount of setups. This is because the products with some demand have to be produced in that month, because no backorders are allowed and there is no start inventory.

Table 6.5: Number of setups needed per month after optimization

(a) Number of setups needed for factory 1 (old)

Month	# of Setups	Avg. per day	Setup hours
July	A	AA	N
August	B	BB	O
September	C	CC	P
October	D	DD	Q
November	E	EE	R
December	F	FF	S
January	G	GG	T
February	H	HH	U
March	I	II	V
April	J	JJ	W
May	K	KK	X
June	L	LL	Y
Average	**M**	**MM**	**Z**

(b) Number of setups needed for factory 2 (new)

Month	# of Setups	Avg. per day	Setup hours
July	A	AA	N
August	B	BB	O
September	C	CC	P
October	D	DD	Q
November	E	EE	R
December	F	FF	S
January	G	GG	T
February	H	HH	U
March	I	II	V
April	J	JJ	W
May	K	KK	X
June	L	LL	Y
Average	**M**	**MM**	**Z**

6.2.5 End-of-month inventory

Different to the current scenario, the optimal solution has end-of-month inventory. It uses this inventory to decrease the number of setups, while still being able to meet demand. In figure 6.3 it can be seen how the end-of-month inventory is used. In the busy months, the inventory is decreasing, since demand is higher than the production amount, while in the other months it is the other way around.

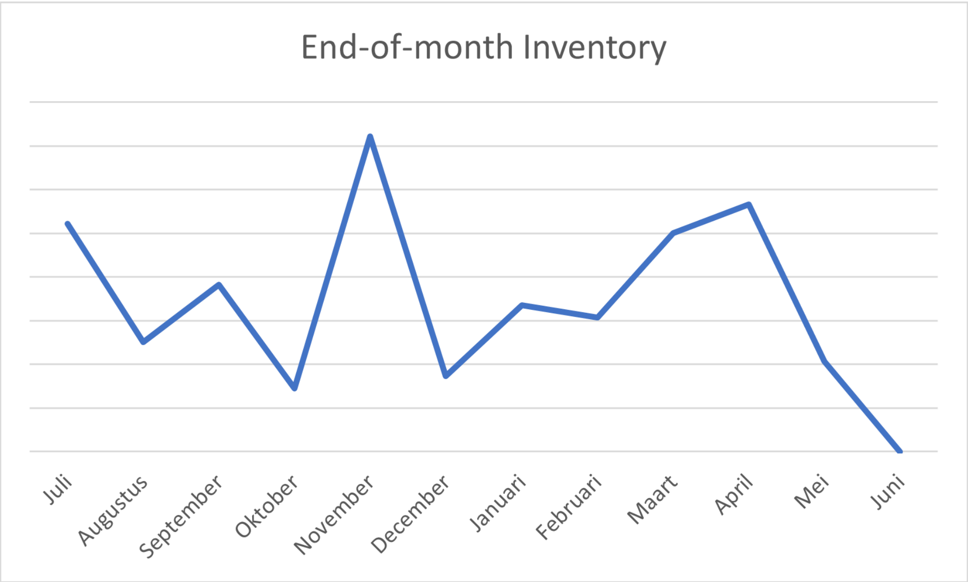

Figure 6.3: The end-of-month inventory

6.2.6 Conclusion mathematical solution

As can be seen in the KPI values of the mathematical solution, it is an improvement of the current scenario. The kilograms of plastic foil needed did not change as still the same number of products have to be created. But by decreasing the number of setups and increasing the inventory, the total costs have been nearly halved. Next to that, the solution is now feasible, whereas the current scenario had capacity exceedance.

6.3 Simulated annealing framework results

After having determined the current KPI values and the optimal values, this section is focused on the results of the simulated annealing framework. The tool has been used to run the simulated annealing framework multiple times. After every run, the objective function was compared with the optimal objective function. The results of multiple runs can be found in table 6.6. Next to the objective function, the run-time is stated as well as the gap to the objective function.

Table 6.6: Simulated annealing runs

Run	Objective function (in €)	Run time	Optimality gap
1	1,061,903	28800	32.4%
2	1,012,285	28800	26.2%
3	999,728	28800	24.7%
4	993,402	28800	23.9%

What can be seen in the table is that the optimality gap is high. It is always above 23% which is huge. In absolute values, this means that the costs of the solution found with the simulated annealing framework is around € 200,000 more expensive. The gap is so high, that it is not an option to accept any of the solutions made by the simulated annealing for this report. More extensive research has to be done on why the simulated annealing cannot find good solutions. Possibly, because of the high number of different solutions possible, the simulated annealing finds it hard to find good solutions within eight hours. Multiple times the code has been upgraded such that more iterations of the simulated annealing could be done within the run time. However, it did not result in better alternatives that could potentially be used. For this research, there was no possibility to dive deeper into the problems with the simulated annealing and how to solve them.

6.4 Conclusion

This chapter showed the results of the research. First of all the current situation is expressed. It can be seen that the company sells a very broad range of products and thus many different products per month. This results in a lot of setups needed to produce all the products and high setup costs. Next to that, the number of employees needed per day can differ a lot per month. This has two reasons, one of them being the holidays, meaning the factories are closed extra days. Another reason is the seasonal demand pattern of the products. Next to the capacity and the setups, the plastic foil consumption is described. The foil pattern follows the demand pattern, which is logical. If more products need to be produced, more foil is needed.

An optimal solution has been generated by solving multiple subproblems and by combining them. This solution showed that by decreasing the number of setups, the total costs can be nearly halved. Next to that, it is shown what the effect is of the optimized schedule on the number of employees needed per day and the number of setups. Next to that, it is shown in which months inventory is built up and how the cumulative inventory position is over the year.

To be able to solve the problem as a whole, a simulated annealing framework has been run. Unfortunately, no good solutions have been found. The optimality gap of all the runs was at minimum around the 24%. This means an increase in costs of € 200,000. For the company this is too high and therefore, the simulated annealing tool cannot be used to solve the problem. The only way possible is by solving it in subproblems optimally and combining them. Possibly, by extensively researching the simulated annealing framework, it could be improved, but for now only the optimal solution and the current scenario give the expected results.

6.5 Excel dashboard & Python tool

To finalize this chapter, the created Excel dashboard and the Python tool are explained. First both tools are explained separately and afterwards the combination of both is explained.

6.5.1 Excel dashboard

The goal of the Excel dashboard is to give the company insights in the upcoming months, regarding the demand, number of employees needed on average per shift and the amount of kilograms of plastic foil needed to produce the demand. The dashboard is separated in three sheets: one for both locations combined, one for factory 1 (old) and one for factory 2 (new).

All of the sheets use the same layout and therefore only one of the sheets is shown. The dashboard can be seen in figures 6.4 and 6.5. Figure 6.4 shows all the monthly capacity vs. monthly demand graphs. These graphs are separated on machine groups. Every machine group has therefore one graph. In Figure 6.5, the graphs can be found for the number of manhours needed as well as the tonnes of plastic foil needed. The graphs show the pattern over the months.

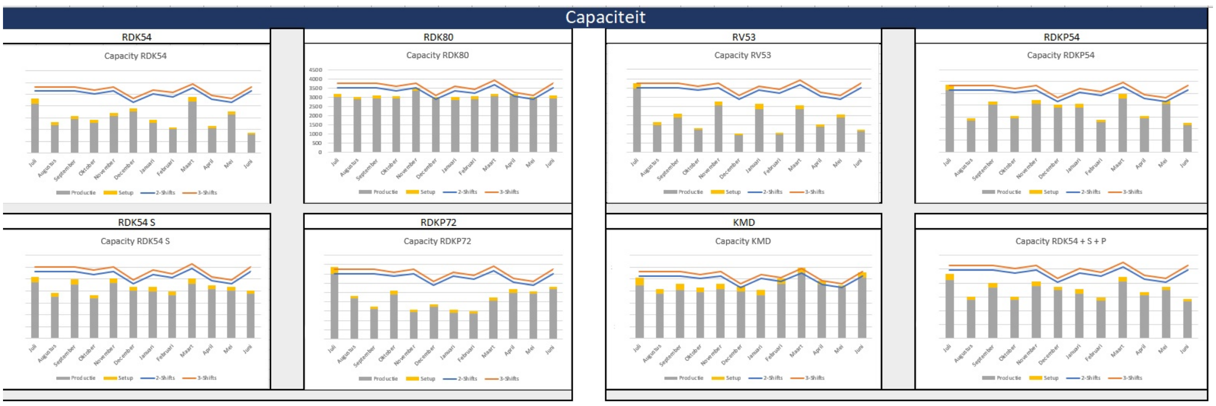

Figure 6.4: Dashboard with KPIs (1/2)

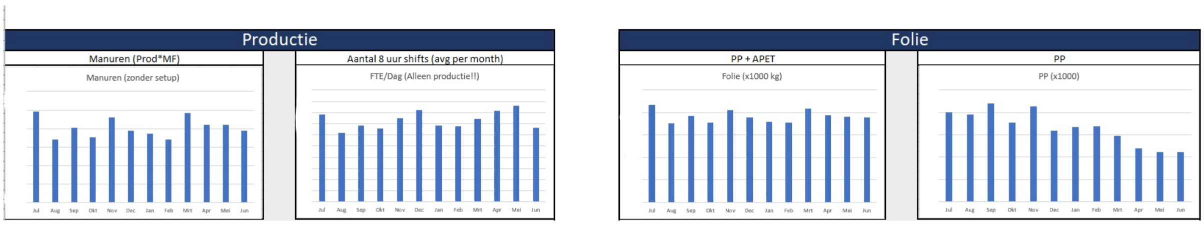

Figure 6.5: Dashboard with KPIs (2/2)

To understand how the dashboard works you can look in Appendix C.

6.5.2 Python tool

A Python tool has been created to create the input for the Excel dashboard. The input of the Python tool are two Excel files. One file with all the product data, think of: the machine type, number of moulds, kilograms of plastic foil needed for one product and many more. The second

file contains the demand forecast of all products.
If all data is inserted, the tool can be run to create the demand based production schedule. The result of the method is an Excel sheet containing the monthly planning of the products. This Excel sheet can be imported into the Excel dashboard.

To understand how the tool works and what it looks like, you can look in Appendix C.

6.5.3 Evaluation of the tools

The end-users of the dashboard and the tool are some of the employees of the company. In close cooperation with the end-users, the dashboard has been made. On forehand, a list of things that need to be shown on the dashboard is created together with the supervisor of the company, who is the main user of the dashboard. All those points have been put into the dashboard. When the draft version of the dashboard was finished, a meeting was scheduled with other end-users, namely the production leaders, planners and the director of the production facility. Together with them, the dashboard was analyzed and for the major part, they liked what they saw on the dashboard. However, they missed some KPIs on it. So, after adding those KPIs, I asked them, what they thought about the dashboard and for them it was practical. They told me: ”Perhaps it is not the most beautiful dashboard, but we understand how we should look at the dashboard and how we can interpret the values. So for us, this dashboard is good enough.”

So to conclude, visually the dashboard could have been better, however, after my explanation it is clear to them and they can use the dashboard whenever needed.

7 CONCLUSIONS & DISCUSSION

In this chapter, the research is concluded in section 7.1. Section 7.2 discusses the effect of assumptions on the results. Section 7.3 states recommendations for the company. Next to that, it is discussed what further research can be done to improve this research or to create new tools that can gain new insights for the company in section 7.4. In section 7.5 the impact of this report on the theory and practice is given.

7.1 Conclusions

In this research, a closer look is taken on the planning of the production process. The aim of this research is to answer the following research question:

What can Hordijk do to improve their planning process and thus reduce their production and inventory costs, without affecting the demand restrictions?

In this section, the most important findings and remarks which are gained throughout the research are explained.

The research has been conducted, because the company was lacking insight into their production planning. The company was looking for information to determine how to make the best production planning. Currently there are two planners at the company, who each make the production planning for a factory. Both planners work according to the same rules. Whenever the expected inventory position drops to 0, a product is scheduled for production. The batch size of the production is equal to a quarter of the yearly demand. With their knowledge and experience as a planner, both planners know that the company has a seasonal demand, which causes the demand to exceed the production capacity. To cope with that demand, the planners decide to produce some products earlier. However, they are uncertain which products are best to produce earlier and when to start producing earlier. Therefore they are willing to use data to answer these questions.

At first, the literature has been checked. In the literature multiple mathematical models have been found, but most of them result in a complete schedule. The company wanted a monthly planning, which does not plan the products in order, but just plans production amounts per month per article. This means without determining the production start time and batch sizes. Therefore a model found in the literature had to be adapted towards the wishes of the company. One of the models found was capable of doing that, however, it is a NP-hard model. This means that it is unlikely to solve in polynomial time for large instances. For small instances the problem could still solve in polynomial time.

It has been checked whether the whole problem could be solved optimally. This was not possible. Therefore the problem has been separated into smaller subproblems. These subproblems could be solved in polynomial time and by combining all the results, the problem has been solved optimally. The optimal objective function found was around € 800,000.

However, the fact that the problem cannot be solved as a whole, means that no constraints can be added which affect the problem as a whole. Therefore it is decided to create an alternative solving method. In this case the alternative solving method was a simulated annealing framework. This framework searched multiple neighbourhood structures to find the best solution. Unfortunately, the framework was not capable of finding solutions close to the optimal objective function, as the smallest optimality gap was 24%.

As the main goal of the company is to gain insight into their production planning, a dashboard has been created for them. On that dashboard, the production demand for the upcoming year can be seen as well as the expected setups, expected number of FTE needed and the tonnes of plastic foil needed. The dashboard is made in twofold. One dashboard focuses on the demand data, meaning that no optimization has been done on that data. It can be seen as the production forecasts per month addressed in production hours. This dashboard clearly shows why it is needed to produce products earlier and in which months this production could be done. The second dashboard is based upon the optimal schedule. By comparing both dashboards it can be seen how much benefit can be gained by producing the correct amounts earlier. The difference in objective function between the optimal solution and the demand based solution is around € 700,000. Thus by combining different monthly demands and producing products earlier, nearly half of the costs can be saved.

To make sure the company is able to produce these insights their selves, a Python tool has been made which creates the different input files for the dashboard. These input files can be loaded into the dashboard, after which all the updated KPIs can be seen again.

7.2 Discussion

During this research there are certain assumptions made, which affect the outcome or the practicality of this research. In this section it is explained why the assumptions have been made, what the effect is on the outcome and what can be done in advance of this research.

The biggest assumption is the one in which is stated that the demand occurs at the end of the month. In reality the demand can be on every day of the month. However, currently the data does not give small periods in which the demand is expected. Only the monthly forecasts are known which means that with this data, it is impossible to incorporate detailed demands. This assumption can cause the gained solution to be infeasible in reality, because the monthly forecasts could for example all occur at the second day of the month. But on average, this is not often the case. Next to that, the planners have enough knowledge and experience to foresee these problems and adapt the solution to it.

Another assumption is that the products can only be produced in one shift per month. It is chosen to do this, since it simplifies the model and in reality the products are only produced around four times in a year. This means that the chance of producing more than once a month is nearly zero.

7.3 Recommendation

As said many times before, the aim of this research is on gaining insight and creating a tool for the company to use for this purpose. The dashboards created have to be regularly updated. It is recommended to update the demand-based dashboard every month, since every month there is a new month of forecast. For the optimal dashboard, it is the companies decision how often they want to update it. It is a lot of work to divide the input data over the eleven subproblems, however, the results of the model are useful. I would suggest updating the optimal solution once every three months, since a lot can change in those three months with regard to the forecasts.

With regard to the usage of the dashboard, it is suggested to use the demand-based dashboard as explanation on why to produce products earlier. As the peak in demand can easily be seen in that dashboard, everyone in the company can understand why production has to be done earlier.
The other dashboard can be used by the planners. They can use the improved solution as aim for their production planning. They can adapt the real-life production planning towards the solution of the dashboard. In that way, the less costly products are produced earlier and thus costs are reduced.

7.4 Further research

After this research there are many things that can be researched. The biggest achievement can be made by looking into the possibility of letting a computer create the production schedule. This research focused on gaining insight in the production planning and giving possibilities to decrease costs and inventory levels. The next step would be to search for parts that could be automated. However, there is a lot that has to be done before automation could be achieved. First of all, all the dates of the demand should be known. Then the number of employees per time unit should be known and there is many more, so multiple reports can be made on this subject.

Looking at the company in its whole, there are more subjects that can be researched. For example the allocation of the products over the factories, the number of machines per factory and the different machine types per factory. However, the company has just finished moving from one factory to another, so it is not a preference of them to start a new movement later this year or next year.

One of the other factors that is very important in the production planning, is the planning of the plastic foil. This foil has to be made in time to be able to follow the production planning. A similar research as done on the production planning can be done on the plastic foil planning. This gives the company extra insights in the effects of the production planning on the plastic foil planning and vice versa.

Another Bachelor thesis could be done on checking the seasonality in the demand. It can be researched whether the forecasts take into account the seasonality or not, and if this is done correctly. The effects of seasonality on the forecasts can be calculated and it can be checked whether this would increase the precision of the forecasts, without over-fitting.

Lastly, a Master or Bachelor thesis can be done on the lot sizing of the production. This research is aimed at calculating the amounts that have to be produced per month which minimize the objective costs. These amounts have to be translated into lot sizes. To be able to do this in the best way possible, more research is needed on this topic.

7.5 Contribution to theory or practice

The contribution of this report towards theory is little. Already there is loads of literature available on this subject and nothing special has been done in this report to the theory to make it unique. For other companies, this report could be useful. Companies that want to make the first step towards data-driven decision making could learn from this report. Many times it is hard for companies to see what is possible with regard to data-driven decision making and many times it is not clear to them what they really want. This report can give those companies small steps which they can recreate themselves and potential future research they can investigate. With regard to Hordijk itself, this report really opened up the eyes of the employees. Of course the employees knew most of the things already, but the graphs helped them to make choices. Next to that, employees really start thinking of new projects that could be done on this subject and the potential benefits of those projects.

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A CAPACITY GRAPHS FACTORY 1

In this appendix the capacity vs demand graphs are stated of the first location, the "old" location. What can be seen is that all three graphs almost never exceed the 2-shift capacity line.

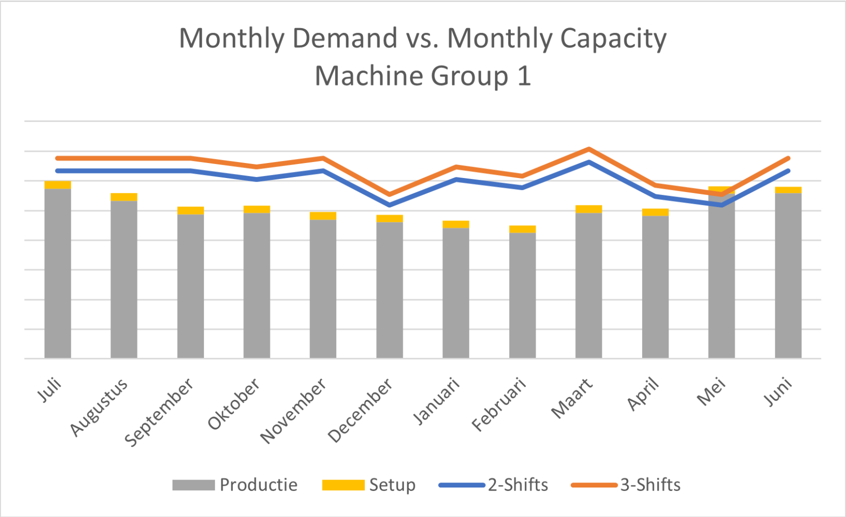


Figure A.1: Capacity vs Demand for machine group 1

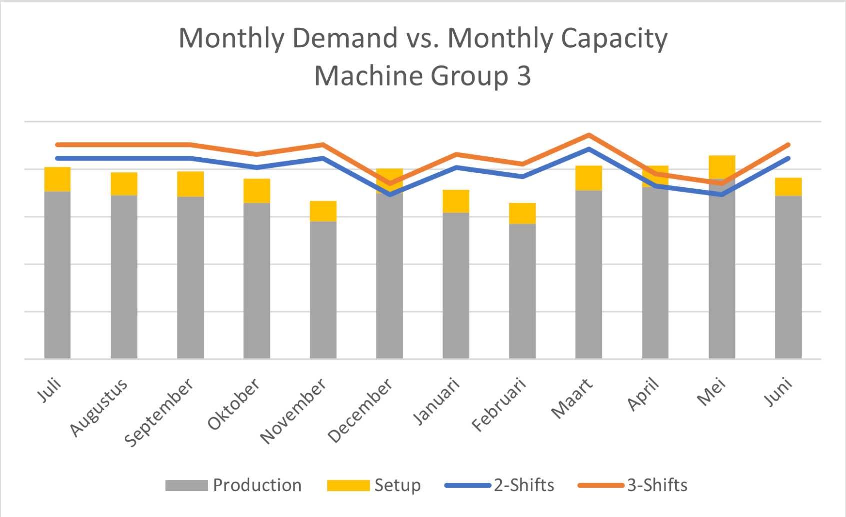


Figure A.2: Capacity vs Demand for machine group 2

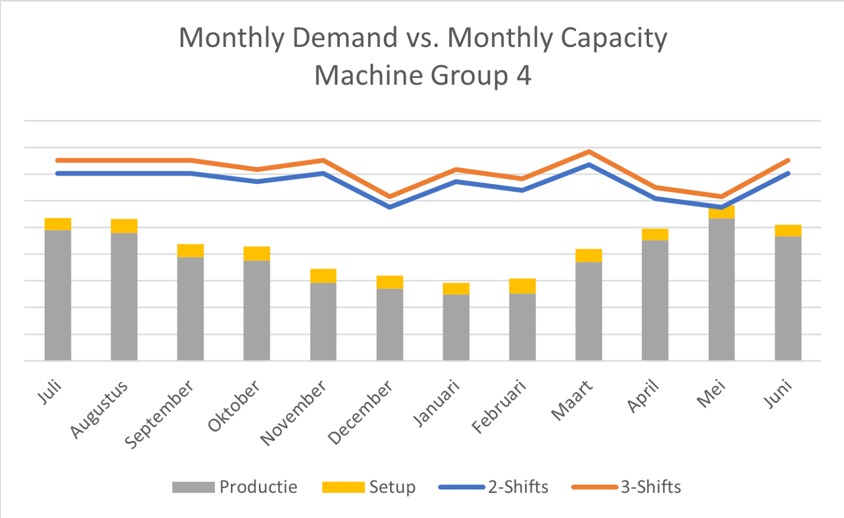


Figure A.3: Capacity vs Demand for machine group 3

B CAPACITY GRAPHS FACTORY 2

In this appendix the capacity vs demand graphs are stated of the first location, the "new" location. What can be seen is that all seven graphs almost never exceed the 2-shift capacity line.

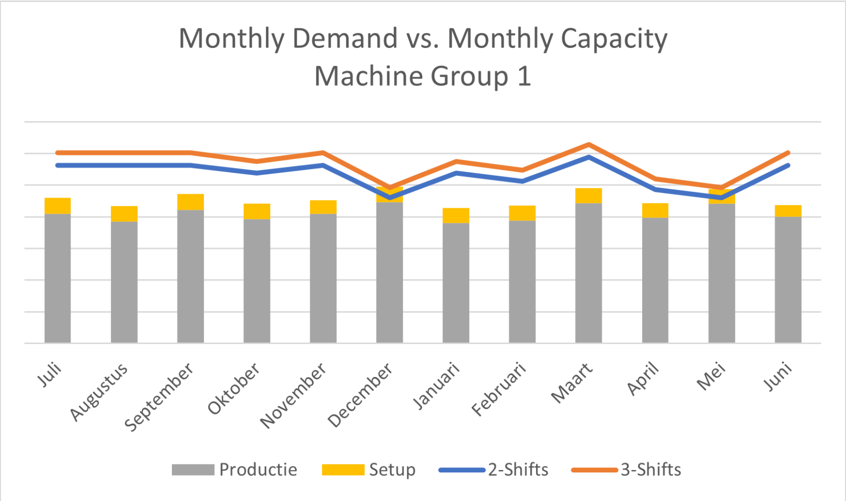


Figure B.1: Capacity vs Demand for machine group 1

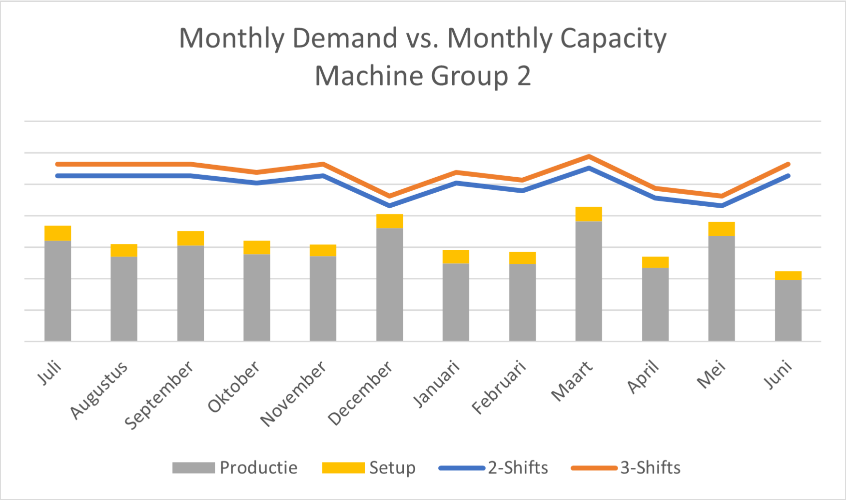


Figure B.2: Capacity vs Demand for machine group 2

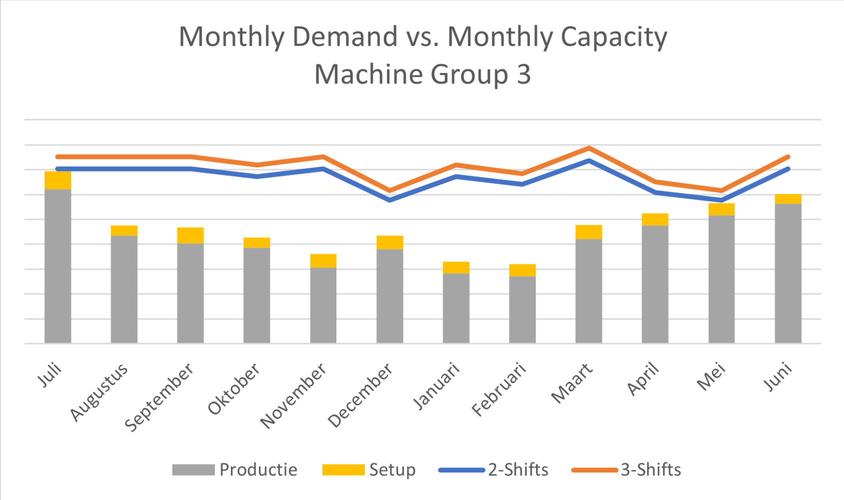


Figure B.3: Capacity vs Demand for machine group 3

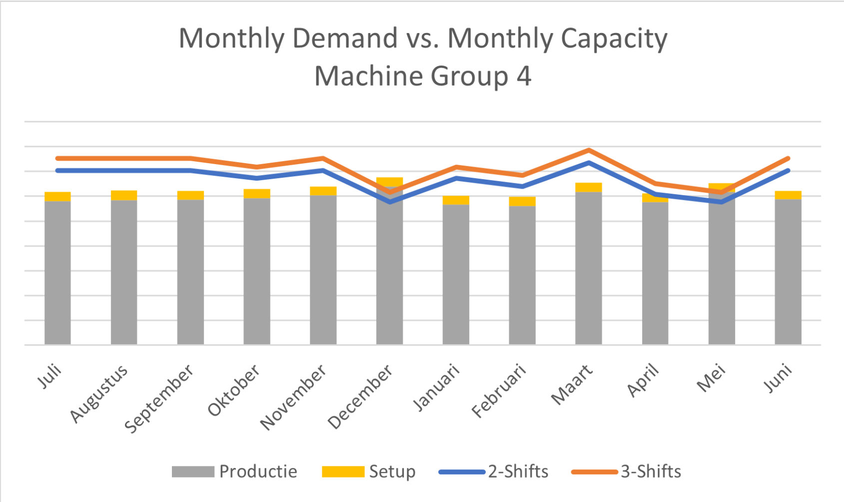


Figure B.4: Capacity vs Demand for machine group 4

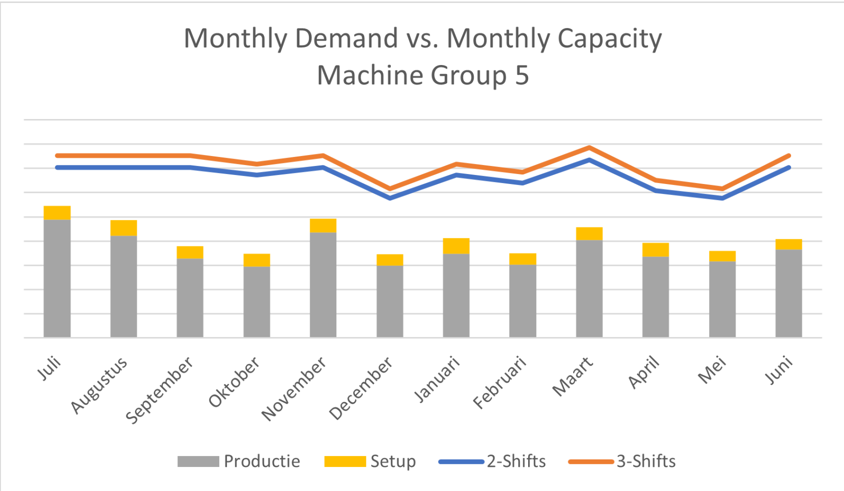


Figure B.5: Capacity vs Demand for machine group 5

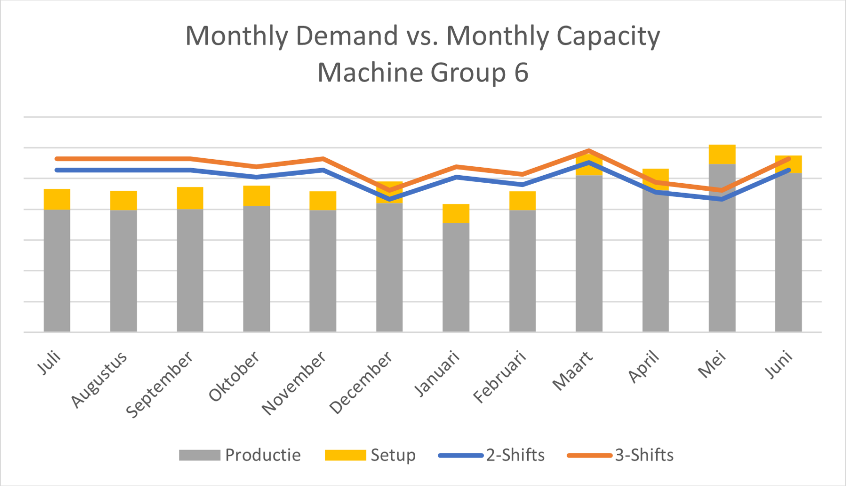


Figure B.6: Capacity vs Demand for machine group 6

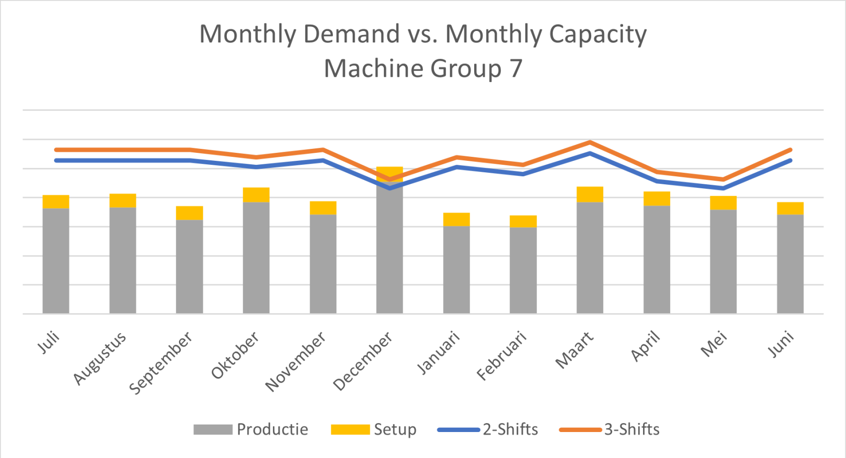


Figure B.7: Capacity vs Demand for machine group 7

C EXCEL DASHBOARD & PYTHON TOOL MANUAL

In this appendix manual for the Excel dashboard and the manual for the Python tool are given. The first section states the manual for the Excel dashboard and the second section

C.1 Python tool manual

This section describes how to use the Python tool. The tool consists of two parts. The first part is creating the input files in a correct way and the second part is importing the input files and to start the tool. First it is explained how to create the input files, after that, the actual Python tool is explained.

C.1.1 Input files

The input files for the tool are two Excel files. One Excel file contains all data about the article. Some examples that belong to this file are the number of moulds, the number of employees needed to run the machine (manfactor), the setup time and the kilograms of plastic foil needed per end product. The other Excel file contains the forecasts per article. These files should not have the same amount of products, as long as all the products in the forecast Excel file are also in the other Excel file.

The input files The rules that apply to the input files are for both the same. For both files, there is a sample file that is pre-made and that contains all the columns which are needed in the Python tool. The first row, so the row with the column headers, cannot be changed. The names should be the same as they are right now or the tool will crash. By recreating the input file, with the same column headers and with the same data field type, the sheet is ready to use. However, there is an issue with copying the data from the software system. The data with the article numbers is namely shown as a text formula, whereas it should be in a number format. To fix this issue, do the following steps:

1. Copy the entire column with article numbers
2. Use paste-special values (ctrl-alt-v + values)
3. A warning will show up stating (Numbers stored as text), resolve this issue by clicking on it
4. The numbers should be stored in a number format now

Since the software of the company creates Excel files, many columns can be copied into the file. Only thing that has to be worried about is that every column that uses numbers, is indeed filled with numbers and no text. Next to that, there are some formulas that have to be checked on potential errors. If they error, they have to be solved. If everything is the same as the example file, there cannot occur an error while running the tool.

The Python tool For this instance, Python has to be installed on the computer. In my own case, I have the Anaconda software installed, and I use Spyder (IDE of Python) to open the python files. To download Anaconda, take a look at their website.

Below a list of steps is given on what to do to make the software work.

1. Make sure no Excel file called ”Output.xlsx” is opened. Also make sure the input files of the forecasts and article data are closed.
2. Open up the Python IDE (Spyder)
3. Open the Python file with the code of the tool
4. Run all the code (for example by doing Ctrl-Enter on the code)
5. A new window will open (see figure C.1)

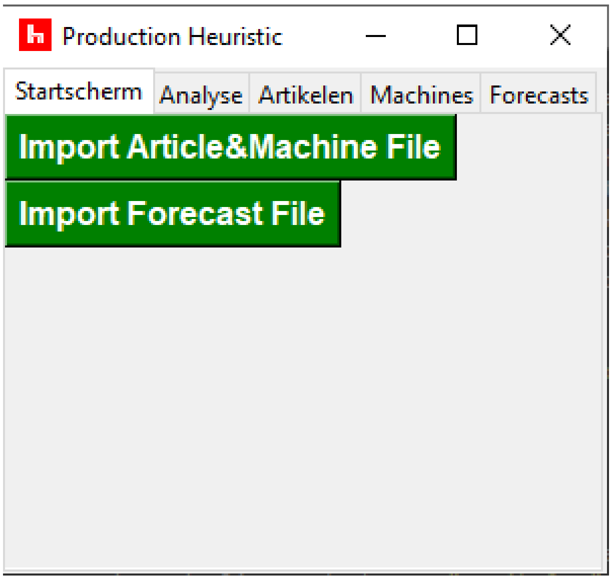


Figure C.1: The home screen of the Python tool

6. There are 2 buttons. To begin, click the upper button with the text: ”Import ArticleMachine File”. A file input screen will pop up (see figure C.2), out of which you can select the correct input file. Click on the file and press the button ”Openen”.

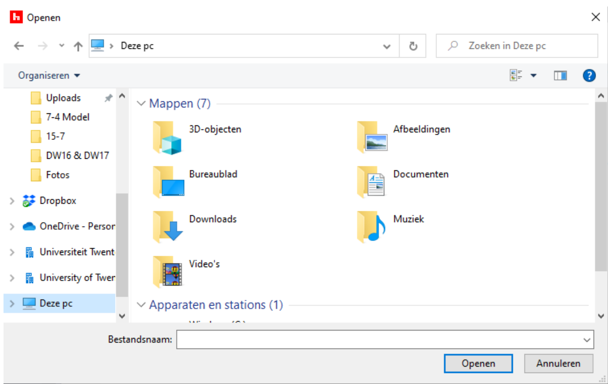
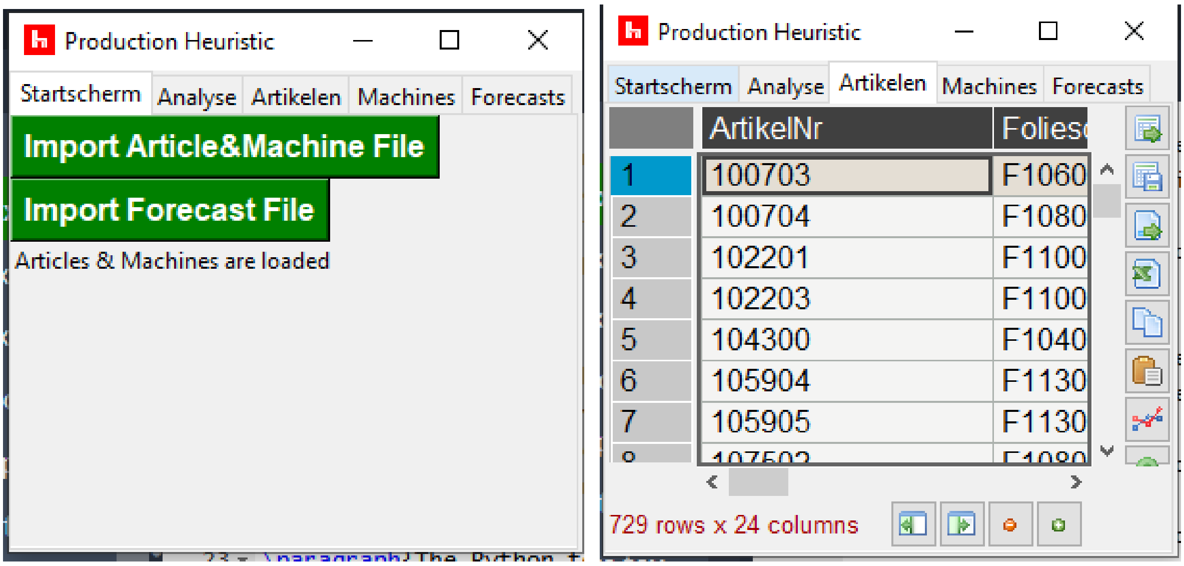


Figure C.2: The input screen

7. The data is loaded and when it is done, the home screen will state it has loaded the data (see figure C.3a). The loaded data can be found under the articles tab (see figure C.3b).



(a) The home screen after loading Article data

(b) The "Artikelen" tab

8. Now step 5 and 6 can be done again, but now for the bottom button called: "Import Forecast File". After finishing, the home screen should look like figure C.3

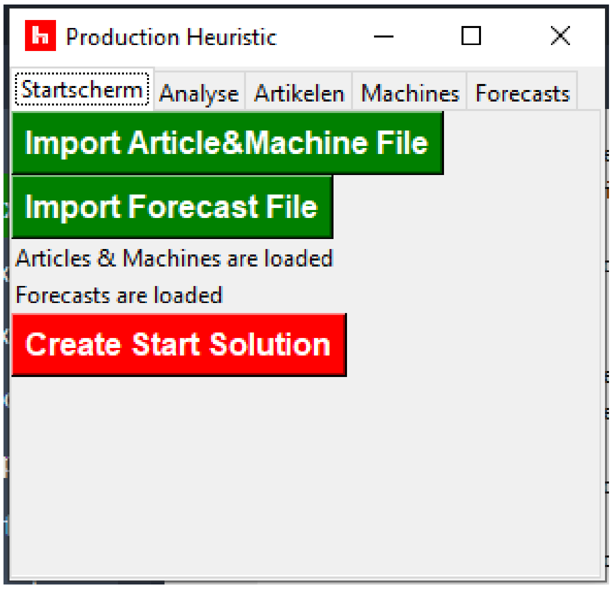


Figure C.3: The input screen after loading forecasts

9. An extra button came up called: "Create Start Solution". Push that button. The button is pressed and will remain pressed during the duration of running (see figure C.4). If the run has been finished, the home screen looks like figure C.3 again.

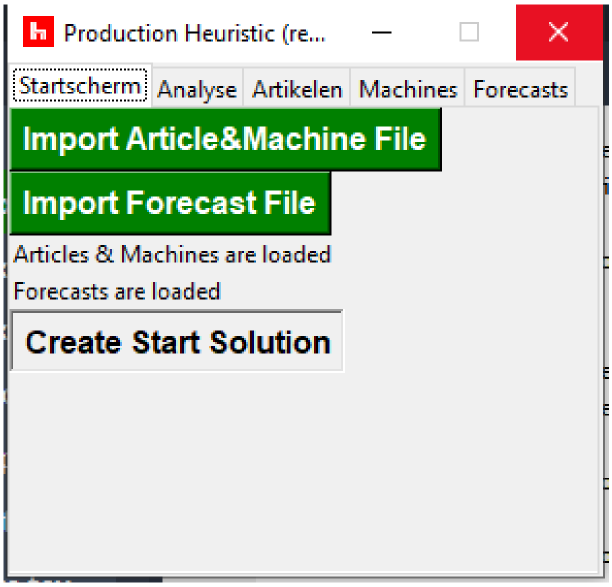


Figure C.4: The input screen after loading forecasts

10. You are done using the tool, and in the folder with all the Spyder files, the Excel file ”output.xlsx” is generated and filled with the solution of the run.

C.2 Excel dashboard manual

If you have followed the Python tool manual, you have created an Excel file called ”output.xlsx”. This Excel file is the input file for the Excel dashboard. In this manual it is explained how to insert the data from the Excel file into the dashboard. This is described in the list of steps below.

1. Open the Excel file ”output.xlsx” and the Dashboard file
2. In the Dashboard file, open the sheet ”Productie”
3. On the sheet ”Productie” click on the button ”Clear Sheet”. The sheet will be cleared such that you can insert the data.
4. Now open the Output file. In the file there is a production list, select the full production list (but only the columns with the data, so no ctrl-a).
5. Copy the selected data, using ctrl-c.
6. Now go to the Dashboard file and in the sheet ”Productie”, select the cell ”A6”.
7. Now press ctrl-v, such that the data from the Output file is pasted into the Dashboard file.
8. The dashboard is now updated with the correct data. Now you can open any sheet with ”Dashboard ...” in the name and you can see the KPIs you would like to see.