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# Operational and tactical production planning at a production company

## Non-confidential version

This is the non-confidential version in which all company names, locations and last names are replaced by fictional company names, locations and last names.



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## Preface

This thesis is the final chapter of my master Industrial Engineering and Management at the University of Twente. In this preface, I would like to thank several persons that helped me with the realization of my thesis.

First of all, I want to thank Peter Janssen for giving me the opportunity to do my master assignment at the production company Taman. In particular, the brainstorming together about the problems I came across and the positivity helped me a lot during the assignment. I also like the way I was treated as a colleague instead of a temporary intern. Besides, I would like to thank my colleagues Dick, Sandra, Ruud, Rogier, Menno, Susan, Gabriël, and Daniël, for supplying me with information, and the focused and relaxed working atmosphere.

Second, I want to thank Marco Schutten and Peter Schuur for helping me improving my thesis to its current state. The feedback about the orthography, structure, and decision explanations were really helpful!

Finally, I want to thank my family, housemates, and friends for their support and their interest in my proceedings during this assignment. This really helped me to carry on and finish the thesis in its current state!

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## Management summary

Taman is a manufacturing company producing mainly garden furniture. Besides, it produces a variety of products for some companies (B2B products) and products for pets (pet life products). Taman has two production locations. The main office and production area is located in Tilburg and the secondary production area is located in Hengelo. This research is done for Taman Hengelo. Taman Hengelo has 25 machines and uses approximately 100 molds to produce roughly 7.5 million kilograms of finished products per year. In 2018, 63% of the total production consisted of garden furniture, 31% of B2B products and 6% of pet life products.

At this moment, Taman wants to increase their cycle service level (CSL-level). The CSL-level reflects the number of orders delivered in time. Taman wants to increase this from 95.4% to at least 98% while minimizing costs. Using a problem cluster, we found the core problem for this low CSL: *“The tactical and operational production planning process are based on estimations”*. Because the process after the master production schedule (MPS) is done completely manually, mistakes happen frequently, and it is difficult to forecast whether a change in the production quantity of an order can be accepted or not.

In the current situation, the planner makes a ‘color image’ in which he roughly plans the parts that are produced on the machines in a certain time frame. Based on this ‘color image’ the production runs are scheduled in the ERP system of Taman. The consequence of a change in production quantity or due date is very difficult to forecast. Besides, the process of checking the feasibility of a changed customer order takes a lot of time because each production run has to be shifted manually. We therefore choose to construct a model that replaces the ‘color image’ process and the scheduling process with the goal of increasing the CSL-level to at least 98% while minimizing the costs.

To decide which kind of model we implement, we look in the literature at comparable scheduling problems. We decide to first use the serial schedule generation scheme method with the earliest due date priority rule. This method is very suitable because it results in a feasible production schedule. We choose the serial schedule generation scheme because it leads to better results and requires less computation time than the parallel variant (Kim & Ellis Jr, 2010). The earliest due date priority rule minimizes lateness which maximizes the CSL-level. Since this is the goal of the new production scheduling method, the earliest due date priority rule is very suitable.

We now have a feasible production schedule that we can improve. To be able to decide whether a production schedule is improved, we use an objective function. This function includes the CSL-level penalty costs, inventory costs, and mold change employee costs. Based on these parameters, the production schedule is assessed and the schedule with the lowest objective value is the best.

We choose to use simulated annealing as our improvement method since this method is often used in literature for scheduling problems and it searches for one neighbor per iteration. Besides, it searches for a global optimum instead of a local optimum which is the case for the more simple heuristics. Tabu search is also a popular improvement method for scheduling problems, but because the execution time of one neighbor is 0.5 seconds, the iteration time using tabu search becomes too long, since all neighbors have to be evaluated in tabu search.

To get the simulated annealing method to work efficiently, we determine the parameters carefully. We choose the start temperature in such a way that 80% of the worse neighbors are still accepted at the start of the cooling schedule. Then, we do multiple experiments to check the highest temperature that did not result in a significant improvement. Thereafter, we calculate the number of iterations we could do by dividing the available time for the heuristic by the duration of one iteration. Finally, we do experiments with different ratios of the decreasing factor and markov chain length to search for the

best combination. Each experiment is run twice to decrease the variation of the results (Table 1). Based on these results, we choose the decreasing factor of 0.9 and the markov chain length of 62. Figure 1 shows the decrease of the objective function against the number of iterations. Due to the characteristics of simulated annealing, some iterations lead to an increase of the objective value, but when the temperature decreases, the probability that a worse neighbor is accepted decreases.

Start temperature	End temperature	Decreasing factor	Markov chain length	Objective value improvement (1)	Objective value improvement (2)
1288	8	0.85	96	13.2%	10.6%
1288	8	0.9	62	15.5%	14.2%
1288	8	0.95	30	8.2%	9.3%

Table 1: Searching for the decreasing factor and markov chain length leading to the best objective value

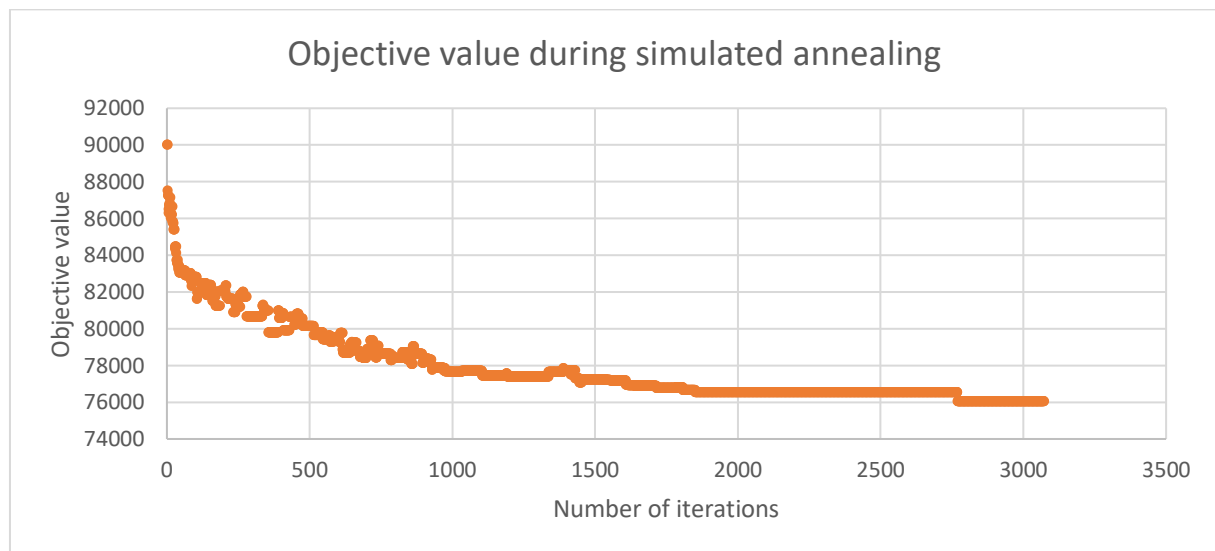


Figure 1: Objective value during simulated annealing

The simulated annealing heuristics resulted in a significant decrease of the objective function by 15.5%. The CSL-level penalty costs did not change, the inventory costs decreased with 29.2% and the mold change employee costs increased with 8.4%. Table 2 shows the results of the production schedule before and after simulated annealing.

Criterion	Before simulated annealing	After simulated annealing	Reduced/increased (%)
CSL-level penalty costs	0	0	0%
Inventory costs	57,262	40,528	-29.2%
Mold change employee costs	27,300	29,600	+8.4%
Objective value	90,022	76,048	-15.5%

Table 2: Objective function parameters before and after simulated annealing

Table 3 and Table 4 show the utilization level of the situation before simulated annealing and after simulated annealing per machine group. We can clearly see that the situation after simulated annealing is more spread out over the season. When a delay occurs, due to for example raw materials that arrived late, this will have a smaller impact on the situation with a more spread out production schedule, while there is more time for absorbing such a delay.

	August	September	October	November	December	January	February	March	April	May	June	July
30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
50	50%	21%	0%	3%	31%	22%	0%	20%	0%	0%	0%	0%
350	68%	88%	97%	99%	94%	94%	93%	94%	71%	0%	0%	0%
650	40%	89%	96%	98%	93%	96%	91%	92%	69%	7%	0%	0%
800	7%	86%	89%	96%	91%	83%	55%	47%	17%	0%	0%	0%
1000	54%	82%	94%	97%	93%	95%	96%	80%	52%	0%	0%	0%
2300	97%	99%	97%	95%	96%	97%	93%	93%	92%	97%	73%	0%

Table 3: Machine utilization per machine group before optimization method

	August	September	October	November	December	January	February	March	April	May	June	July
30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
50	0%	0%	0%	0%	62%	22%	8%	30%	0%	0%	0%	0%
350	58%	64%	79%	79%	82%	81%	98%	94%	77%	68%	28%	0%
650	41%	76%	88%	85%	90%	92%	90%	92%	74%	50%	0%	0%
800	3%	41%	51%	53%	61%	71%	88%	61%	63%	39%	23%	0%
1000	46%	60%	86%	81%	94%	93%	76%	72%	77%	56%	3%	0%
2300	97%	99%	96%	92%	96%	94%	85%	71%	86%	87%	95%	25%

Table 4: Machine utilization per machine group after optimization method

The model is verified by comparing the results of the production schedule and the utilization overview of the model to the expected results by the planner and the plant manager. These results all seemed to be correct. To validate the model, we want to compare the model with the current situation, however, this is not possible with the use of historic data. We therefore made an instruction manual to implement the model. This model can be run simultaneously with the current method. Based on differences and comparisons between the model and the current method, a conclusion can be drawn whether to implement the model in its current form or that first some changes have to be made before the model is implemented.

Finally, we made some recommendations for Taman. These recommendations are ordered based on their priority where the first recommendation has the highest priority. We advise to start performing point 1 on a regular basis to see the differences in the production schedule and the utilization of the machines and molds when a customer order is changed. Point 2 has to be implemented on a short term since it improves the production scheduling model and leads to less manual work and therefore less errors. Point 3 and 4 are recommendations for the medium term. After each point, the function of the person that has to execute the task is shown.

1. Use the production scheduling model to evaluate whether a changed customer order can be accepted (planner)
2. Improve the data quality
  - a. Let all B2B customers place their forecasts and orders in SAP (SAP consultant, planner)
  - b. Couple each forecast to the corresponding customer that places the forecast. In this way customers that place larger orders than their forecast do not use the finished products made for customers that forecast the correct amount (SAP consultant)
  - c. Contact the customer when a forecast is not changed to a customer order in time. Give them the choice to change their forecast in a customer order or remove their forecast (customer relations)
  - d. Update the location of the machines and molds in time, so production orders always arrive at the correct production location (plant manager)
  - e. Reduce the number of variations per products (plant manager)
3. Consider leasing, hiring, or buying a 2300 ton machine. This machine group has a very high utilization during the whole season. A delay on one of these machines can have large consequences for the whole season (plant manager)
4. Introduce a preventive maintenance plan for the most busy machines to decrease the chance of a breakdown (technical support)





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## 1 Introduction

This report is the result of my master assignment at Taman Hengelo. Taman is a manufacturing company located in Hengelo. It produces mainly garden furniture using spray-casting techniques. With a production of more than 7.5 million kilograms of finished products per year, it is one of the largest spray casting companies in the Netherlands. For a company with such a large production output, it is important to have a good capacity and production plan. This research focuses on the development and implementation of a tactical and operational production planning method at Taman.

First, Section 1.1 gives a description of the context that explains the structure of the company, the basics of spray casting and types of products made by Taman. Section 1.2 continues with the research motivation. Based on this research motivation, we identify the core problem with the help of a problem cluster in Section 1.3. Next, in Section 1.4, we discuss the research goal and scope. Then, Section 1.5 defines the research questions and their approach. Finally, Section 1.6 contains a list with the deliverables of this research.

### 1.1 Context description

Taman Netherlands B.V. is a spray-casting company with two production locations, both located in the Netherlands. The headquarters with two large production areas is located in Tilburg and the secondary production area is located in Hengelo. Taman is a subsidiary of Retek. Retek is the world's leading manufacturer and marketer of resin-based household and garden consumer products. Examples of products made by Retek are garden sheds, garden furniture, garden accessories, storage boxes, baskets and trash cans.

Spray casting is a process that uses plastic pellets, colorant, and sometimes recycled material to make plastic products. A mix of these three types of granules are inserted in the machine via the hopper. Then, using heater bands and a long reciprocating screw, the granules are heated up and moved to the front of the barrel. When the granules are here, the plastic is molten. The screw then pushes the molten plastic with huge force into the mold where the plastic is cooled down maintaining the structure in the mold (Figure 2).

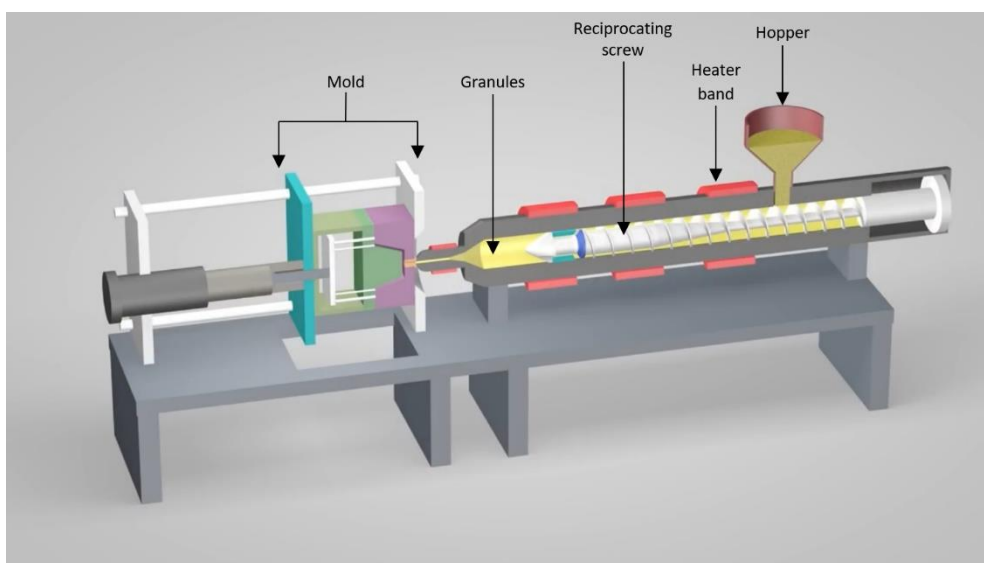


Figure 2: Mold casting process

A finished product often consists of multiple parts or semi-finished products. After all parts are made, they are assembled to get the finished products. Because this assembly process does not have to be executed immediately after production, the parts also do not have to be produced simultaneously.

Approximately 69% of the kilograms produced by Taman Hengelo is made for Retek. These products can be divided in two product groups. The first group are the garden furniture products such as seats, sofas, loungers and tables meant for outside use. The second group are the pet life products such as dog baskets and cat litter boxes. Besides production for Retek, Taman Hengelo also produces for her own customers. This product group is called the Business 2 Business products (B2B products). The products of this group are very diverse. A few examples of B2B products are wheelbarrows, urns, rain barrels, and compost bins. In 2018, 63% of the total production in kilograms is done for garden furniture, 6% is done for pet life, and 31% is done for B2B.

## 1.2 Research motivation

Currently, Taman is not satisfied with their customer service level (CSL). The CSL identifies what percentage of orders is delivered in time to their customers. This CSL level was 95.4% in 2018. Retek wants Taman to be at 98% for next year, so Taman has to deliver more orders on time. A lower CSL leads to unsatisfied customers that may start looking for other manufacturers. A higher CSL can lead to a higher satisfaction level of customers, which can lead to larger orders and potentially new customers.

## 1.3 Core problem

Figure 3 shows the problem cluster that we use to determine the core problem. A problem cluster gives a clear overview of the causes and consequences of a problem. The goal is to bring structure in the problem context and consequently identify the core problem. The core problem can be identified by going back in the problem cluster. This means finding the problems that do not have any preceding causes (Heerkens & van Winden, 2012).

A problem can only be a core problem if it is easy to influence and it does have a large impact. The red boxes in Figure 3 show the causes that are hard to influence, and the yellow boxes shows the causes that have a small impact. These problems can therefore not be identified as the core problem. The blue boxes show the causes that are easy to influence and do have a large impact. These are the potential core problems.

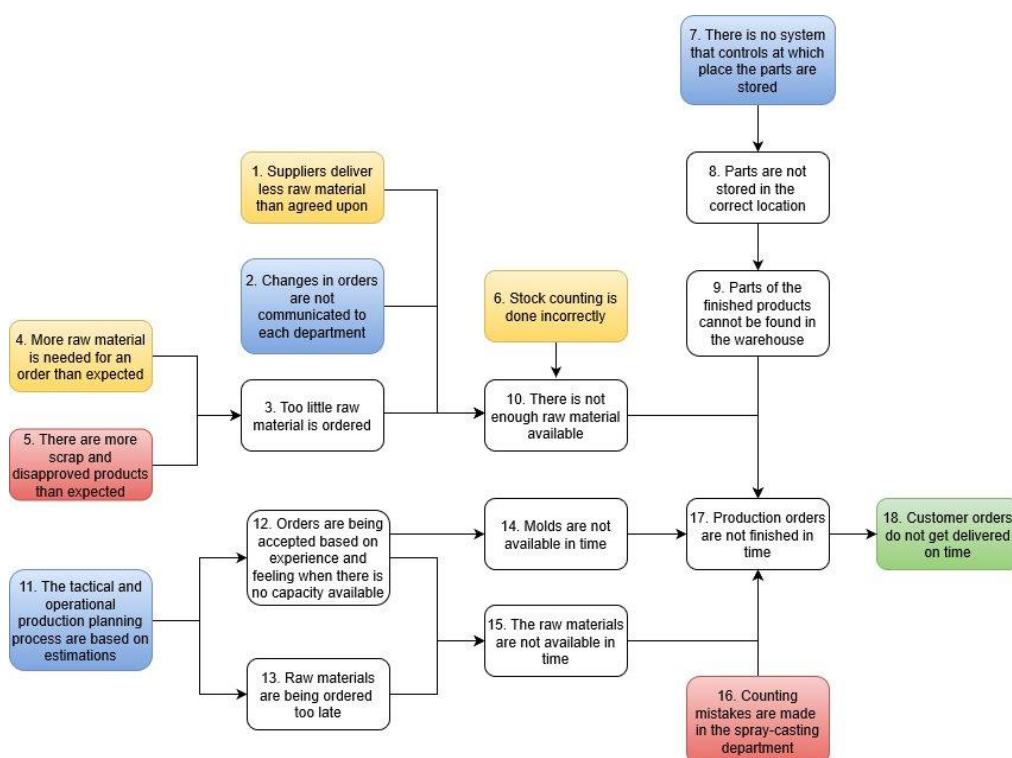


Figure 3: Problem cluster of failing to deliver on time

The research motivation, and therefore the start of the problem cluster, is stated in the green box: Customer orders do not get delivered on time (18). This is caused by production orders that are not finished in time (17). This problem has five causes which are, together with their preceding causes, explained at the bullet points below.

- The parts for the finished products cannot be found in the warehouse (9) due to the fact that these parts are not always stored in the correct locations (8). When the correct location is already full, the pallet driver puts the parts somewhere else in the warehouse. Because there is no system that stores the location of the parts (7), these parts cannot be found when needed. This problem is easy to influence and the impact when this problem is solved can be significant, therefore we consider this problem as a potential core problem.
- Another reason for the production orders that are not finished in time is that there is not enough raw material available (10). When there is not enough raw material available, the production cannot start. This problem can have four causes, which we mention below.

The first reason is the suppliers that deliver less raw material than agreed upon (1). Because, the arrival of raw material is not always fully checked, the shortage is often noticed just before production starts. Because this problem occurs not that often, the impact will be small. We therefore not consider this problem as a potential core problem.

The second reason for not having enough raw material available is about lack of communication between the different departments (2). When for example an order amount is increased and the purchaser is not informed, he can order too little raw material. This communication problem can have a large impact and is easy to influence, therefore we consider it as a potential core problem.

The third reason for a shortage of raw material is the incorrect counting of stock (6). At the start of the season, a stock count is done. When the stock levels according to the system differs from the actual counted stock, the stock levels of the system will be updated. When due to a counting mistake, the updated stock levels of finished products are higher than in reality, less raw material is purchased than necessary. When Taman finds out that there are less finished products in inventory than expected, more products have to be made. This can lead to a shortage of raw material. It is very hard to influence the counting tasks of employees. Some of them even say: 'Counting is the hardest thing in the world'. Because a stock count only happens once a year, it will have a small impact. We therefore do not consider it as a potential core problem.

The fourth reason for a shortage of raw material is the fact that too little raw material is ordered (3). This can have two causes: more material is needed than expected or there are more scrap and disapproved products than expected.

The discrepancy between expected requirements and actual requirements can be a cause of too little raw material being ordered (4). For a new product, a forecast is made of the amount of raw material needed for production. Also, when this discrepancy per product is very small, a production quantity of 10,000 products still leads to a significant shortage of raw material. The introduction of a new product, for which the expectation of raw material is too low, does happen very sporadically and therefore, we do not consider it as a potential core problem.

The discrepancy between expectation and reality of the volume of scrap and disapproved products can also lead to more raw materials needed than expected (5). Products can be scrapped when for example the mold is damaged or a color change did not happen flawlessly.

When a color change is happening, there are always a handful of products with a combination of the two colors. Sometimes the number of products with a combination of two colors is larger than expected leading to more scrapped products. Because the number of scrapped and disapproved products is hard to influence, we do not consider it as a core problem.

- The third reason for the production orders not finishing in time, are the molds that are not available in time (14).
- The fourth reason for the production orders that are not finished in time is caused by raw materials that are not available in time (15). Problem 10 is about not having enough raw material, so the raw material is indeed delivered in time, but something went wrong afterwards (see problem 1-6). Problem 15 is about not receiving the raw materials in time. This problem has two causes: Orders are accepted based on experience and feeling when no capacity is available (12) and raw materials that are ordered too late (13). Problem 12 is also a consequence of problem 14.

A cause of problem 12 and 13 is that the tactical and operational production planning is based on estimations (11). The tactical and operational production planner estimates roughly how much products have to be made and where to schedule these production runs in the production schedule. When a change occurs, he has to shift all planned production runs in his schemes. Because changes are made multiple times a week, it is almost a full-time job to reschedule all production runs due to these changes. When the planning is modelled based on data instead of only experience and then checked by the planner for potential risk factors, the chance of accepting orders while no capacity is available decreases. The implementation of an automatic tactical and operational production planning method purely based on data can have a high impact and is not hard to influence; we consider it as a potential core problem.

- The final reason for production orders that are not finished in time, are the counting mistakes in the spray-casting department (16). Similar to cause 6, counting mistakes can also be made at the spray-casting department. When more products are counted than produced, the run will consist of less products than planned and this can lead to orders that cannot be fulfilled in time. Because counting mistakes in this department happen rarely, it will have a small impact, we therefore do not consider it as a potential core problem.

#### Potential core problems

The problem cluster leaves us with three potential core problems. We choose to research the most important one. The enumeration below lists these 3 potential core problems.

1. There is no system that controls at which place the parts are stored
2. Changes in orders are not communicated to each department
3. The tactical and operational production planning process are based on estimations

Taman already investigates whether it is useful to introduce a warehouse management system that controls the storage location of all parts (1). Because this problem is currently being tackled, we focus on another core problem in this research.

The lack of communication between the different departments mainly occurs when orders get changed within two months of delivery. This information should be shared with all departments. In this way, the purchaser can alter his purchase order or place a new purchase order, the production planner can change the production plan, and the logistic planner can investigate where to store the extra products and if necessary, move finished products to external warehouses, so there is inventory space available for the extra products. The costs of a way to improve the communication between the

departments will be quite low, because no large investments are required to introduce a new communication plan. The improvement will be medium, because there will only be an improvement in the case of a changed order that is not communicated to every department.

‘The tactical and operational production planning process is based on estimations’ (3) is the third potential core problem. Because the estimations can differ significantly from the reality, it is very hard to get a correct overview of the capacities of the machines and molds. Without a good overview of these capacities, it is also very difficult to make correct decisions regarding accepting or declining a new order. Accepting new orders while actually not enough capacity is available leads to a lower CSL. Also, production runs with a longer production run duration than estimated lead to other production runs being shifted to a later time period. Consequently, this may result in orders that are delivered late, also leading to a reduced CSL. By having a tactical and operational production plan based on hard data, less changes will occur and more accurate production run durations are used which leads to more products being delivered on time.

The costs of setting up a tactical capacity plan can differ a lot. The costs can be very low when for example an internal project is executed, but when outsourcing the operational and tactical planning process or buying a software tool can lead to high costs. The improvement will be medium to high, because the planning is made on more accurate data leading to less changes in the planning and better decisions regarding accepting or declining orders. Since the effect is estimated to be larger than for the second potential core problem, we choose this third problem as the core problem for this research. Accordingly, the core problem in this research is: *“The tactical and operational production planning process is based on estimations”*.

#### 1.4 Research goal and scope

Based on the problem cluster, the research goal is to use tactical and operational planning techniques to create a production planning method that leads to an increase of orders being delivered on time from 95.4% to at least 98%, while minimizing the total costs.

In this research, the focus is on constructing a production planning and production scheduling method. We do not focus on the decisions that have to be made by the purchasing department and the logistics department.

#### 1.5 Research questions and approach

This section discusses the research questions and explains the structure of the report.

1. *How is the production scheduling process currently executed?*

Chapter 2 discusses the current situation at Taman. It explains the types of products produced and discusses the whole process from receiving a forecast until the delivery. It also discusses the current production planning and scheduling process. Interviews with the employees of Taman and the company website are the main sources of information for this chapter.

2. *Which models are available for constructing a feasible production schedule and which methods are available for optimizing a feasible production schedule?*

Chapter 3 includes a literature research that positions this research in the manufacturing planning and control framework. It then continues to discuss multiple production scheduling methods and production scheduling optimization techniques.

3. *How can a feasible production plan be constructed for Taman?*

Chapter 4 focusses on the method of constructing a feasible production plan for Taman by explaining all changes that must be executed in each step of the planning and manufacturing framework. We used the information in the literature for the construction of the method.

4. *How can an optimization method be used to improve a feasible production schedule for Taman?*

Chapter 5 discusses the implementation of an optimization method. We build an objective function and choose an optimization method. By carefully choosing the input parameters, we made the optimization method efficient. This chapter is a continuation on the last chapter where using input from the literature, and the use of heuristics and creativity result in an improved production schedule.

5. *What are the results of the production schedule before and after the optimization regarding the production schedule, and the machine and mold utilization?*

The first part of Chapter 6 analyses the results of the production schedule before and after the optimization. The focus lies on the differences between the objective value, machine utilization, and mold utilization. This chapter uses evaluation methods to analyze the results of the optimization method.

6. *How can the production scheduling model be verified and validated?*

The second part of Chapter 6 discusses the verification and the validation process. It also provides an instruction manual on how to use the model since this is part of the validation. This chapter uses expected results of employees and a validation plan to answer the research question.

## 1.6 Deliverables

This research contains some deliverables which are summed up below:

- A report containing a list of recommendations for Taman
- A production planning and scheduling model
  - This model is flexible, so it is easy to adapt when new machines are added, or new products are added.
  - The model can also be used for comparing different scenarios to see the difference in machine and mold capacity when for example a large order is accepted or rejected.
- An instruction manual for the employees of Taman that explains step-by-step how the production planning and scheduling model can be used.



## 2 Current situation

This chapter analyses the current situation at Taman Hengelo regarding the process from forecast to delivery where extra attention is paid to the production planning and scheduling process. First, Section 2.1 discusses the history of Taman. Then, Section 2.2 describes the three different product groups that are produced at Taman Hengelo. Thereafter, Section 2.3 focusses on the software programs used by Taman and what their function is. Subsequently, Section 2.4 investigates the current production planning and scheduling process. Then, Section 2.5 explains the complete process after the production scheduling process until delivering the order. Next, Section 2.6 explains the shortcomings of the current production planning and scheduling process and the goals for the improved production planning and scheduling process. Finally, Section 2.7 makes some concluding remarks regarding the current situation.

### 2.1 Introduction

This section frames the history of Taman Hengelo and discusses the relation between Taman Tilburg and Taman Hengelo.

#### Background of Taman Hengelo

In 1968, Frans Hartman founded Bemico in Hengelo which produced steel leisure products. Because the steel market became saturated, Hartman decided to change their production to resin-based products using spray-casting in 1982. Six years later, they changed their company name to Hartman and later to Hartman Outdoor Products. Their garden furniture products became very popular in this period. However, in 2005, Hartman is declared bankrupt and the factory is bought by the Enschedese Kunststof Fabriek (EKF). Six years later, Taman takes over EKF including all machines and personnel. Taman needed a second production area since their main plant in Tilburg could not keep up with the increasing demand.

#### Relation between Taman Tilburg and Taman Hengelo

The main production area of Taman is located in Tilburg with a total of 250 employees. Taman Hengelo is the expansion of Taman Tilburg, therefore all main decisions regarding Retek products are made in Tilburg. Hengelo has only 30 employees of which 20 are production employees and 10 are office employees. The functions of these office employees are in the fields of operations, planning, purchasing, warehousing, logistics, quality, technical support, and customer service of B2B customers. Each of these functions is executed by 1 or 2 employees. Most of these employees already work several years for Taman Hengelo, so they know how to execute the tasks of their colleagues when they are absent. Departments such as Sales, Finance, Supply Chain and Human Resource are only located in Tilburg.

The employees of Hengelo are expected to keep the plant of Hengelo running using the input provided by Tilburg. Tilburg makes decisions regarding which products to produce, which customers to deliver to, and what quantity to produce. Because Tilburg provides the input for the production in Hengelo, there is a lot of communication with Tilburg. Last-minute changes of the input provided by Tilburg leads to a lot of last-minute changes in Hengelo. Because Tilburg does not see the consequences for Hengelo, it is difficult for Tilburg to decide whether they choose to make changes or decide to look for other options. To evade this problem, Hengelo wants to also gather information themselves so they can make decisions regarding their own plant more on time instead of last-minute via Tilburg.

### 2.2 Product groups

As introduced in Chapter 1, there are three product groups manufactured by Taman Hengelo. These are garden furniture products, pet life products and products for B2B customers. The next three

paragraphs discuss these product groups in more detail. After that, an overview is given of the produced kilograms per product group for each month in 2018.

#### Garden furniture products

The main product group is the garden furniture products which includes chairs, sofas, tables, loungers, and water butts. The demand for these products is very seasonal dependent. The main part of the customer orders has to be delivered between January and May. In this way, the customers can sell their products to the end customers in the spring and summer season. Because the demand between January and May is larger than the maximum production capacity, Taman needs to start the production of garden furniture already in October and continue to May. Therefore, the stock levels of garden furniture will rise until January and from this moment slowly decrease because from January onwards, the quantity sold is higher than the quantity produced. At the end of the garden furniture season in May, the goal is to have hardly any stock of garden furniture left.

#### Pet life products

Taman Hengelo also produces pet life products. These products include litter boxes and carriers for cats, and baskets for dogs. In contrast to the garden furniture, the sale of pet life products is quite constant over the year. Because the total production of pet life products is small in comparison with garden furniture products, less attention is paid to this product group. Taman tries to fit the production runs of the pet life products between the production runs of the garden furniture products.

#### B2B products

Besides the products produced for Retek, Taman Hengelo also produces for B2B customers. The products made for these B2B customers are for example: a rainwater drain system, a wheelbarrow, a fish crate, a trolley, and an urn. All B2B customers supply Taman with the mold(s) for their products and Taman makes the products. Some of the B2B customers also supply Taman with the raw materials for their products. There are two large B2B customers and several smaller ones. Production for the large B2B customers takes place during the whole year. Production for the smaller B2B customers is mainly done between June and September because this is the least busy period for Taman.

#### Production in kilograms per month

The production season of Taman starts in August and ends in July. The months of June, July, August, and September are always the least busy months. These months are often used for installing and testing new molds and to make sure everything works before October, when the production quantity increases. In these summer months, Taman also does a stock count to update their stock values. Figure 4 shows the production in kilograms per month for each of the product groups.

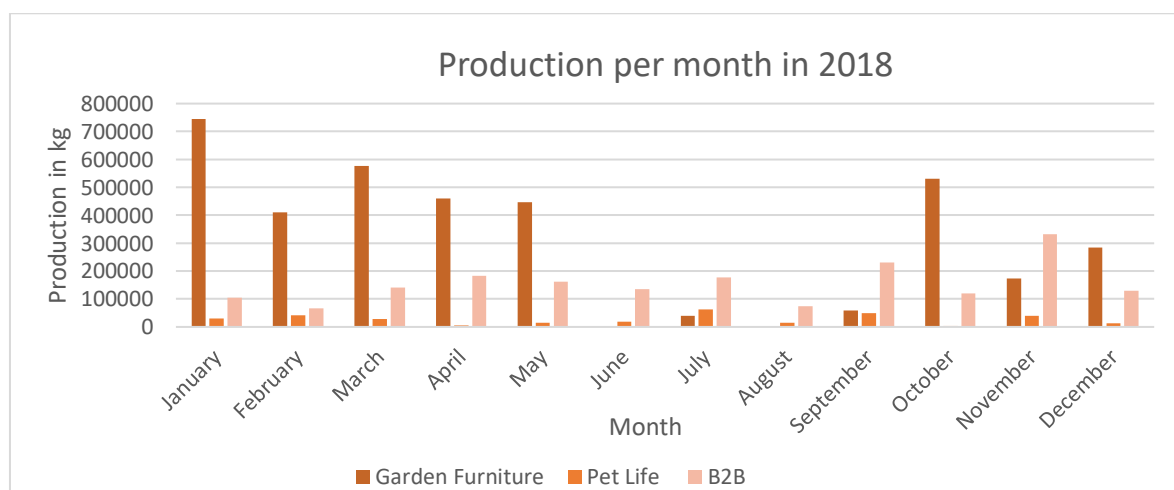


Figure 4: Production in kilograms per month for each of the product group

## 2.3 Software tools

This section describes four different software tools used by Retek. SAP is the main software program and all other software tools are connected to SAP.

### 2.3.1 SAP

Systeme, Anwendungen und Produkte (SAP) is an enterprise resource planning software to manage business operations and customer relations. All information including the bill of materials, production schedules, stock levels, forecasts, logistics, transactions and invoices is saved in SAP. It is a very useful tool for a large company like Retek to keep track of all this data in one place. By using SAP, all actions taken in the company are transparent and available for everyone in the organization.

### 2.3.2 EDB

Extended DataBase (EDB) is linked to SAP and provides a useful overview of the data available in SAP. It is mainly used for analysis of the KPIs of the company and to make comparisons between current data and historic data.

### 2.3.3 APO

Advanced Planning and Optimization (APO) is a software tool in which all forecasts for each customer are shown. These forecasts are divided in 'Preliminary Forecasts' (PF) and 'Ready To Produce' (RTP). The PF is the unconfirmed forecast. The RTP is the forecast that is already confirmed by the customers and therefore production can be planned. APO is very useful for the input data of the master production schedule.

### 2.3.4 kMES

Manufacturing Execution System (kMES) is a short-term machine planning tool that shows in real time which products are made on which machines and which molds are used. It also shows the expected and the actual cycle time of the products, the number of products that are already produced and the number that still has to be produced. It is connected to SAP; therefore, SAP is always up to date with the real-life production status.

## 2.4 Production planning and scheduling process

This section describes the current production planning and scheduling process step by step. The production planning starts with a rough forecast based on historic data. Thereafter, a forecast is made based on the customer inputs. Subsequently, a master production schedule is made based on this forecast. Then, a 'color image' is made that gives a rough overview of which parts are produced on which machine and in which period. Finally, a production schedule is created based on this color image. The first two steps are mainly executed by Taman Tilburg, the third step is executed by SAP and the last two steps are executed by Taman Hengelo. Subsections 2.4.1 until 2.4.5 discuss these steps in detail.

### 2.4.1 Rough forecast

The rough forecast is a process that gives a first prediction of the number of products that will be made in the next season. This rough forecast is often made in June and based on historic data and predictions of the sales department. The rough forecast of the garden furniture and pet life products is done by Taman Tilburg and the rough forecast of the B2B customers is done by Taman Hengelo. The forecast of the B2B customers is also based on historic data and predictions of the sales manager.

Based on the rough forecast, Taman Tilburg can decide whether the product range of Taman Hengelo remains the same. Sometimes, a product will be switched with another production location, a product will be added to the product range of Hengelo or a product will be removed from the product range of Hengelo. These decisions are quite substantial and therefore often taken in June, after the busiest

period. When a product is added to the product range, the required molds are sent to Hengelo. These molds are then installed on the machines and tested. Next, the new molds, and product details should be added to SAP. This whole process is very time consuming and ideal to be performed in the tranquil summer period.

#### 2.4.2 Customer based forecast

At the start of the new season, each customer is asked to make a preliminary forecast. This is a forecast showing the quantity and type of products forecasted by the customers. This forecast is not binding and purely used for Taman to start their tactical planning process. When the preliminary forecast is very large, Taman can decide to start production of the garden furniture already in September instead of October. When forecast is low, Taman can choose to start their production in November.

When a customer wants to place an order, they have to notify the sales department at least three months in advance. The customer has to state the number of products they want to buy and in which month they want the products to be finished. At this moment, the number of products the customer wants to buy is deduced from its preliminary forecast. This confirmed forecast is also called the 'Ready to Produce' (RTP) quantity. This RTP quantity is placed in SAP, so the planner knows all production quantities that have to be made and the month that these production quantities need to be finished.

Once an RTP order is placed, the customer can, generally speaking, not change the RTP quantity. However, the sales department still often accepts a proposed RTP change by the customer. The main reason for this is that the sales department is assessed based on their customer satisfaction and the number of sales they have made instead of the overall functioning of the company. An increase of RTP quantities leads to a new production plan that can lead to orders being shifted and therefore being delivered late. However, when Taman always declines a change of the RTP amount, the customer can decide to go to another garden furniture manufacturer that is more flexible.

At least one month before the date of the RTP, the customer must place its corresponding purchase orders. Some customers place in September already their RTP orders for the whole season and change their RTP orders to purchase orders a few months before the order date. But other customers place their RTP orders and purchase orders just in time.

This process is the same for both the Retek products and the B2B products. However, there is one exception. There is a contract with one B2B customer that states that one of the machines is reserved for him every first week of the month. That customer delivers every month a certain amount of raw material and Taman produces the number of products that can be made using the provided raw material. When all raw material is used or five production days have passed, Taman can use this machine again for other production tasks.

#### 2.4.3 Master production schedule

Based on the RTP orders and the purchase orders, SAP constructs the master production schedule (MPS). An MPS is a plan that shows per week the number of products ordered for each product. This includes both the RTP orders and the purchase orders. Since this MPS shows for each week and for each product the number that has to be ready for delivery, the planner can construct a production plan. In this MPS, the orders of different customers with the same product and delivery date are combined. Therefore, it is difficult after the MPS-step to figure out which delivery order corresponds to which customer.

#### 2.4.4 Color image

Based on the master production schedule, the planner can start constructing a production plan. He uses the Bill of Materials (BOM) for finding out all the parts that are needed for the finished product.

Then, by using this BOM and the MPS, the planner ascribes the production runs of the parts to the machines.

Figure 5 shows a part of the color image made by the planner. The left columns show the machines and their corresponding tonnage. The top row shows the date where each grey column indicates a weekend. The orange colored squares show that a certain part is produced, the blue squares indicate a mold change is done, and the yellow squares show that no production is executed.

Ton	Machine	18-mrt		25-mrt		1-apr		8-apr		
350	20 / 4516									
650	21 / 4543	Back california		Back california		Back california		Back california		
650	22 / 4544	Seat california		Seat california		Seat california		Seat california		
650	23 / 4525	Back cover california		Back cover california		Back cover california		Back cover california		
650	24 / 4526	font cover california		font cover california		font cover california		font cover california		
650	25 / 4541									
650	26 / 4542									
350	27 / 4517			Table plugs columbia		Table leg plugs columbia				
550	28 / 4524	Parts waterbutt		Parts waterbutt						
2700	30 / 4538	chair+seat+cover columbia		Jaipur		Jaipur		Aufenacker		
1000	51 / 4535	Daytona		Daytona						
1000	52 / 4534			Legs Jaipur		Legs Jaipur				
1000	54 / 4540			left side california		left side california		left side california		
1000	55 / 4539			right side california		right side california		right side california		
800	56 / 4530	Akola		Waterbutt deksel		Waterbutt deksel				
800	57 / 4531	Akola		Drawer		Drawer				

Figure 5: Part of the color image made by the planner

The planner constructs the color image for a whole year. The first version is made when the customer-based forecast is known. When an RTP quantity or due date changes, or when a customer order quantity or due date changes, he also changes this in his color image. Especially shifting production runs in the start of the season leads to a lot of changes further down in the color image. Because changes in the forecasts and MPS happen quite frequently, the planner spends a lot of time updating the color image, so he always has a good overview of the production plan during the season.

#### 2.4.5 Production scheduling process

Based on the color image, the planner starts filling the production schedule in SAP. The planner cannot directly implement the color image as the production schedule because the color image is not always feasible. It is used as a guideline for the production scheduling process. Based on the color image, the planner constructs a production run and assigns it to a machine. He also indicates when a mold change has to be performed. The production schedule is made for 8 weeks ahead.

The way the production is planned is not optimal, because first production runs are made and then tried to fit in the production schedule. When the production run does not fit, the planner moves the run to another date or to another machine where it does fit. So, the planner uses a trial and error method for the production scheduling process. He tries to plan the finished date of the production runs to be always at least two days before the due date. In this way, an unexpected delay does not immediately lead to orders being delivered late and therefore a lower CSL.

Changes in the color image due to changes in the MPS can lead to short-term changes in the production schedule. Changes in the production schedule are avoided as much as possible because it leads to a lot of stress for the planner. When a change in the production schedule still has to be made, the purchaser is notified so he can purchase the required materials for the new production schedule. Also the warehouse manager is notified and he checks whether there is enough stock space available. Finally, the logistics manager is notified, so he can check whether a transport is required for the new production schedule or whether a planned transport has to be canceled.



## 2.5 Process from purchasing until delivery

This section describes the process from purchasing until delivery. First the purchasing process includes the process of obtaining all materials for the production. Then, the production process starts using these materials. Thereafter, the warehousing process includes the process of storing the parts and finished products. Finally, the delivery process explains the process of getting the finished products from the warehouse to the customer. Subsections 2.5.1 until 2.5.4 discuss these processes in detail.

### 2.5.1 Purchasing process

The largest part of the purchased materials are the plastic pellets and colorant. These are the two most important raw materials for the products. Sometimes, recycled material is also added to the raw material. Recycled material leads to a less robust product, but the products that do not have to withstand high forces can be made using recycled material. The recycled material can be made by shredding scrapped products. A product can be scrapped when, for example, it does not meet the quality requirements.

Besides the raw materials, the purchaser also orders boxes, non-plastic products, packing material, stickers, cushions and pallets. The raw materials, packing material, stickers and pallets are ordered from Dutch companies and the boxes, non-plastic components, and cushions are ordered from other European countries and China. Because suppliers outside the Netherlands quite frequently deliver late, it is not possible to produce just in time. The purchaser chooses to order the products of these suppliers a week before they are needed to reduce the chance of having to make changes in the production schedule. The extra inventory costs that are attached to ordering a week in advance outweigh the consequences of changing the production schedule.

### 2.5.2 Production process

The production process is executed based on the production schedule. Before the production of a part can start, the mold corresponding to the part has to be mounted in the machine. There are mold change employees who change molds using cranes. Depending on the size of the machine in which the mold is mounted, a mold change time takes between 30 minutes and 4 hours. After a mold change is done, the raw material is moved to the machine. Now, test spray-casting can start. A few parts are test sprayed to check whether everything works like it is supposed to. When this is the case, the production run starts. Figure 6 shows an example of a machine at Taman.



Figure 6: Spray-casting machine at Taman

When a new production run starts with the same part as the last run but another color, the mold is not changed. The colorant of the raw materials is changed which results in a new color. However, when a new colorant is added, the first few parts will have a hybrid color of the two colors. It takes some time for all colorant of the first color to leave the machine. These parts are removed from the production batch and shredded.

### 2.5.3 Warehousing process

After a production run is finished, there are two options. The parts are assembled immediately after production or the parts are moved to the warehouse. When multiple parts of the same sub-assembly are produced at the same time, these parts will be assembled immediately after production and the sub-assembly will be moved to the warehouse. If the parts are not part of a sub-assembly or when the parts are not produced at the same time, the parts are moved to the warehouse before assembly. The warehouse where the parts and the sub-assemblies are stored is owned by Taman and located behind the production hall. After all parts and sub-assemblies of a finished product are produced, everything is packed in the corresponding carton box. Sometimes cushions, non-plastic products and packing materials are added as well. These boxes including finished products are then put on pallets for transport. On average 80 pallets of finished products are produced each day.

There are two options for the boxes with finished products. They are moved to the docking area of Taman or they are moved to an external warehouse. When the products will be picked up within three days after assembly, the parts are moved to the docking area of Taman (Figure 7). All pet life products and almost all products for B2B customers are moved to the docking area as well. Some of the products for B2B customers are stored outside instead of in the docking area. The garden furniture products with a delivery date of more than three days after assembly are moved to the external warehouses to be stored. Because the volume of a finished product is quite large, not all these products can be stored at Taman. Taman stores her finished garden furniture products in four different warehouses, so storing place has never been a bottleneck for Taman.



Figure 7: Docking area of Taman

#### 2.5.4 Delivery process

At the moment of the delivery date, the finished products are sent to the customer. The customers in Europe are supplied by truck. The customers in Africa, South America, and North America are supplied by ship. A delivery is always done in full truck load (FTL). This is possible because customers can only place orders of multiples of FTLs. When a delivery is done of a batch of products that are stored at an external warehouse, the external warehouse loads the truck and sends it on its way.

When a part of the order consists of products that are made in Tilburg, the truck first loads the required products in Hengelo and thereafter loads the remaining products in Tilburg. Subsequently, the truck drives to the customer. In this way, it is possible that the trucks are not fully loaded when going to Tilburg. When this is the case, often another set of products that also has to go to Tilburg are sent with this same transport. There are on average 3-4 trucks leaving Taman Hengelo per day with only finished products.

### 2.6 Shortcoming and goals of production planning and production scheduling process

This section discusses the planning and scheduling process after the MPS is made; the constructing of the color image and the production schedule process. The current way these processes are done has two types of shortcomings. First, the process is not flexible and second, the process is not efficient. Based on these shortcomings in the current situation, some goals for the new production planning and production scheduling process are discussed. Subsection 2.6.1 and 2.6.2 discuss the two shortcomings in detail and subsection 2.6.3 explains the goals of the new production planning and production scheduling process.

#### 2.6.1 Flexibility of the production planning and production scheduling process

Changes in the production planning and in the MPS happen quite frequently. The main reason for a change in the production planning is caused by the sales department of Tilburg accepting an order change. Also, an unexpected machine failure or a delay in the ordered raw materials can lead to a change of the production planning. Such a change in the RTP leads to a change in the MPS which leads to a change in the color image and finally a change in the production schedule.

The current process of constructing the color image, and based on that, construct the production schedule is not flexible at all. A small change in the number of products to produce costs a lot of time to process in the color image and the production schedule. This process should be improved so that it becomes easier to apply changes and evaluate the results.

#### 2.6.2 Efficiency of the production planning and production scheduling process

In the current situation, the color image is made manually based on the MPS. Thereafter the production scheduling process can start. Because the color image does not result in a feasible production schedule, the scheduling process is also done manually. These two manual steps are not efficient to do by hand and can be automated.

#### 2.6.3 Goals of the production planning and production scheduling process

To make the process of production planning and production scheduling more flexible and efficient, it would be a good start to change the color image process in such a way that it results in a feasible production schedule that in theory can get implemented immediately. To improve the efficiency even more, the color image should be constructed based on hard data instead of estimations. This leads to a more accurate input for the production scheduling and therefore a better output. In the current color image, the length of a production run is not calculated, but based on predictions. For example, 3000 pieces of the lounge 'Jaipur' are needed. The planner predicts that this will take around two weeks and plans the production of the Jaipur for two weeks while this process actually takes 9 working days. Besides, the mold changes in this color image are all placed on Monday (see Table 1), but this is not



the case in reality. Moreover, there is a limit of the number of mold changes that can be executed in one day.

When constructing a feasible production planning method, so that the steps of constructing the color image and the production schedule can be combined to one step, a few goals should be kept in mind. These goals are mentioned below:

1. The CSL level as a result of the production schedule should increase from the current 95.4% to at least 98%.
2. The storage costs must be minimized. So, production should finish as closely as possible before the due date.
3. The lateness must be minimized. If an order is delivered late, the lateness indicates the number of days this order is delivered late.
4. The number of mold changes should be minimized. A mold change is the process of changing the mold on a machine. A mold change leads to less production time and there are some restrictions regarding the number of mold changes that can be performed per day. Less mold changes lead to a more fluent production process.
5. The production planning model must incorporate the days available for production, so holidays and weekends that production is closed may not be available for production in the production plan.
6. The production planning model must be adaptive. It must be easy to add new machines, molds or products. It also must be easy to test new scenarios when for example a few weekends are available for production when demand increases with 20.000 products.
7. The production planning model must be easy to use for the employees of Taman.

## 2.7 Conclusions

The main production area of Taman is located in Tilburg. Because their production area became too small, they bought EKF in Hengelo and took over their employees and machines. Taman Hengelo now produces approximately 7.5 million kilograms of finished products last year. The products made by Taman Hengelo can be divided in three groups. These are garden furniture products, pet life products and products for B2B customers. The distribution of kilograms produced of each product group are respectively 63%, 6% and 31%.

The production planning and production scheduling process consists of multiple steps. It starts with a rough forecast based on historic data. Thereafter, a forecast is made based on the customer inputs. Subsequently, a master production schedule is made based on this forecast. Then, a 'color image' is made that gives a rough overview which parts are produced on which machine and in which period. Finally, a production schedule is created based on this color image. The first two steps are mainly executed by Taman Tilburg, the third step is executed by SAP and the last two steps are executed by Taman Hengelo. These last two steps are also the steps that can be improved.

At this moment, the steps of constructing the color image and the production schedule are not flexible and efficient enough. These two separate steps require a lot of time and small changes can not be implemented easily. The goal is to replace the color image and production schedule step with one step leading to a feasible production schedule based directly on the MPS. This step has some goals it must incorporate. The most important goals are that the production schedule must be feasible, the CSL level must be at least 98%, the costs must be minimized, the production planning model must be adaptive, and finally, the production planning model must be implemented and easy to use by the employees of Taman.



### 3 Literature review

This chapter investigates the literature relevant for our research. It consists of three sections. First, Section 3.1 introduces the manufacturing planning and control framework and explains each step. Then, Section 3.2 focusses on different production scheduling methods. Finally, Section 3.3 discusses two optimization methods.

#### 3.1 Manufacturing planning and control framework

Manufacturing planning and control (MPC) is a framework that identifies the required steps in the field of production planning and capacity planning to get to a production schedule. Figure 8 shows a simplified version of the MPC (Vollman, Berry, & Whybark, 1997). The MPC framework addresses decisions regarding the acquisition, utilization and allocation of production resources to satisfy customer requirements in the most efficient and effective way (Graves, 1999). The goal is to ensure that materials and equipment are available when needed and that the production planning process is efficient.

The first step of the MPC consists of the sales and operations planning (S&OP) and the aggregated capacity planning (ACP) and is based on strategic decisions. Subsequently, the master production scheduling (MPS) and the rough-cut capacity planning (RCCP) are carried out. These two processes are based on tactical decisions. Third, the materials requirements planning (MRP) and capacity requirements planning (CRP) are done. These two processes are also based on tactical decisions. Finally, the production scheduling and the output control are executed. These processes are based on operational decisions. Subsections 3.1.1 until 3.1.3 explain in detail the processes that are executed in each decision level.

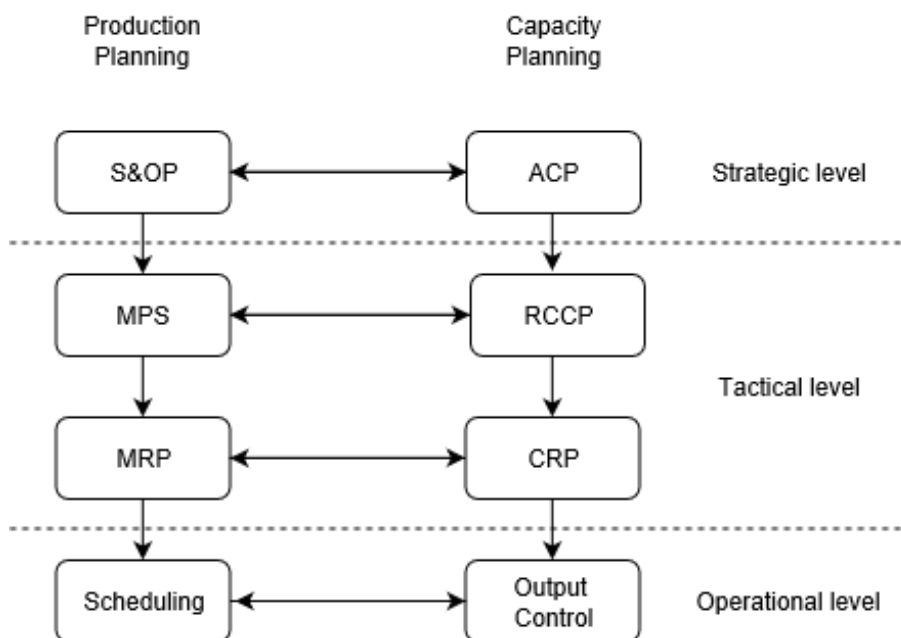


Figure 8: MPC Framework

##### 3.1.1 Strategic level

Decisions made in the strategic level are long-term decisions. These long-term decisions always try to pursue the vision of the company. Within this strategic level, decisions are made regarding the production planning and the capacity planning. The most important strategical processes in these planning areas are respectively the sales and operations planning and the aggregated capacity planning. Subsections 3.1.1.1 and 3.1.1.2 explain these two planning processes in detail.

#### *3.1.1.1 Sales and Operations Planning*

The goal of the sales and operations planning (S&OP) is to create a balance between the sales plan and the production plan. This requires two actions: The demand has to be modified to match the production constraint and the available capacity has to be modified to match the sales plan. The demand can for example be modified by advertisement, price changes, or the introduction of a new product. The available capacity can be modified by for example outsourcing, subcontracting, or working overtime.

#### *3.1.1.2 Aggregated Capacity Planning*

Aggregated Capacity Planning (ACP) is done simultaneously with S&OP. ACP can be used to get a quick overview of the capacity levels of the resources per month based on a rough estimation of the number of items to produce. The ACP gives a first impression of the number of resources required for the number of products to produce. The S&OP together with the ACP lead to the Master Production Schedule and the Rough-Cut Capacity Planning.

#### *3.1.2 Tactical level*

Decisions of the tactical level are medium-term decisions. These decisions relate to the implementation of strategic decisions. The decisions made regarding production planning and capacity planning are first respectively the master production scheduling and the rough-cut capacity planning and thereafter the materials requirements planning and the capacity requirements planning. Subsections 3.1.2.1 until 3.1.2.4 discuss these four processes in detail.

##### *3.1.2.1 Master Production Schedule*

The Master Production Schedule (MPS) is a schedule that indicates when and how much of each product will be made. The MPS depends on a lot of factors such as forecast demand, production and inventory costs, lead time, working hours, machine capacity, and inventory levels. Herrera & Thomas (2009) defines the MPS as: “a plan with the goal of scheduling production quantities in each period of the planning horizon, minimizing the cost and maximizing the bottleneck utilization.” This MPS can be vertically integrated which consists of the elaboration of the MPS so that it remains feasible at an operational level. This vertical integration can be approached in two ways: operational constraints can be added, or a mathematical and simulation model can be combined to ensure feasibility.

##### *3.1.2.2 Rough-Cut Capacity Planning*

Rough-cut capacity planning (RCCP) is a medium-term capacity planning method that verifies whether there is sufficient capacity available to meet the capacity requirements. RCCP calculates a rough estimate of the workload of the resources by the proposed MPS. This workload is compared to the maximum available capacity per resource to check whether the MPS is feasible. The RCCP can be set up using finite capacity planning or infinite capacity planning. In finite capacity planning, the due date of the orders is relaxed and lateness is allowed. This is also called the resource-driven approach. In infinite capacity planning, the available capacity is relaxed so there is no limit in available capacity. The available capacity can be affected by for example: working overtime, subcontracting, or adding or removing machines. This is also called the time-driven approach (De Boer, 1998). In most companies, a hybrid approach is used to find the optimal balance between irregular capacity and lateness.

##### *3.1.2.3 Material Requirements Planning*

The material requirements planning (MRP) is the next step after the MPS and the RCCP. The MRP can be deduced from the MPS using the Bill of Materials (BOM). The BOM is an overview of all the parts of which a finished product is composed. The result of the MRP is a plan that shows for all the parts how much is needed and when it is needed.

There are two processes with the abbreviation: MRP. Material Requirements Planning (MRP I), which focusses solely on internal component planning, and Manufacturing Resource Planning (MRP II), which is much broader and focusses also on the resources and their restrictions, such as machine capacities and employee availability. Overall MRP II is seen as the combination of MPS, MRP I and Scheduling. So, MRP II is more integrative and strategically oriented than MRP I. (Comelli, Gourgand, & Lemoine, 2008)

#### *3.1.2.4 Capacity Requirements Planning*

Capacity requirements planning (CRP) is executed based on the MRP. This process is used to determine the available production capacity of a company. It first assesses the MRP and then analyzes the company's actual production capacity to see if the MRP is feasible. If the MRP is not feasible, it is changed in such a way that it becomes feasible.

#### *3.1.3 Operational level*

Decisions of the operational level are short-term decisions. These decisions are made on a weekly or daily basis and are based on the decisions made in the tactical level. The decisions made regarding production planning and capacity planning result in respectively the production scheduling process and the output control process. Subsections 3.1.3.1 and 3.1.3.2 discuss these processes in detail.

##### *3.1.3.1 Scheduling*

When the MRP is finished, all production tasks can be scheduled in the production plan. There is a large variety of scheduling methods that can be used. A few of these methods are explained in Section 3.2. There are basically two types of production scheduling methods: The production runs in the production schedule can be scheduled from the end of the season to the start of the season or from the start of the season to the end of the season. When scheduling from the end to the start, the orders are scheduled so that no lateness occurs, but this can result in an infeasible schedule. When scheduling from the start to the end, the production tasks are planned in chronological order resulting in a feasible capacity plan but with more lateness and inventory costs.

##### *3.1.3.2 Output Control*

The output control is a technique for capacity control where the planned production and actual outputs are monitored. If the planned production is not equal to the actual output, the cause will be investigated and when necessary, the production schedule will be adjusted.

### *3.2 Production scheduling methods*

There are many production scheduling techniques, but the focus in this research is on priority rule based scheduling. Priority rule based scheduling is an often used algorithm, because it is a fast and easy method to get to a feasible production schedule. The priority rule based scheduling method consists of a priority rule and a generation scheme. These two parts are discussed in subsections 3.2.1 and 3.2.2.

#### *3.2.1 Priority rule*

A priority rule gives a priority to all production orders that have to be scheduled. The priority of the production orders is the sequence in which the production orders are scheduled. There are many different priority rules of which the earliest due date and the shortest processing time priority rules are well known. The earliest due date method schedules the orders based on their due date starting with the order with the earliest due date. This priority rule tends to minimize the maximum lateness. The shortest processing time method schedules the orders based on their processing time length. This priority rule schedules the order with the shortest processing time first. This priority rule tends to minimize the mean flow time which is the average finished date of all jobs.

### 3.2.2 Generation scheme

A generation scheme is a method of scheduling a list of production orders. The sequence of the production runs that are scheduled is determined by the priority rule. When scheduling the items, a serial schedule generation scheme or a parallel schedule generation scheme can be used. Both generate a feasible schedule. Subsections 3.2.2.1 and 3.2.2.2 discuss these two types of generation schemes.

#### 3.2.2.1 Serial Schedule Generation Scheme

A serial schedule generation scheme (SSGS) selects the production order with the highest priority. This production order is then scheduled on the machine that can fit in this production order the earliest as possible. Thereafter, the next production order with the highest priority is selected and this process is repeated until all activities are scheduled.

#### 3.2.2.2 Parallel Schedule Generation Scheme

A parallel schedule generation scheme (PSGS) selects the machine with the earliest available time slot. Now the priority list is checked starting with the production order with the highest priority. When a production order can be scheduled on that machine taking into account all constraints, the activity is scheduled. When no production order can be scheduled, the next machine with the earliest available time slot is selected. After a production order is scheduled, the process is repeated until all production orders are scheduled.

### 3.3 Optimization techniques

After a feasible production schedule is created, local search techniques can be used to improve the initial production schedule. Local search techniques make small changes to the current production schedule and evaluate whether the new schedule is better than the current schedule. There are four frequently used operators in local search techniques that result in small changes. These are:

- Move operator: a production order is moved to another machine or another start date
- Swap operator: a production order is swapped with another production order
- Merge operator: two production orders are merged together as one production order
- Split operator: a production order is split into two different production orders

If a schedule can be obtained by performing a small change on the current schedule, the new schedule is called a neighbor of the current schedule. At each iteration, the local search technique evaluates one or more neighbors depending on the algorithm and the (best) neighbor is then accepted or rejected based on a criterion that also differs per algorithm (Pinedo, 2005).

The choice whether a neighbor is accepted or rejected depends on the objective value of the current schedule and the objective value of the neighbor schedule. The objective value of a schedule is a way to assess the production schedule. This value can be based on, for example, inventory costs, lateness, personnel costs, and machine costs. The objective value is used to be able to compare different production schedules. When two production schedules are made and their objective values are calculated, the production schedule with the best objective value is also the best production schedule.

The two most used local search algorithms are simulated annealing and tabu search (Farnane, Minaoui, & Aboutajdine, 2018). These are both advanced local search techniques because they can escape from a local optimum. This means that these techniques can accept worse outcomes in order to arrive in a better local optimum or a global optimum. Basic local search techniques do not have this feature. Subsections 3.3.1 and 3.3.2 explain simulated annealing and tabu search in detail.

### 3.3.1 Simulated annealing

Simulated annealing has its origin in the fields of material science and physics. It was first developed as a simulation model for describing the physical annealing process of condensed matter. Nowadays, simulated annealing is used in many different fields including production scheduling. It is popular due to its relative ease of implementation, convergence techniques and its possibility to escape from a local optimum. (Henderson, Jacobson, & Johnson, 2003).

Simulated annealing starts with a feasible initial schedule, also called the first current schedule. This first current schedule can be constructed in combination with a generation scheme. Then, using an operator, a so-called neighbor schedule  $X^n$  is selected from the neighborhood of the current schedule  $X^c$ . This selection can be in a random or an organized way. Thereafter, the objective value of this neighbor schedule,  $E(X^n)$ , is compared to the objective value of the current schedule,  $E(X^c)$ . If  $E(X^n) \leq E(X^c)$ , the neighbor schedule  $X^n$  becomes the current schedule  $X^c$ . In case  $E(X^n) > E(X^c)$ , there is a probability that the neighbor schedule  $X^n$  becomes the current schedule  $X^c$ . This

probability can be calculated by:  $e^{\frac{E(X^c) - E(X^n)}{T_i}} > y$ .

In this formula  $T_i$  is a control parameter also referred to as the temperature. This temperature is dependent on  $i$  which reflects the current number of temperature changes. The number of iterations after which the temperature decreases is equal to the length of the markov chain. When the markov chain length,  $m$ , reaches  $M$ , the next temperature cycle starts. There are multiple methods of calculating the next temperature. The most used method follows an exponential cooling schedule:  $T_{i+1} = \alpha T_i$  where  $\alpha \in (0,1)$ .

At the start of the algorithm, the temperature will be high and during the algorithm, the temperature will decrease until it approaches zero. Due to this temperature characteristic, the probability that a neighbor schedule with a worse objective value than the objective value of the current schedule is accepted decreases over time. Because the difference between the objective value of the current schedule and the objective value of the neighbor schedule is taken into account, the probability of accepting a far worse neighbor also has a low probability (Pinedo, 2005). Summarizing, at the start of the algorithm, a lot of worse neighbors are accepted. This number decreases over time until the temperature is almost zero when (almost) no worse neighbor solutions are accepted.

There are several stop criteria that could be used to prevent too many iterations. For example, a stop temperature can be chosen. When the temperature,  $T_i$ , reaches this stop temperature, the algorithm stops. Another method can be that the algorithm stops when after a certain number of iterations,  $I$ , without improvements. Figure 18 in Appendix A shows a flowchart of the explained simulated annealing algorithm.

### 3.3.2 Tabu search

Tabu search is in many ways similar to simulated annealing in that it also moves from one schedule to another with the next schedule possibly worse than the one before. The main difference between the two algorithms is that the acceptance-rejection criterion is a probabilistic process in simulated annealing and a deterministic process in tabu search.

Tabu search starts with a feasible initial schedule. Using operators, all neighbor schedules,  $X^{c_n}$ , of the current schedule are evaluated. The neighbor schedule with the best objective value that is not in the tabu list is chosen, even if this objective value is worse than the objective value of the current schedule  $X^k$ . The neighbor schedule that is chosen becomes the new current schedule.

During the tabu search process, a tabu list of mutations is kept. A mutation is a change initiated by an operator, for example, switch production order 4 and 6. When such a mutation is on the tabu list, the

procedure is not allowed to construct a neighbor schedule using this mutation. The length of the tabu list is preset and often the 'magic' length of 7 is proposed (Dammeyer & Voß, 1993). After each iteration, the reverse mutation is entered at the top of the tabu list and all other mutations are shifted down one position so that the last mutation is deleted from the tabu list. By placing the reverse mutation on the tabu list, the tabu list avoids the possibility of returning to a local minimum that already has been visited before. The length of the tabu list should be chosen carefully. When a tabu-list is too small, cycling may occur; if it is too large the search may be unduly constrained (Pinedo, 2005). The stop criterion of tabu search is often a predetermined number of exchanges without improvement,  $N$ . Figure 19 in Appendix A shows a flowchart of the explained tabu search algorithm.



## 4 Solution design: Production schedule

This chapter describes the process we have gone through and the decisions we have made to construct a feasible production schedule while taking into account all constraints. Section 4.1 elaborates on the manufacturing planning and control framework introduced in Chapter 3 and draws conclusions on the steps that have to be changed to create the production schedule. Thereafter, the three steps that have to be changed are discussed. First, Section 4.2 describes the changes in the master production schedule step. Then, Section 4.3 describes the changes in the materials requirements planning step and Section 4.4 describes the changes in the scheduling step. Thereafter, Section 4.5 shows the result of the new production schedule. Finally, Section 4.6 draws some conclusions regarding this chapter.

### 4.1 Manufacturing planning and control scope

The manufacturing planning and control framework is first explained in Section 3.1. This framework consists of a production planning part and a capacity planning part (Figure 9). We only focus on the production planning part while incorporating all capacity constraints. The production planning consists of four steps: S&OP, MPS, MRP, and Scheduling. We now discuss for each step the actions that have to be taken to get to a feasible production schedule.

1. S&OP is similar to the rough forecast and the customer based forecast discussed in Subection 2.4.1 and 2.4.2. For all Retek products, this step is fully executed by Tilburg. For the B2B customers, this step is executed by Taman Hengelo. Nothing is changed to this step with respect to the current situation.
2. The process of getting from a good forecast to an MPS is discussed in Subsection 2.4.3. This process is automated by SAP based on the RTP values and the purchase orders of the customers. All Retek products are included in this MPS, but not all B2B customers of Taman Hengelo are included. It is important that all RTP and purchase orders are present in the MPS because the MPS is the basis of the production schedule. In Section 4.2, we explain how we manage to expand the MPS with the RTP and purchase orders of the B2B customers.
3. The process of getting from the MPS to the MRP is not an indistinct process in the current situation. The planner constructs a color image based on the MPS while using the BOM (Subsection 2.4.4). The planner does not calculate the exact amount of time a part has to be produced for the production order, instead, he estimates the number of days the part has to be produced. To construct a good production schedule, the schedule has to be based on hard data. We therefore construct a method that the MRP can be made using the MPS and machine, mold, and product related data. In Section 4.3, we explain this process in detail.
4. The final step is to get from the MRP to a feasible production schedule. In the current situation, the planner schedules each production run of the color image in the production schedule one by one and makes some changes when a production run cannot be scheduled (Subsection 2.4.5). This process takes very long and a small change in the color image can lead to a long process of rescheduling. We therefore construct a new method to get from the MRP to a feasible production schedule. In Section 4.4, we explain this process in detail.

The first step does not have to be changed in order to improve the production schedule. In the second step, only small changes have to be executed (blue square in Figure 9). Step 3 and 4 require completely new methods and are therefore discussed in more detail (red square in Figure 9)

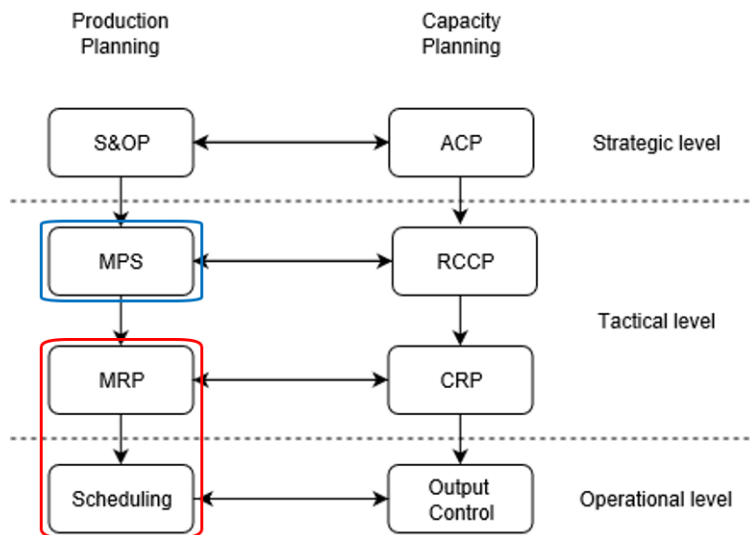


Figure 9: Scope of the MPC framework

## 4.2 Master Production Scheduling

The Master production schedule (MPS) is constructed by SAP based on the RTP orders and the purchase orders. All RTP orders and purchase orders of Retek products and most of the B2B customers are present in SAP, so the MPS for these products is made automatically. However, the RTP orders and purchase orders for some of the B2B orders are emailed to Taman Hengelo and not added to SAP. When these orders are not added to SAP, they will not be in the MPS and therefore also not be in the production schedule. To solve this problem, we propose three methods. The first method is to teach the B2B customers how they can place orders in SAP themselves via a customer login. The second method is to let Taman Hengelo place the orders they receive per email in SAP. The third method is to add the orders of these B2B customers manually to the MPS after the MPS is created. Because the improvement of data collection of these B2B customers is not part of this research, we use the third method for now, but we strongly advice Taman to implement the first or second method to make things easier for the long-term.

Figure 10 shows a part of the MPS which is made by SAP. The last row in Figure 10 is a product of a B2B customer that is manually added to the MPS. Since the MPS is now complete, we discuss how we constructed the MRP.

Material	Material Description	2020/13	2020/14	2020/15	2020/16	2020/17	2020/18	2020/19
198846	Cat Litter Box White	1.664	1.408	2.576	528	0	1.648	0
213720	Daytona Graphite	2.939	3.594	234	1.197	1.854	1.561	793
222252	Indigo Waterbutt	280	1.200	1.240	3.600	80	1.200	2.680
243533	Pet Basket S White	0	0	0	0	0	0	0
198858	Pet Carrier Green	440	220	0	0	640	0	0
235162	Jaipur Cappucino	33	156	208	338	650	546	0
235175	Columbia Balcony Graphite	1.072	1.824	0	0	0	0	0
232706	Columbia Dining 5-set Graphite	513	594	0	0	0	24	0
217801	California 3-sofa Graphite	0	180	248	128	168	0	56
217741	California Table Anthracite	0	200	198	0	145	248	0
228798	Q-BIC 4	1850	0	0	1850	0	0	1850

Figure 10: Example of a part of the MPS

## 4.3 Materials Requirements Planning

The materials requirements planning (MRP) is a plan that shows for each part when it has to be produced, in which quantity, which machine is used, which mold is used, and what the due date for the part is. To be able to make the MRP, a lot of data needs to be acquired. Subsection 4.3.1 explains how we acquire the required data and use these to make the MRP. Then, Subsection 4.3.2 shows the result of the MRP.

#### 4.3.1 Acquiring input data

All required data for the MRP is available in SAP. However, this data cannot be used immediately. All required data can be divided into four groups. These four groups are stated below. Thereafter, these groups are explained in detail.

1. All orders including quantity and due date for each product (MPS)
2. The bill of materials and the current inventory level of each finished product, subassembly, and part
3. The machine group and mold belonging to each part
4. The required production time for each part

##### *1) All orders including quantity and due date for each product*

In the second to last step of the MPC framework, the MRP is made. The MPS is required for the MRP but cannot be used immediately. SAP can construct the MPS in two ways: the MPS is made with a time interval of a day for 52 days ahead or it is made with a time interval of a week for 52 weeks ahead. Because we want to use the available data as much as possible, we decide to use the first MPS overview for the first 52 days and the second MPS overview for the rest of the season. The due date of the orders of the second overview are placed on the first day of that week. In this way, we prevent orders being delivered late.

When looking half a year in the future, a lot of orders still have the status 'preliminary forecast' and not yet RTP or purchase order. For this forecast, it is unknown whether the customer is going to place orders equal to, larger than, or smaller than their preliminary forecast. To be able to construct a good MRP, we introduce a forecast factor to be able make the MRP more accurate in each phase of the season. This forecast factor is multiplied with each preliminary forecast before it is used in the MRP. When making a production schedule at the start of the season, Taman can set the forecast factor on 1.1 so the schedule is made in such a way that it can cope when purchase orders appear to be larger than their preliminary forecast. This can be regarded as a sort of safety factor. When making a production schedule at the end of the season, the forecast factor can be set to 0.8 when Taman expects less purchasing orders for certain preliminary forecasts. This forecast factor can easily be changed each time the MRP is made

##### *2) Bill of Materials (BOM) and the current inventory level of each finished product, subassembly and part*

The bill of materials (BOM) is a list that shows the composition of a finished product. Each finished product is made of subassemblies (SAS) and parts. Each SAS is again composed of parts. A SAS is a combination of parts that is assembled immediately after production of the parts. Obtaining the type and number of parts present in a finished product can be quite difficult. Some finished products consist of multiple SAS and parts, of which some of these SAS again consist of parts. Using the BOM, we made a list presenting for each finished product, the type and number of parts of which they are composed. Table 5 shows the BOM of all mold-casted parts of a Daytona, which is a sunlounger. The first column shows the BOM level. The second BOM level shows the SAS one level higher in the BOM. The third BOM level show the materials, SAS and parts of the second BOM level. Finally, the fourth BOM level shows the parts of the third BOM level.

BOM level	Material	Component	Object description	Component Quantity.	Inventory level
1	213720	213720	Daytona grap + cus cool grey 009 std	1	20
2	213720	688907	SAS TABLETOP DAYTONA GRAPHITE	1	10
2	213720	688918	SAS BACK/BASE DAYTONA GRAPHITE	1	5
3	688907	683541	Tabletop Arizona/Daytona graph	2	0
3	688907	683542	LEGS MIDDLE DAYTONA (2x) GRAPHITE	2	0
3	688907	683543	Feet Arizona / Daytona graph	8	10
3	688907	666022	Montageset stelschroef Daytona	1	5
3	688907	639394	Stelschroef TPE Lago/NY/Ariz/Luna/Dayto	8	100
3	688918	683537	Back Daytona graph	1	20
3	688918	683538	Base Daytona graph	1	50
3	688918	683539	Backsupport Daytona graph	1	0
3	688918	683540	HINGE 2x DAYTONA GRAPH.	1	0
4	666022	639394	Stelschroef TPE Lago/NY/Ariz/Luna/Dayto	8	100

Table 5: Example of the BOM of a Daytona

In the example of Table 5, the Daytona consists of two SAS parts and those SAS parts consist of respectively 5 and 4 production parts. The 'Montageset stelschroef Daytona' consists of 8 'Stelschroef TPE Lago/NY/Ariz/Luna/Dayto' (see BOM level 4), and some other non-mold-casted parts. Because 'Montageset stelschroef Daytona' is not a mold-casted part itself and should therefore not be considered when making the part list per product. Table 9 shows the part list for the Daytona example of Table 5.

Material number	Material Description	Production quantity
683541	Tabletop Arizona/Daytona graph	2
683542	LEGS MIDDLE DAYTONA (2x) GRAPHITE	2
683543	Feet Arizona / Daytona graph	8
683537	Back Daytona graph	1
683538	Base Daytona graph	1
683539	Backsupport Daytona graph	1
683540	HINGE 2x DAYTONA GRAPH.	1
639394	Stelschroef TPE Lago/NY/Ariz/Luna/Dayto	16

Table 6: Part list for the Daytona

To be able to know how many parts need to be produced, we need to know how many finished products are needed and what the inventory level is of the finished product, the SAS and each individual part. For example, we want to produce 100 Daytona's. And the current inventory level per part is shown in column 5 of Table 5, we can calculate how much of each part has to be produced (see Table 7). When we calculate the number of 'Feet Arizona / Daytona graph' we have to produce, we know that we need in total 800 pieces ( $100 * 8$ ). There are 20 finished products in inventory that contain a total of 160 feet pieces ( $20 * 8$ ). There are 5 'SAS TABLETOP DAYTONA GRAPHITE' in inventory that contain 80 ( $10 * 8$ ) feet pieces. Finally, there are 10 feet pieces in inventory. So, in total, there are  $160 + 80 + 10 = 250$  feet pieces in inventory, which results in a production quantity of ( $800 - 250 =$ ) 550 feet pieces. After the quantities for this production order is made, all inventory levels are updated and the process is repeated for the next order. These orders are sequenced based on their delivery date starting with the order with the first delivery date. In this way, the inventory is first used for the orders that have to be delivered first.

Material number	Material Description	Production quantity	Needed	Inventory	To produce
683541	Tabletop Arizona/Daytona graph	2	200	40	160
683542	LEGS MIDDLE DAYTONA (2x) GRAPHITE	2	200	40	160
683543	Feet Arizona / Daytona graph	8	800	250	550
683537	Back Daytona graph	1	100	35	65
683538	Base Daytona graph	1	100	75	25
683539	Backsupport Daytona graph	1	100	25	75
683540	HINGE 2x DAYTONA GRAPH.	1	100	25	75
639394	Stelschroef TPE Lago/NY/Ariz/Luna/Dayto	16	1600	250	1350

Table 7: Overview of production quantities considering inventory levels

### 3) All parts and their machine group and mold that are needed for production

To make the MRP, we need to know which machine group and mold are needed for the production of a certain part. The machines can be divided in 6 machine groups, each machine group has a certain force they can use on the mold to cast the parts. These groups are divided in 50, 350, 650, 800, 1000 and 2300 ton machines. Each group consists of 1 to 7 machines with a total number of 25 machines. Each mold is dedicated to a certain machine group. Every part is therefore made on a machine of the same group. In the current situation, each mold has a preference machine to be installed on, but as long as the machine group is correct, the mold can be installed on every machine of the same machine group.

When a machine is going to produce another part, the mold has to be changed since the mold is part specific. This job requires personnel, equipment and time. At this moment there are two employees that are allowed to perform mold changes. A mold change on larger machines take significantly more time than a mold change on smaller machines. Table 8 shows the number of hours it takes to change a mold. These durations are averages because some molds are easier to change than others. The personnel that executes the mold changes are only available in the day shift from 7:00 to 15:00, so mold changes can be executed 8 hours per day. Due to the personnel limitation and the time limitation, there are 16 hours available per day to execute a mold change. When two parts using the same mold are produced one after the other, no mold change is required. This can be the case when, for example, a color change is done.

Machine group	Mold change duration (hours)
50	0.8
350	2.8
650	4
800	4.8
1000	6.4
2300	8

Table 8: Number of hours it takes to perform a mold change

### 4) Production time needed for each part

Each mold has a certain number of parts that can be made in one cycle. A cycle is the period when the synthetic grains are pushed into the mold, the mold is being pressed together by the machine and the finished product is picked up from the mold. The number of parts made in one cycle varies between 1 and 8 pieces and is only dependent on the mold. The time of one cycle varies between 26 and 210 seconds depending on the mold and the machine group. Based on these data, we can calculate the machine time to produce a certain number of parts. Not all parts are produced solely on a mold. For example, the left armrest and the right armrest of the 'California' are produced together in one cycle. The left armrest is in this case the main part and the right armrest is considered as the 'shadow product'. These shadow products will always be produced in the correct ratio with the main products. We therefore do not need to take into account the shadow products in the MRP.

When a part is being produced and the corresponding mold is installed on the machine, not all production time can be used for actual production. Sometimes, the parts do not meet the required quality conditions and the machine has to stop to investigate the cause. It is also possible that the machine fails, or a mold is not mounted correctly. To cope with these kinds of possibilities, a yield factor is introduced. This yield factor is a number larger than 1 and this number is multiplied with the cycle time of the duration to produce one product. This leads to a more realistic view of the reality and besides, the production schedule does not have to be restructured each time a small delay of some sort occurs. This yield is set to 1.1 based on the experience of the employees but can easily be changed each time the MRP is made.

#### 4.3.2 MRP output

After we have acquired all needed data, we can start making the MRP. First, based on every forecast and purchase order in SAP, a line is created for each finished product including the due date and the quantity of the order. Next, using the BOM, a list is made of the parts that are used for the finished products. This list also contains the number of parts needed for one finished product. When combining these two lists, we know of each part how many pieces have to be produced and what their due date is. Now, we can add the routing and add the information about the corresponding mold, machine group, cycle time, and number of parts per mold press. Then, we only need to know the current inventory levels of the finished product, SAS and the parts to calculate how many of each part still has to be produced. To do this, we need to sort all parts based on their due date since the inventory will first be used for the parts that are produced with the earliest delivery date. Using the cycle time and the number of parts per mold press, we can calculate the number of shifts required for production. Table 9 shows an overview of a small part of the MRP. In some of the production order lines, the number to produce is 0. This can be the case when there is enough inventory available for the purchase order, so no production is required.

Material number	Part number	Machine group	Mold	Number of parts per mold press	Due date	Quantity needed per finished product	Purchase order quantity	Numbers to produce	Cycle time per mold press (sec)	Number of shifts to produce
213720	683542	650	683542	1	27-4-2019	2	500	0	57.78	0
217683	683542	650	683542	1	27-4-2019	2	225	0	57.78	0
217683	683542	650	683542	1	1-5-2019	2	500	0	57.78	0
218754	683542	650	683542	1	1-5-2019	2	345	0	57.78	0
228637	683542	650	683542	1	1-5-2019	2	1850	3500	57.78	8
234729	683542	650	683542	1	1-5-2019	2	1200	2400	57.78	5
198768	670127	650	670127	1	6-5-2019	1	1500	1500	155.00	9
235984	737624	650	737624	1	10-5-2019	1	3200	3200	100.00	11
206455	661852	650	661852	1	26-4-2019	2	312	0	57.78	0
217982	661852	650	661852	1	26-4-2019	2	297	0	57.78	0
244437	661852	650	661852	1	27-4-2019	2	684	0	57.78	0
198861	675885	650	675885	1	16-9-2019	1	500	0	53.33	0
198861	675885	650	675885	1	30-9-2019	1	1000	750	53.33	2
198861	675885	650	675885	1	14-10-2019	1	750	750	53.33	2
198861	675885	650	675885	1	28-10-2019	1	2500	2500	53.33	5
198861	675885	650	675885	1	11-11-2019	1	500	500	53.33	1
198861	675885	650	675885	1	25-11-2019	1	4000	4000	53.33	8

Table 9: Overview of a small part of the MRP

#### 4.4 Production scheduling

After the MRP is finished, the production scheduling process can start. Based on this MRP, the production scheduling process decides when to start a production run, how long this run will take, and on which machine the run will be. While constructing this production schedule, all constraints are taken into account so the production schedule will be feasible. To make a feasible production scheme, we choose to use a priority rule based scheduling method. This is a fast and easy method that is often used to build a feasible production schedule. The priority rule based scheduling method consists of a priority rule and a generation scheme. Subsection 4.4.1 discusses which priority rule we choose. Then, Subsection 4.4.2 discusses which generation scheme we have chosen. Finally, Subsection 4.4.3 explains the way we implement the priority rule based scheduling method taking into account all constraints.

##### 4.4.1 Priority rule

There are a lot of different priority rules that can be used. We discuss the earliest due date method and the shortest processing time method. These are two well-known priority rules and are often applied in production scheduling. The earliest due date method schedules the jobs based on their due date starting with the job with the earliest due date. This priority rule tends to minimize the maximum lateness. The shortest processing time method schedules the jobs based on their processing time length starting with the job with the shortest processing time. This priority rule tends to minimize the mean flow time which is the average finished date of all jobs. Because the main goal of this research is to increase the orders delivered on time, we choose the priority rule that minimizes the maximum lateness, which is the earliest due date method.

##### 4.4.2 Generation scheme

There are two generation schemes that can be used for the production scheduling process: the serial schedule generation scheme (SSGS) and the parallel schedule generation scheme (PSGS). The SSGS method selects the job with the highest priority and schedules this job on the first available machine taking into account all constraints. The PSGS method selects the first machine that is available and then searches in the priority list which job can fit here, starting at the top of the priority list. When a job fits on the selected machine while all constraints are taken into account, the job is scheduled. According to Kim & Ellis Jr (2010), the SSGS method leads to better results than the PSGS method. Furthermore, The SSGS method requires less computation time than the PSGS method.

##### 4.4.3 Implementation of the priority rule based scheduling method

Before we can start constructing the production schedule, we need to change the MRP so that it is ready to be used as input for the priority rule based scheduling method and we need to define the constraints. Subsection 4.4.3.1 and 4.4.3.2 discuss these two subjects.

###### 4.4.3.1 Prepare the MRP for use as input for the priority rule based scheduling method

The MRP cannot be used immediately as input for the scheduling method. First, the production order lines of the same part numbers and the same due dates are summed together in one row. For example, rows 3 until 7 of Table 9 have the same part number and the same due date and are therefore merged to one row. The total production quantity of the merged row is  $0 + 0 + 3500 + 2400 = 5900$  pieces and the total number of shifts are  $\frac{\text{Number of seconds needed}}{\text{number of seconds per cycle}} = \frac{5900 * 57.78}{60 * 60 * 8} = 11.8$  shifts. Because we do not plan parts of a shift, we reserve 12 shifts for this merged production order. Table 10 shows the updated MRP schedule when this rule is implemented.



Material number	Part number	Machine group	Mold	Number of parts per mold press	Due date	Quantity needed per finished product	Purchase order quantity	Numbers to produce	Cycle time per mold press (sec)	Number of shifts to produce
217683	683542	650	683542	1	27-4-2019	2	225	0	57.78	0
217683	683542	650	683542	1	1-5-2019	2	3895	5900	57.78	12
198768	670127	650	670127	1	6-5-2019	1	1500	1500	155.00	9
235984	737624	650	737624	1	10-5-2019	1	3200	3200	100.00	11
217982	661852	650	661852	1	26-4-2019	2	297	0	57.78	0
244437	661852	650	661852	1	27-4-2019	2	684	0	57.78	0
198861	675885	650	675885	1	16-9-2019	1	500	0	53.33	0
198861	675885	650	675885	1	30-9-2019	1	1000	750	53.33	2
198861	675885	650	675885	1	14-10-2019	1	750	750	53.33	2
198861	675885	650	675885	1	28-10-2019	1	2500	2500	53.33	5
198861	675885	650	675885	1	11-11-2019	1	500	500	53.33	1
198861	675885	650	675885	1	25-11-2019	1	4000	4000	53.33	8

Table 10: Updated MRP overview for production schedule (1)

Although some of the production order lines are merged, the updated MRP cannot be used as input for the production schedule yet. A mold change between two production runs takes some time and there is a limit on the mold change employees available per day. Therefore, we choose to use a minimum number of shifts per production run. Together with the employees of Taman, this minimum number of shifts is set to 9 shifts (three days) but can easily be changed every time the production schedule is made. When a production run is shorter than 9 shifts, the next production run of the same part is added to this production run. This process is repeated until the production run is at least 9 shifts. When two production runs are merged, the due date remains the due date of the first production run. For example, production order lines 7 until 10 of Table 10 are merged so the total number of shifts is at least 9 (0 + 2 + 2 + 5) shifts. The due date of this combined production order is set on the first due date of the combined orders when production is required. In this case, the due date is set to 30-09-2019. Table 11 shows the new updated MRP overview including this new rule.

Material number	Part number	Machine group	Mold	Number of parts per mold press	Due date	Quantity needed per finished product	Purchase order quantity	Numbers to produce	Cycle time per mold press (sec)	Number of shifts to produce
217683	683542	650	683542	1	1-5-2019	2	3895	5900	57.78	12
198768	670127	650	670127	1	6-5-2019	1	1500	1500	155.00	9
235984	737624	650	737624	1	10-5-2019	1	3200	3200	100.00	11
198861	675885	650	675885	1	30-9-2019	1	4250	4000	53.33	9
198861	675885	650	675885	1	11-11-2019	1	4500	4500	53.33	9

Table 11: Updated MRP overview for production schedule (2)

Now, the updated MRP overview is ready to be sorted based on the priority rule. We choose for the earliest due date priority rule and therefore we sort all production orders based on their due date. In the case of the example of Table 11, the production orders are already sorted based on their due date. After this step, the priority list is ready to be used by the SSGS method for constructing the production schedule

#### 4.4.3.2 Constraints for the priority rule based scheduling method

Before the SSGS method can start, the constraints have to be defined. There are constraints on the machine availability, mold availability, and mold changes. When a job can be scheduled without interfering with any of these constraints, the job is planned, otherwise, the next possibility where none



of the constraints are interfering is chosen. The next three sections explain the constraints in more detail.

#### Machine availability constraint

The machine on which the job is scheduled must be empty for the whole time period the job is scheduled. If the job requires a mold change, the machine should also be available during this mold change. In the weekends and in holidays, usually no production is done and therefore, these shifts are not counted when deciding how long the job is on the machine. For example, if a job starts at a machine on Wednesday and it takes 12 shifts to produce, the job will be finished on Monday because no production is done in the weekends.

#### Mold availability constraint

The same constraints as for the machine availability also appears for the mold availability; a job can only be scheduled when the mold is not already in use by another job, since only one mold is available of each type. When the job requires a mold change, the mold should also be available during this period. If there are multiple machines available of the same product group and at the same time and one of these machines has the correct mold already installed, the job is placed on this machine.

#### Mold change constraint

A mold change can only be executed in the second shift of the day. So, a job that requires a mold change can only start in the third shift of the day. Besides the moment of the mold change, there is also a limitation of the number of mold changes that can be executed per day. This number is dependent on the machine groups on which the mold changes are required. There are in total two mold change employees and a shift takes 8 hours. So, there are a total of 16 hours available per day. This means that two mold change on machines of the 2300 machine group can be executed, or two mold changes on an 800 machine group and one on a 1000 machine group (see Table 8).

### 4.5 Results of the priority rule based scheduling method

The priority rule based scheduling method is finished and the constraints are defined. The next step is to construct and analyze the production schedule. When analyzing the production schedule, we saw two remarkable characteristics.

First, there were some machines with only a few jobs scheduled for the season. These are the machines of the smallest machine group. Due to the earliest due date method, these jobs are planned as early as possible. Due to this rule, some products which are due in June, were already finished in October. To decrease the number of days production is finished before its due date, we introduced a release date for the jobs. This release date was set to 150 days before its due date. In this way garden furniture production for the months January and later can already start in September, which is also happening in the current situation, but jobs on the smallest machine group are produced a bit later to decrease their stock level and inventory costs.

Second, the orders being delivered on time were 94.2% while the goal of this production planning is 98%. One of the reasons for this decrease is the 10% increase of planned production for this season compared to last season. To cope with this issue, there are two possibilities. We can decrease the demand or increase the capacity. Decreasing the demand can be done by declining some of the customer forecasts or giving them a certain maximum order amount. Taman does not want to limit their customers, so we have to look at the other possibilities. Increasing the capacity can be done by adding extra machines or increasing the number of production days. Because there is no more space available in the production hall, adding extra machines is not possible. Increasing the number of production days, however, is possible and is also done in busy periods of earlier seasons. We choose to start production in weekends from January because this is the start of the season of garden furniture

and is therefore very busy. We start by adding one weekend and check the new ratio of orders being delivered on time. When adding four weekends, the ratio was 98.5%, so we choose the production hall to be available for all four weekends of January (Table 12).

Number of weekends available for production	Orders being delivered on time (%)
0	94.2%
1	95.5%
2	96.3%
3	97.3%
4	98.5%

Table 12: Orders being delivered in time (%) per number of weekends available for production

The production schedule is now completely finished. Figure 20 in Appendix B shows the flowchart of the process from the moment the priority list is finished to the production schedule. A part of the production schedule is shown in Figure 11. The first row of this figure shows the date and the second row the shift number. The date only shows production dates, so weekends and holidays are removed from the production schedule. The letter 'M' indicates that a mold change is performed. The total mold change capacity will never exceed the maximum mold change capacity per day. The number in the most left column indicates the tonnages of the different machines. The colored bars in the production schedule show in which time period the production of a certain job is done. When two successive parts use the same mold, no mold change is required and the parts are produced immediately after each other, such as in the last row.

Date	1-11-2019			2-10-2019			3-10-2019			4-10-2019			7-10-2019			8-10-2019			9-10-2019		
Shift	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
350				M			HINGE 2x DAYTONA GRAPH.														
350										M			HINGE 2x DAYTONA GRAPH.								
650	Back cover California Graph.									M			ACHTERPOOT FLORION 5-POS. R. GREY								
650	Front California Graph.												M			SIDE COVER L CALIFORNIA					
650	Back California Graph.												M			LEGS MIDDLE DAYTONA					
650	Seat California Graph..																				
800				M			ARMLEGGER R. FLORION 5-POS R. GREY						ARMLEGGER L. FLORION 5-POS. R. GREY								
1000				M			Base Daytona graph						-			M			Leg Jaipur graphite		
2300							M			Seat Jaipur cappuccino						Seat Jaipur graphite					

Figure 11: Example of a part of the production schedule

## 4.6 Conclusions

To design a process for constructing a production schedule, a few steps in the manufacturing planning and control framework have to change considering the current situation. Small changes are made in the master production schedule step. The materials requirements planning step and the production scheduling step are completely redesigned.

Some of the B2B customers do not place their forecasts and purchase orders in SAP. For these customers, it is important to add their forecast and customer orders to the MPS manually or spend time to get those customers enter their forecasts and orders in SAP themselves.

The materials requirements planning is a step that requires a lot of calculations. This step results in an MRP of which each line reflects a production run including the part number, the number of parts to produce, the corresponding machine and mold, the cycle time, and the number of shifts it takes to produce. Each line in this MRP has a minimum length of at least 9 shifts long. The sequence of these lines in this MRP is then chosen based on the priority rule.

Many decisions are made in the production scheduling method. We choose to use the earliest due date priority rule to minimize the maximum lateness. We also choose for the serial schedule generation scheme method because this method leads to better results and its computation time is shorter than the parallel variant (Kim & Ellis Jr, 2010). Finally, three constraints are discussed, so that the resulted

production schedule is also feasible. The constraints are based on the machine availability, mold availability, and mold change possibility.

After the first production schedule is constructed, two decisions are made. The first decision is the choice for setting release dates for each job 150 days before its due date. The second decision is to produce in four weekends of January. This decision is made, so that the ratio of orders delivered on time is at least 98%. After these changes, the production schedule is feasible while 98.5% of the orders are delivered on time.

Using the SSGS and the earliest due date priority rule, we make a feasible production schedule. In Chapter 5, we introduce an objective function and use an optimization method to improve the current production schedule.



## 5 Solution Design: Optimization Model

This chapter describes the process of optimizing the feasible production schedule of Chapter 4. Section 5.1 discusses a way to assess a production schedule which results in an objective function. Section 5.2 describes possible optimization methods and explains the choice for simulated annealing. Section 5.3 explains the decisions for the parameters of simulated annealing. Finally, Section 5.4 draws conclusions regarding the optimization model.

### 5.1 Assess a production schedule

The goal of this chapter is to improve the production schedule made using the serial schedule generation scheme and the earliest due date priority rule explained in Chapter 4. To know how good a production schedule is, we have to be able to assess a production schedule. Subsection 5.1.1 explains the parameters used to assess the production schedule. Subsection 5.1.2 explains the weights that are used to incorporate the long-term effects. Finally, Subsection 5.1.3 discusses the objective function that is used to assess the production schedule.

#### 5.1.1 Parameters for the objective function

The assessment of the production schedule should be done based on characteristics of the production schedule. The goal of this research is to improve the percentage of orders being delivered in time (CSL). This CSL-level penalty costs is therefore an important assessment criterion. Another important criterion are the inventory costs. Finally, the mold change employee costs is an important criterion. Subsection 5.1.1 until 5.1.3 elaborates on these criteria in more detail. Besides these three criteria, there are some other criteria such as machine costs, personnel costs and lateness that are not included in the objective function. Subsection 5.1.4 elaborates on these other criteria.

##### 5.1.1.1 CSL-level penalty costs

The CSL-level of Taman is the most important parameter of the production schedule. Retek assesses Taman mainly based on its CSL-level and Taman has to clarify their CSL-level each month when it is less than 98%. To penalize a production schedule with a CSL level less than 98%, we decide to give a large penalty for each percent that the CSL is less than 98%. This penalty is set to 10.000. We choose for a static penalty instead of a dynamic penalty because the number of iterations we can do is limited. A dynamic penalty will accept more production schedules that lead to a lower CSL at the beginning of the optimization method. Due to the limitation of the number of iterations, not all production orders leading to a penalty can be moved to another period in the schedule while maintaining a good overall production schedule. By using this static penalty, the chance of accepting a production schedule with a CSL less than 98% becomes very small. When the CSL-level is not taken into account in the objective function, the production schedule will lead to a lot of orders that are not delivered in time because the inventory costs will be lower when producing last minute instead of building up an inventory before the busy season.

The formula for the total CSL-level penalty is:

$$CSL \text{ level penalty} = \max \left( \left( 98 - 100 * \frac{\sum_{o=1}^N B_o}{N} \right) * f_c, 0 \right)$$

Where:

$N$  = total number of production order lines

$B_o$  = 1 if order of production order line  $o$  is finished before its due date, 0 otherwise

$f_c$  = fine for each percent the CSL-level is lower than 98%

#### 5.1.1.2 Inventory costs

The inventory costs cannot be calculated exactly, but a good estimation can be done. In the MRP phase of the production planning, the part orders are disconnected from the product orders. So, when we finish a certain part, we cannot be certain which product this part is going to be used for since a lot of products use the same parts. Because it is not possible to calculate the inventory costs per product, we decide to calculate the inventory costs per part. The inventory costs per part is calculated over the period that the part is made until the due date of the order of the part.

The inventory costs consist of capital costs, risk costs and storing costs. Because it is impossible to calculate the exact costs of capital and risk, we make some assumptions based on frequently used values in the literature. The first part of the inventory costs are the capital costs. The capital costs are the costs the company has spent on the production of a part, which they could have also invested into something else. The capital costs are approximately 8% of the value of the product per year.

The second part of the inventory costs are the risk costs. The risk costs are the costs based on a probability that the product will not be sold. This can have multiple reasons. The product can be obsolete due to for example a new version of the product. The product can get damaged in the transportation process to the storage location or at the storing location due to, for example, fire- or water damage. These risk costs are set to 5% of the product value per year.

The third part of the inventory costs are the storing costs. The storing costs are dependent on the external storage location, the number of pallets stored, and the duration of the storage. Taman has five external storage locations, and each has their own pricing schedule. To be able to calculate the storing costs, we use the average storing costs of €0.69 per pallet per week. Because the capital costs and the risk costs are also calculated as costs per year, we also want to convert the storing costs to costs per year. This is  $€0.69 * \frac{365}{7} = €35.98$  per pallet per year. The storing costs per part is calculated by dividing the storing costs per pallet by the number of parts per pallet. Unfortunately, not for all parts, the number per pallet is known. For these parts, the average percentage of storing costs per year is used, which is 15% of the value of the part. So, it costs on average 15% of the value of the part to store that part for a whole year.

The inventory costs for a part can be split in two sections. The first section are the inventory costs during production of the part and the second section are the inventory costs after the production of the part (Figure 12). Section 1 is always a constant increasing line until the production equals the order quantity, because Taman starts sending the order only once it is complete. The length of Section 2 is the length of the due date of the order minus the finished date of the order. When the finished date of the order is after the due date of the order, Section 2 will be zero. The formulas for these two sections for a certain part are now explained.

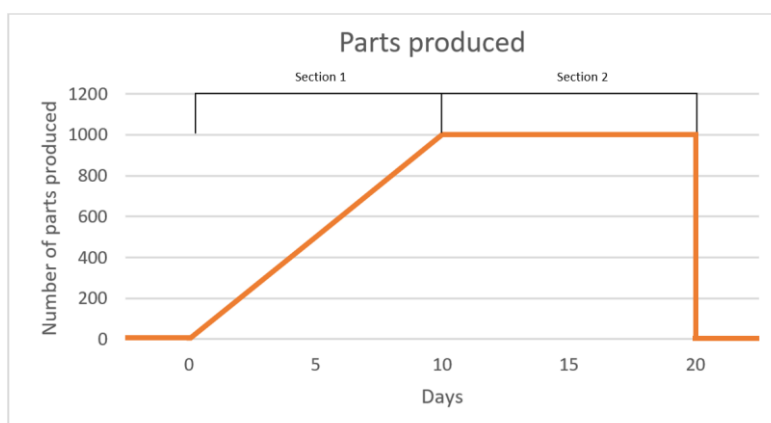


Figure 12: Sections during production cycle

For Section 1, the parts in inventory are increasing due to production. The average number of parts in inventory are half the total number of parts in inventory at the end of Section 1. The inventory costs during Section 1 is calculated using the following formula:

*Inventory costs during Section 1*

$$= \frac{1}{2} * \left( \frac{0.08 * v_o + 0.05 * v_o + K_o * \frac{35.98}{n_o} + (1 - K_o) * 0.15 * v_o}{365} * (f_o - s_o) \right) * p_o$$

Where:

$v_o$  = value of the part of order line  $o$

$n_o$  = number of parts per pallet of order line  $o$

$s_o$  = start date of production order line  $o$

$d_o$  = due date of production order line  $o$

$f_o$  = finished date of production order line  $o$

$p_o$  = number of parts to produce for production order line  $o$

$K_o$  = 1 if parts per pallet of order line  $o$  is known, 0 otherwise

When all parts of a production run are produced and waiting for the due date (Section 2), the inventory costs for this period is calculated using the following formula:

*Inventory costs during Section 2*

$$= \left( \frac{0.08 * v_o + 0.05 * v_o + K_o * \frac{35.98}{n_o} + (1 - K_o) * 0.15 * v_o}{365} \right) * \max(d_o - f_o, 0) * p_o$$

When combining the inventory costs of Section 1 and Section 2, we get the following two formula:

*Inventory costs during Section 1 and Section 2 =*

$$\frac{0.08 * v_o + 0.05 * v_o + K_o * \frac{35.98}{n_o} + (1 - K_o) * 0.15 * v_o}{365} * p_o \left( \left( \frac{1}{2} * (f_o - s_o) \right) + \max(d_o - f_o, 0) \right)$$

It is important to integrate the inventory costs in the objective function. If the inventory costs would not be included, the production schedule will prefer solutions where production starts very early, so no lateness occurs. To avoid this from happening, we have to include the inventory costs in the objective function.

#### 5.1.1.3 Mold change employee costs

Different production schedules can lead to a different number of mold changes. A production schedule with a lot of small production runs requires a lot of mold changes and a production schedule with a lot of large production runs requires few mold changes. Because the production schedule has a lot of influence on the total costs of mold changes, we decide to include these costs in the objective function.

Depending on the molds that have to be changed, 0, 1, or 2 mold change employees are needed. When no mold change employees are needed for changing molds, these employees are assigned to other tasks and no temporary workers are assigned to these tasks. Temporary workers are approximately €100 per day. So, when a mold change employee is not needed for changing molds, 1 less temporary

worker has to be hired, so €100 will be saved. The formula for the mold change employee costs for a certain day is therefore:

$$\text{Mold change employee costs} = \sum_{d=1}^T (\text{roundup}(m_d)) * c_e$$

Where:

$T$  = total number of days in production schedule

$m_d$  = number of mold change employees needed at day  $d$

$c_e$  = costs per mold change employee per day

#### 5.1.1.4 Other criteria

There are a few other criteria not included in the objective function. For example, the machine costs, the personnel costs and the costs of lateness. We now discuss these three criteria and the reasoning for not including them.

##### Machine costs

The machine costs are the costs to run the machines. These costs include energy costs and wear and depend on the type of machine. Larger machines are more expensive to run than smaller machines. Because the total number of machine hours will be the same in different production schedules, the machine costs will also be the same. It is therefore unnecessary to include the machine costs in the objective function.

##### Personnel costs

The personnel costs reflect the costs of the personnel at the machines. These personnel are responsible for assembling the parts, moving the parts, making orders ready and maintaining the machines. The personnel costs are also not included in the objective function for the same reason as the machine costs are not included; independent of the production schedule, the total personnel costs remain the same and are only dependable on the production orders. When a decision is made to produce in a weekend, the production tasks that were scheduled at the end of the season are moved towards this weekend. Also in this situation, the total number of hours personnel is needed is the same. We therefore do not include the personnel costs in the objective function.

##### Lateness

Lateness occurs when a production order cannot be finished before its due date. Each customer deals with lateness in a different way. Some customers do not give a penalty when a product is delivered late if this is communicated in time. Other customers give a penalty of 5% of the order value each week the order is late, with a maximum of 25%. And, again other customers also take into account their extra logistic costs and declare these costs as well.

Because the CSL level and lateness both give a penalty to orders that are delivered late, we have chosen not to include the lateness costs in the objective function. If lateness would be included in the objective function, a production order that is delivered late would be penalized twice which would unbalance the objective function.

#### 5.1.2 Weights

Some criteria have long term consequences or accompanied risks. To include these, we decide to use weights. The more severe the consequence or the higher the risk, the higher the weight. We give each criteria a weight between 1 and 2 in which 1 reflects no negative long-term effect and no risk involved and 2 reflects massive negative long-term effects or large risk. This weight is multiplied with the costs of the criteria in the objective function. The weights of each of the three parameters is now discussed.



- *CSL-level penalty costs*

The cycle service level is a very important criteria of the production schedule. Delivering late can have multiple long-term effects. For a start, customers can start looking for other more reliable suppliers when Taman is structurally delivering late. This leads to less orders for Taman, and with that, less profit. It is also possible that customers decide to place their forecasts on a date a few weeks before they are going to place the customer order. In this way, customers are more certain that their products will be in stock. The drawback for Taman is a distorted view of the requirements per month of the customers and therefore higher and unexpected inventory. The long-term consequence of lateness is high and with the risk of potentially losing customers, the weight of the lateness parameter is set at 1.7.

- *Inventory costs*

The inventory costs are the capital costs, risk costs and storing costs of inventory. There are some negative long-term effects of holding inventory. The products are, for example, not sold which leads to inventory without demand. These products have to be thrown away or sold cheaply to a wholesaler. Products can also get damaged at the storage location. However, both these consequences are already covered in the risk costs of the inventory costs. Therefore, the weight of the inventory costs is set at 1.0.

- *Mold change employee costs*

There is no direct long term consequence of performing a mold change but there is a risk the mold change employee is absent unexpectedly. In this case, less mold changes can be executed than planned in the production schedule. This can lead to a new production schedule. Due to this risk, the weight of the mold change parameter is set at 1.2.

### 5.1.3 Objective function

The objective function is used to assess a production schedule while carrying out the optimization process. The objective function consists of three parts. The first part reflects the CSL-level penalty costs criteria, the second part reflects the inventory costs criteria and the third part reflects the mold change employee costs criteria. To understand the objective function, first the indices of sets, parameters, decision variables and auxiliary variables are defined.

#### Indices of sets

$o$  = production order line  
 $d$  = number of the day in the production schedule

#### Parameters

$N$  = total number of production order lines  
 $T$  = total number of days in production schedule  
 $d_o$  = due date of production order line  $o$   
 $fc$  = fine for each percent the CSL-level is lower than 98%  
 $ce$  = costs per mold change employee per day  
 $v_o$  = value of the part of order line  $o$   
 $n_o$  = number of parts per pallet of order line  $o$   
 $K_o$  = 1 if parts per pallet of order line  $o$  is known, 0 otherwise  
 $wc$  = weight factor of the CSL-level penalty costs  
 $wi$  = weight factor of the inventory costs  
 $wm$  = weight factor of a mold change employee costs

#### Decision Variables

$s_o$  = start date of production order line  $o$   
 $p_o$  = number of parts to produce for production order line  $o$

#### Auxiliary Variables

$f_o$  = finished date of production order line  $o$

$B_o$  = 1 if order of production order line  $o$  is finished before its due date, 0 otherwise

$m_d$  = number of mold change employees needed at day  $d$

#### Objective function

$$\min \left( \max \left( \left( 98 - 100 * \frac{\sum_{o=1}^N B_o}{N} \right) * fc * wc, 0 \right) + \sum_{o=1}^N \frac{0.08 * v_o + 0.05 * v_o + K_o * \frac{35.98}{n_o} + (1 - K_o) * 0.15 * v_o}{365} * p_o \left( \left( \frac{1}{2} * (f_o - s_o) \right) + \max(d_o - f_o, 0) \right) * wi + \sum_{d=1}^T (\text{roundup}(m_d)) * ce * wm \right)$$

Some of the parameters of this function are set for this model. These set parameters are shown in Table 13. Each of these parameters can easily be changed in the model.

Parameter	Value
$N$	520
$T$	365
$fc$	10.000
$ce$	100
$wc$	1.7
$wi$	1.0
$wm$	1.2

Table 13: Parameters and their chosen values

Since the objective function is fully defined, it is now possible to assess a production schedule. Assessing a production schedule makes it possible to compare multiple production schedules to see which one is the best. There are a few ways to improve the production schedule using the objective function as a measure. These ways are explained in Section 5.2.

## 5.2 Optimization methods

In Chapter 4, a feasible production schedule is made using the serial schedule generation scheme method and the earliest due date priority rule. In Section 5.1, the objective function is defined. These are the two requirements for the next step; optimizing the production schedule. In the literature research of Chapter 3, we discussed two optimization methods we can use for improving an already feasible production schedule. Subsection 5.2.1 discusses simulated annealing and Subsection 5.2.2 discusses tabu search.

### 5.2.1 Simulated annealing

Simulated annealing has a probabilistic acceptance-rejection criterion, where in each iteration one neighbor is evaluated. The process of generating a neighbor and calculating its objective value takes approximately 0.50 seconds. Because simulated annealing is a good algorithm for improving production schedules while trying to reach a global minimum, we decide to implement simulated annealing as an improvement method.

### 5.2.2 Tabu search

Tabu search has a deterministic acceptance-rejection criterion, where in each iteration all neighbors are evaluated. In our situation, we have 520 production runs that have to be planned on 25 machines. While each production run has multiple operators that can generate neighbors in a large variety of

ways, the number of possible neighbors that has to be evaluated is enormous. Because the time it takes to evaluate one neighbor, this method takes too long for a reasonable amount of iterations and is therefore not used as an optimization method in this research.

### 5.3 Implementation of simulated annealing

Simulated annealing is an iterative process where each iteration consists of the generating of a neighbor and the evaluation of this neighbor. To make simulated annealing work, a cooling schedule is used to decrease the acceptance ratio over time so that the number of worse production schedules accepted approaches 0. Subsection 5.3.1 explains the neighbor selection and Subsection 5.3.2 explains the neighbor evaluation. Thereafter, Subsection 5.3.3 defines the cooling schedule.

#### 5.3.1 Neighbor selection

The neighbor selection process can be divided in two parts. The first part is the operators used to generate the neighbors and the second part is the process of generating the neighbors. Subsections 5.3.1.1 and 5.3.1.2 discuss these two parts.

##### 5.3.1.1 Neighbor operators

We discussed four operators in the literature research; these are the move operator, the swap operator, the merge operator, and the split operator. We choose to include the move, swap, and merge operator for generating neighbors, but we do not use the split operator. The split operator will often lead to a production order that takes less than 9 days to produce which is not allowed (see Subsection 4.4.3.1). Therefore, a split operator will often lead to an infeasible production schedule. Because we have a relatively long iteration time of 0.50 seconds, we have to optimize the quality of the generated neighbors and therefore, we decide to only use the move, swap, and merge operators.

##### 5.3.1.2 Neighbor selection process

We want the neighbor selection process of the algorithm to choose neighbors with a reasonable chance of improving the production schedule. When a neighbor has a small chance to improve the production schedule, the evaluation time is wasted, and less good neighbors can be evaluated. The production schedule is very full at the start of the season due to the earliest due date priority rule. A change of a production run in this period is not likely to lead to an improvement. However, at the end of the production schedule, a lot of production runs are already produced two or three months before their due date. These production runs can easily be moved backwards resulting in less inventory costs and probably a better objective value. We therefore sort all production runs based on their start date of the production and select a production run of the last 5 for generating a new neighbor when using the move or swap operator and select the last 50 production runs when performing a merge. We choose to use the last 50 production runs for the merge operator because the chance of performing a feasible merge in the last 5 production runs is very small. The number of production runs of which new neighbors are selected, will increase when the temperature increases. So, the lower the temperature of the cooling schedule, the more production runs can be selected for generating a new neighbor. In this way, we improve the quality of the selected neighbors leading to more accepted neighbors than when we search for neighbors in the whole solution space.

#### Infeasible production schedules

When a new solution is generated, the new production schedule can become infeasible in three ways.

1. Two production runs are scheduled at the same time on the same machine
2. A mold is used at the same time on two different machines
3. The number of mold change employees required on a day exceeds the limit of two

There are two options when at least one of these situations occur. A penalty can be given to the infeasible production schedule or the production schedule can be made feasible. When a penalty is given, we encourage the model to accept every change leading to a feasible production schedule at a lower temperature. However, because we are limited in the number of iterations and a lot of changes can lead to an infeasible production schedule, we choose to use the second option and change an infeasible production schedule to a feasible production schedule before using the objective function to assess the schedule.

To change an infeasible production schedule to a feasible one, only the production runs of the machine group in which the infeasibility occurs changes. Every production run of this machine group after the infeasible production run is deleted from the schedule. Now the run that resulted in the infeasibility is moved one shift later in the production schedule. If this is still infeasible, it will be moved another shift until it is feasible. When a moved production run is feasible, the next production run is rescheduled starting at the shift from which it was deleted. This is done for all next production runs, so that the new production schedule generated by a neighbor is always feasible. The process of changing an infeasible production schedule into a feasible production schedule takes some time, however, this increases the number of feasible and simultaneously good neighbors drastically compared to only evaluating neighbors which resulted immediately in feasible solutions. Now, we discuss the different operators and how these are implemented in the model.

#### Move operator

The move operator selects a production run to perform the move on. This production run is a random number chosen from the range of:

$$\left( \frac{\text{current temperature}}{\text{start temperature}} * (\text{total production runs} - 5, \text{total production runs}) \right)$$

In this way, at the start of the algorithm, the range only allows to move production runs at the end of the production schedule and as the temperature decreases, more and more runs are allowed. When a production run of the last 120 runs is selected, the run can be moved anywhere from the date chosen by the SSGS method of Chapter 4 to the last date of the season while still delivering in time taking into account the production time. When a production run before the last 120 runs is selected, the production run can move between 6 shifts earlier and 6 shifts later on a machine of the same machine group. This change at 120 production runs is chosen using trial and error and checking what number of runs resulted in the most good neighbors.

#### Swap operator

The swap operator swaps two production runs of the same machine group. The production run to swap is chosen in the same way as explained in the move operator paragraph. The next step is to select a neighbor to swap with. When a production run in the last 120 runs is selected, the swap will be performed with a production run between the chosen production run and another run of the same machine group that is in the range:

$$\left( \text{first selected production run} + 1, \max \left( 9, 15 * \frac{\text{current temperature}}{\text{start temperature}} \right) \right)$$

When a production run before the last 120 runs is selected, the swap will be performed with a production run between 10 runs before the selected production run and 10 runs after the selected production run of the same machine group. The values 9 and 15 are again chosen using trial and error and by visually checking what values could result in good neighbors.

### Merge operator

The merge operator merges two production runs of the same part together to one long production run reducing the number of mold changes required but simultaneously increasing the inventory costs. The production run on which the merge operator will be applied is chosen randomly within the range:

$$\left( \frac{\text{current temperature}}{\text{start temperature}} * (\text{total production runs} - 50, \text{total production runs}) \right)$$

The next step is to select the next production run that is merged with the selected production run. To do this, we loop over the next production runs until we come across a production run producing the same part. This second production run is now merged with the first production run, so a merge always moves the later scheduled production run to the end of the first scheduled production run.

### Choice for operator

Based on multiple test runs, we have chosen the frequency that the move operator, swap operator, and merge operator is selected for generating a neighbor. Move operators lead by far to the most improvement, then merges and then swaps. By using trial and error, we defined the frequency these operators are selected for generating a neighbor. These frequencies are respectively set to 70%, 20%, and 10%.

#### 5.3.2 Neighbor evaluation

After a new neighbor is scheduled, its objective value is calculated. Based on this objective value, the neighbor will be accepted and becomes the current production schedule, or the neighbor will be rejected, and the current production schedule remains the same. If the neighbor has a better or equal objective value compared to the current solution, the neighbor is accepted. If the neighbor has a worse objective value than the current solution, the neighbor is accepted with a chance equal to  $e^{\frac{E(X^c) - E(X^n)}{T_i}}$ . Where  $E(X^c)$  is the objective value of the current solution,  $E(X^n)$  is the objective value of the neighbor solution, and  $T_i$  is the temperature after  $i$  temperature changes. The smaller the difference between the objective value of the neighbor solution and the current solution, and the higher the temperature, the higher the chance that the neighbor solution is accepted.

#### 5.3.3 Cooling schedule

For the cooling schedule, a few parameters have to be defined. In the first section we discuss the start temperature and in the second section we discuss the decreasing factor, end temperature, and markov chain length. These three parameters all influence each other, so therefore they are discussed together.

##### Start temperature

There are multiple ways to determine the start temperature for simulated annealing. We use the method that is recommended by Ledesma, Aviña, & Sanchez (2008). We set the start temperature,  $T_s$ , in such a way that during the first cooling stage, the probability of accepting a worse solution is roughly equal to 80%. This first cooling stage is equal to the number of possible neighbors. Because this number is excessively large, we choose a cooling stage of 250 iterations.

We test multiple start temperatures to check which temperature leads to an 80% probability of accepting a worse objective value ( $p_0 = 0.8$ ), so when at least 200 of the 250 worse solutions are accepted. Table 14 below shows for different start temperatures,  $T_s$ , the probability of accepting a worse objective value. We start testing at a start temperature of 3000 and decrease this until we get to just over 80%. We see that a start temperature of 1000 leads to a probability of 80.28% which is just a bit higher than the goal of 80%. Now, we can calculate the start temperature for the simulated annealing. To do this, we first calculate the average increase of the objective value for all accepted

worse solutions,  $\Delta$ . This  $\Delta$  is 282.92. So, a worse objective value is on average 282.92 worse than the current solution. Using the method of Ledesma, Aviña, & Sanchez (2008), we can now calculate the start temperature,  $T_s$  using:  $T_s = \frac{-\Delta}{\ln(p_0)} = \frac{-282.92}{\ln(0.8)} = 1268$ . So, the start temperature is set at 1268.

Start temperature $T_s$	Probability of accepting worse solution
3000	93.06%
2500	89.06%
2000	88.73%
1500	86.67%
1250	82.61%
1000	80.28%
750	77.14%

Table 14: Probability of accepting worse objective value depending on start temperature

#### Decreasing factor, end temperature, and markov chain length

The decreasing factor, end temperature, and markov chain length are all influenced by the maximum running time of the algorithm. In this research, the maximum running time is set at 25 minutes because this is the maximum duration Taman wants the optimization method to run. This means that at most,  $\frac{25 \cdot 60}{0.5} = 3000$  iterations can be done.

The decreasing factor  $\alpha$  is the factor with which the temperature decreases after a number of iterations equal to the markov chain length. The decreasing factor  $\alpha$  is often a value between 0.8, and 0.99. To determine the end temperature, we made different cooling schedules with a decreasing factor of 0.85, 0.875, 0.90, 0.925, and 0.95. We choose a markov chain length of 25 and looked for the temperature after which the objective value would not further improve significantly (>1%). Table 15 shows the results of this experiment

Decreasing factor	Temperature after which no significant improvement was found
0.85	12.0
0.875	8.4
0.9	15.2
0.952	46.2
0.95	28.5

Table 15: Last temperature with improvement per decreasing factor

We see in Table 15 that after a temperature of 8.4 no significant improvements are made. We therefore set the end temperature to 8. We now have to determine the decreasing factor and the markov chain length. Because we can do 3000 iterations in total, we can determine the markov chain length when we know the decreasing factor. The markov chain length is then calculated by:

$\frac{\text{number of iterations}}{\log_{\text{decreasing factor}} \frac{\text{end temperature}}{\text{start temperature}}}$ . So, when in our situation the decreasing factor is 0.9. The markov chain length is  $\frac{3000}{\log_{0.9} \frac{8}{1268}} = 62$ .

To determine the combination of decreasing factor and markov chain length, we decide to do some experiments. We do the experiments with the decreasing factors of 0.85, 0.9, and 0.95 and the corresponding markov chain lengths of respectively 96, 62, and 30. We run these experiments twice to decrease the randomness factor. The results of these experiments can be seen in Table 16.

Start temperature	End temperature	Decreasing factor	Markov chain length	Objective value improvement (1)	Objective value improvement (2)
1288	8	0.85	96	13.2%	10.6%
1288	8	0.9	62	15.5%	14.2%
1288	8	0.95	30	8.2%	9.3%

Table 16: Searching for the decreasing factor leading to the best objective value

Based on the results of Table 16, we see a significant difference between the objective value improvements at the decreasing factor of 0.85. The reason for this is the simulated annealing mechanics. Simulated annealing searches for a random production run within a certain range and uses a random operator to generate a neighbor. When fewer good neighbors are generated during the simulated annealing, the objective value improvement is lower. When a lot of good neighbors are generated, the objective value is larger.

Although the results are partly based on randomness, we conclude that the simulated annealing algorithm with a decreasing factor of 0.9 and a markov chain length of 62 leads to the best improvement and we use these parameters for the results in Chapter 6.

## 5.4 Conclusions

We use the CSL-level penalty costs, inventory costs, and mold change employee costs as the assessment criteria for the objective function. Each of these criteria are given a weight to incorporate the risk and the long term consequences. Based on the objective function we can compare different production schedules. We have chosen to implement the simulated annealing algorithm since this algorithm is often used for improving production schedules and tries to find a global minimum. Tabu search is not feasible to implement in our situation since the number of neighbors is very large. It is not possible to evaluate all possible neighbors for each iteration.

The neighbors are selected using the move, swap, and merge operators with a chance of respectively 70%, 10%, and 20%. At the start of the algorithm, only the production runs at the end of the production schedule are selected by the operators for generating neighbors. When the temperature decreases, more and more production runs can be selected. Because the initial production schedule is made using the earliest due date priority rule, the start of the production schedule is very full, so a change here would have a small chance to lead to improvement.

When a change is made that leads to an infeasible production schedule, the production schedule is automatically changed in such a way that it becomes feasible again while still keeping the change initialized by the operator. When the neighbor production schedule is constructed, the objective function is used to assess the production schedule. The simulated algorithm parameters decide whether the neighbor is accepted or rejected. The acceptance ratio is calculated using  $e^{\frac{E(X^c) - E(X^n)}{T_i}}$ , where  $E(X^c)$  is the objective value of the current solution,  $E(X^n)$  is the objective value of the neighbor solution, and  $T_i$  is the temperature after  $i$  temperature changes. The start temperature is calculated to be 1268, so that approximately 80% of the worse neighbor production schedules are still accepted. Next, the algorithm is run multiple times with different decreasing factors to check when no significant improvements are happening. This is the case from a temperature of 8. So, the end temperature is set to 8.

The algorithm running time can be at most 25 minutes according to Taman. Based on the running time and the decreasing factor, we can determine the maximum markov chain length. We do three experiments with a decreasing factor of 0.85, 0.90, and 0.95 and a markov chain length of respectively 96, 62, and 30. The decreasing factor of 0.9 and the markov chain length of 62 resulted in the highest improvement. However, randomness plays a role in simulated annealing, so we cannot say with 100% certainty that a decreasing factor of 0.9 leads to the best results overall.





## 6 Results and validation

This chapter discusses the results of the serial schedule generation scheme and the optimization method. Besides, it explains the verification and validation process. Section 6.1 analyses the serial schedule generation scheme model and the optimization model. Thereafter, Section 6.2 evaluates the machine utilization and Section 6.3 the mold utilization. Subsequently, Section 6.4 discusses the ways that the model is verified and validated. This validation process also incorporates an instruction manual which is also discussed in Section 6.4. Finally, Section 6.5 gives some concluding remarks regarding the results and the verification and validation process.

### 6.1 Model analysis

This section analyses the process and the results of the serial schedule generation scheme (SSGS) and the simulated annealing optimization method. First, Subsection 6.1.1 discusses the SSGS and then Subsection 6.1.2 discusses the simulated annealing optimization method.

#### 6.1.1 Serial schedule generation scheme

The serial schedule generation scheme (SSGS) method with the earliest due date priority rule results in a feasible production schedule that can be used as the initial production schedule for the optimization method. In the SSGS method, each order is scheduled as soon as possible after each other. Therefore, orders are often finished a few weeks before they are due. Table 17 shows for each month the average number of days an order is finished before its due date. These production orders have to wait for a long time before they are delivered to the customer which leads to high inventory costs. The optimization method shall move some production runs to a later moment in the production schedule reducing the number of days a finished product stays in inventory and with that reducing the inventory costs.

Month of the due date	Average number of days production run is finished before due date
September	14
October	31
November	30
December	66
January	66
February	60
March	44
April	40
May	44
June	56
July	76

Table 17: Average number of days production run is finished before its due date

#### 6.1.2 Simulated annealing

We made many changes to improve the efficiency of the simulated annealing algorithm. The first test was the basic simulated annealing algorithm without changing the production schedule if it was infeasible. If the schedule was infeasible, it would not be accepted, and another neighbor would be generated. The second test added the changing of the production schedule in such a way that it became feasible while still including the proposed change by the operator. The third test added a different ratio of the three operators. The move operator resulted more often in an improved production schedule than the swap and merge operator, so we changed the ratio of the operator selection. The fourth test added the feature that not all neighbors could be generated at the start of the simulated annealing, reducing the chance bad neighbors are chosen. Figure 13 to Figure 16 show the results of these four tests.

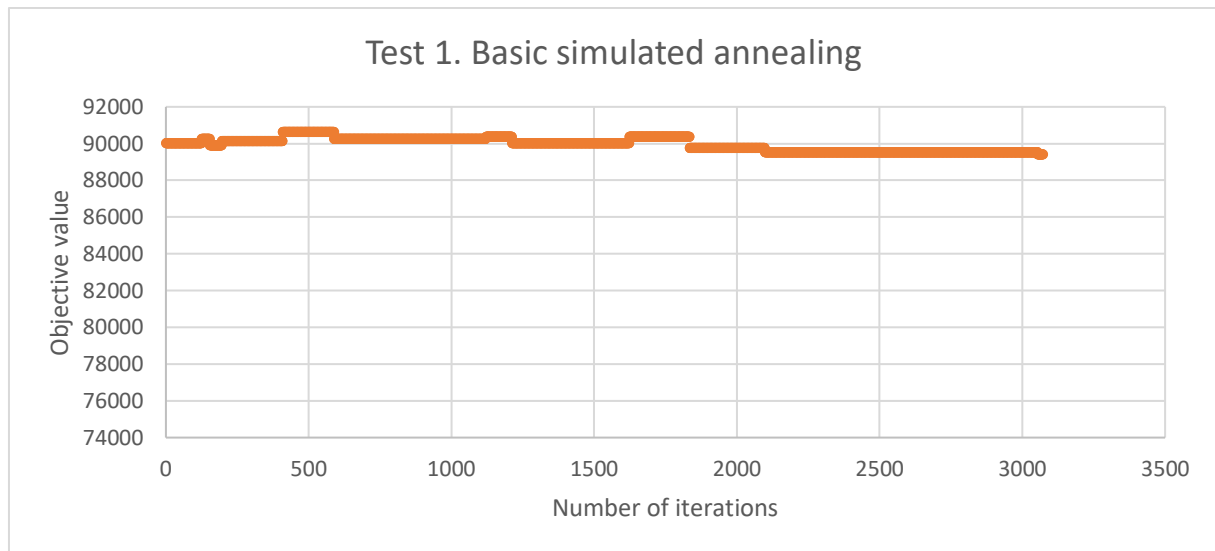


Figure 13: Simulated annealing output of test 1

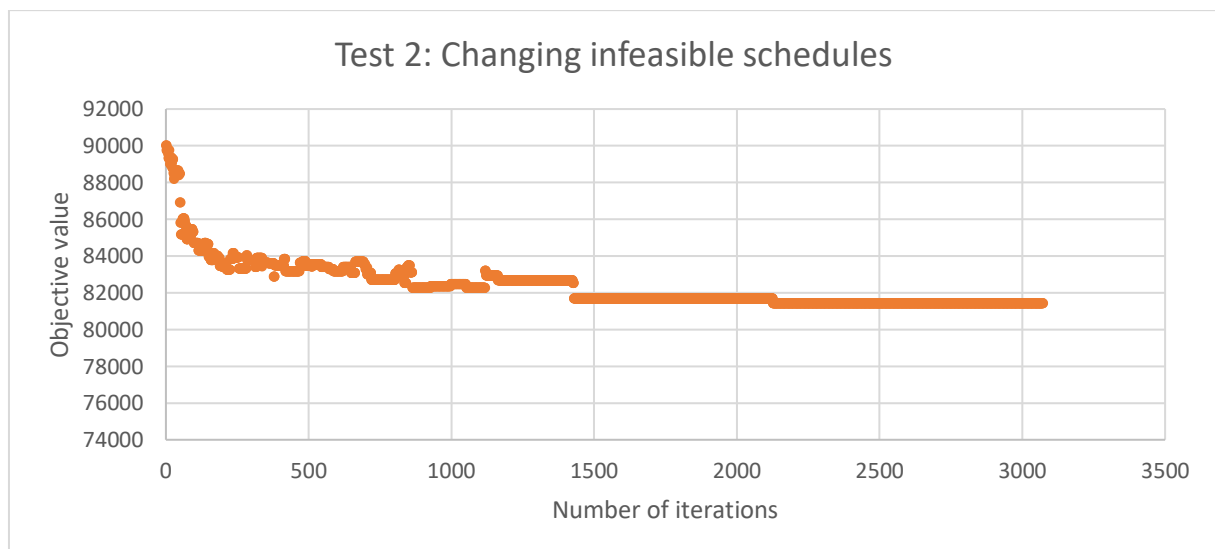


Figure 14: Simulated annealing output of test 2

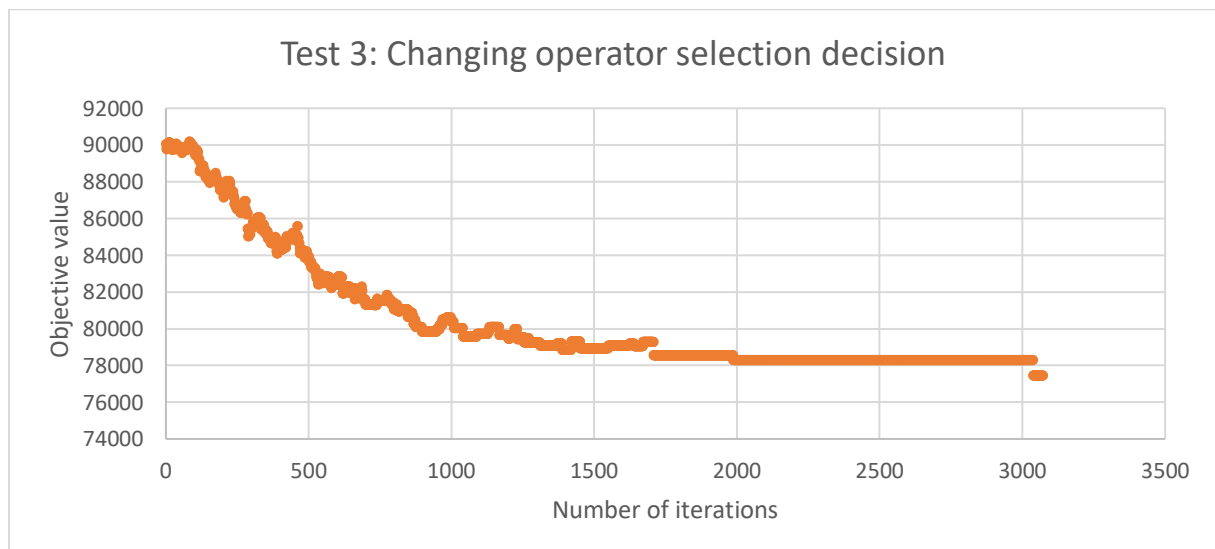


Figure 15: Simulated annealing output of test 3

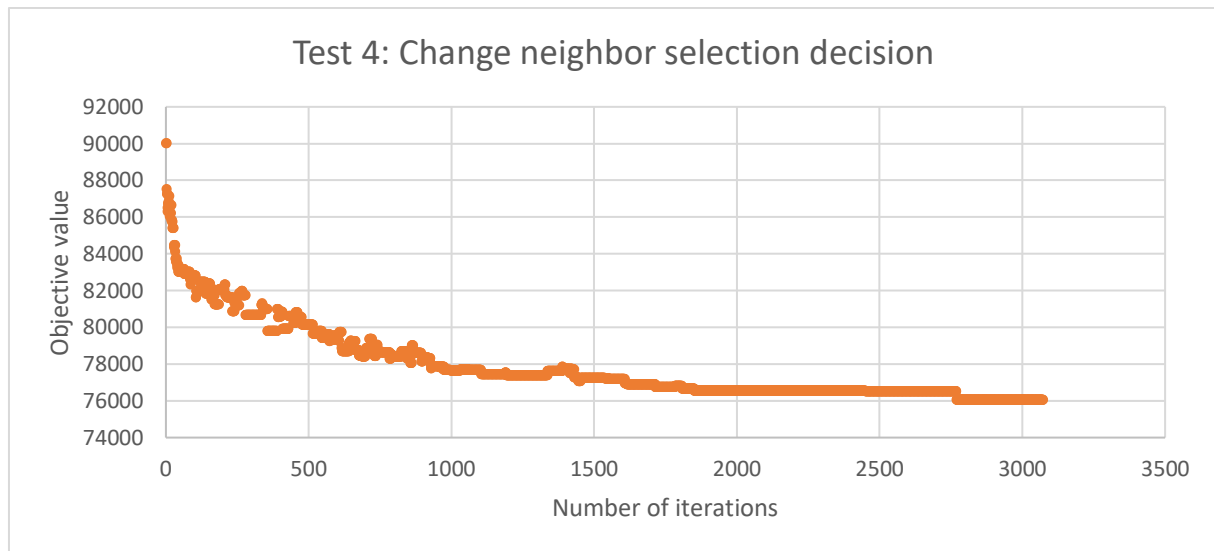


Figure 16: Simulated annealing output of test 4

We see a clear improvement in these four tests. The first test resulted in a marginal improvement. The reason for this is that 97% of the generated neighbors were infeasible. The second test improved the results a lot leading to a decrease of the objective value with 10.5%. The third test improved the algorithm even more by finding better neighbors for a longer number of iterations. This third test decreased the objective value with 13.1%. Finally, the fourth test made a large improvement jump at the start of the algorithm and kept finding a lot of good neighbors all the way until the 1850<sup>th</sup> iteration. Thereafter, the best objective value became stable until one more improvement was found at iteration 2750. The objective value of this test decreased with 15.5%. Table 18 shows the results of this fourth test for each criterion of the objective function compared to the result of the SSGS.

Criterion	Before simulated annealing	After simulated annealing	Reduced/increased (%)
CSL level penalty costs	0	0	0%
Inventory costs	57,262	40,528	-29.2%
Mold change employee costs	27,300	29,600	+8.4%
Objective value	90,022	76,048	-15.5%

Table 18: Objective function parameters before and after simulated annealing

The CSL level penalty costs is 0 before and after the simulated annealing algorithm. The reason for this is the large penalty when the CSL level is lower than 98%. Neighbors with a CSL level lower than 98% are often not accepted and neighbors that increase the CSL level to at least 98% are always accepted. The inventory costs are reduced a lot. The earliest due date priority rule is a bad rule for minimizing the inventory costs and this is the main reason that a lot of improvement is made using simulated annealing. Finally, the mold change employee costs increased. So, more mold changes needed to be done after simulated annealing. The main reason for this is the spread of the production runs. Before simulated annealing, production runs were more grouped. For example, when three mold changes has to be executed on the 50, 350, and 650 machine groups on a certain day, this required respectively 0.8, 2.8 and 4 is 7.6 hours of mold change employee time. Because 7.6 hours can be done by one employee, only one employee is required. After the simulated annealing, the production runs are more spread, and these mold changes can be spread over three days requiring three times one employee. This leads to an increase of mold change employee costs. Overall the objective value decreased with 15.5% leading to a significant improvement with respect to the production schedule before simulated annealing.

Figure 17 shows the objective value during the cooling period. We see that a large improvement is made after the first cooling cycle and that the relative improvement decreases with the temperature.

After the temperature of 50, only one more improvement is found. We also see some increases of the objective function for example at the temperature of 675 and 350. These increases can occur due to the ability of simulated annealing to also accept worse neighbors with higher objective values.

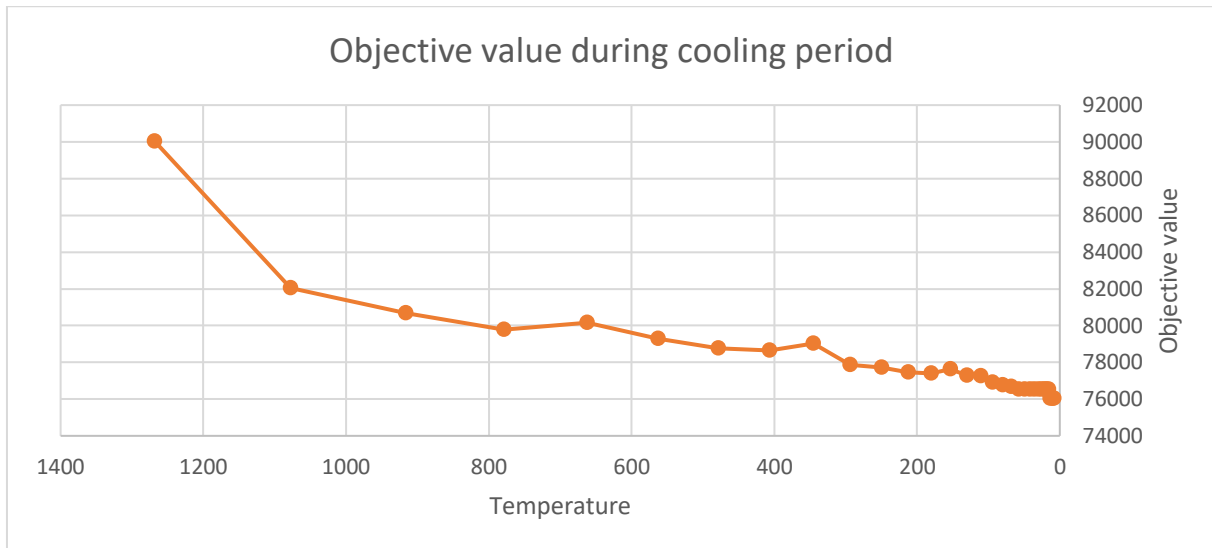


Figure 17: Objective value during cooling period

Since the differences in the objective value and its criteria is explained between the model before simulated annealing and after simulated annealing, we now look at the differences in machine utilization and mold utilization. Section 6.2 and 6.3 discuss these two subjects.

## 6.2 Machine utilization

Based on a production schedule, an overview of the machine capacity can be made. The machine capacity shows the percentage of time that the machine is occupied and not available for a new production task. This percentage includes all production days, so weekends and holidays are not considered as available for production. Table 19 shows the machine utilization based on the serial schedule generation scheme with the earliest due date priority rule and Table 20 shows the machine utilization based on the the production schedule after the simulated annealing improvement method.

	August	September	October	November	December	January	February	March	April	May	June	July
30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
50	50%	21%	0%	3%	31%	22%	0%	20%	0%	0%	0%	0%
350	83%	89%	97%	98%	87%	99%	90%	94%	59%	0%	0%	0%
350	77%	89%	97%	100%	96%	97%	97%	88%	74%	0%	0%	0%
350	67%	92%	97%	98%	96%	84%	87%	95%	71%	0%	0%	0%
350	47%	84%	97%	98%	100%	97%	100%	98%	80%	0%	0%	0%
650	57%	95%	97%	97%	98%	98%	75%	98%	70%	0%	0%	0%
650	57%	94%	96%	97%	96%	89%	97%	76%	89%	21%	0%	0%
650	57%	84%	96%	98%	98%	100%	100%	100%	100%	29%	0%	0%
650	57%	97%	94%	98%	100%	98%	97%	100%	62%	0%	0%	0%
650	27%	97%	93%	100%	91%	97%	88%	88%	50%	0%	0%	0%
650	27%	75%	100%	98%	82%	96%	85%	94%	64%	0%	0%	0%
650	0%	84%	97%	98%	89%	98%	95%	85%	45%	0%	0%	0%
800	7%	81%	99%	98%	100%	88%	67%	55%	2%	0%	0%	0%
800	7%	90%	80%	94%	82%	79%	43%	39%	32%	0%	0%	0%
1000	50%	95%	74%	95%	93%	92%	93%	100%	42%	0%	0%	0%
1000	80%	97%	100%	97%	93%	98%	98%	48%	32%	0%	0%	0%
1000	60%	89%	97%	98%	87%	92%	95%	97%	55%	0%	0%	0%
1000	50%	68%	96%	98%	100%	100%	100%	100%	86%	0%	0%	0%
1000	67%	65%	94%	97%	89%	93%	92%	76%	65%	0%	0%	0%
1000	67%	100%	99%	92%	96%	92%	98%	41%	35%	0%	0%	0%
1000	7%	59%	96%	100%	96%	97%	95%	100%	45%	0%	0%	0%
2300	97%	100%	100%	100%	100%	97%	90%	89%	94%	97%	82%	0%
2300	97%	98%	94%	90%	91%	97%	97%	97%	91%	97%	65%	0%

Table 19: Machine utilization before optimization method

	August	September	October	November	December	January	February	March	April	May	June	July
30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
50	0%	0%	0%	0%	62%	22%	8%	30%	0%	0%	0%	0%
350	47%	90%	64%	68%	93%	69%	100%	94%	86%	75%	48%	0%
350	67%	59%	88%	97%	100%	96%	98%	98%	61%	97%	23%	0%
350	73%	43%	84%	92%	71%	96%	93%	89%	91%	14%	0%	0%
350	47%	63%	80%	59%	64%	63%	100%	95%	70%	86%	41%	0%
650	47%	97%	83%	60%	78%	87%	92%	95%	76%	21%	0%	0%
650	57%	90%	75%	89%	89%	99%	97%	82%	48%	79%	0%	0%
650	57%	67%	97%	86%	98%	100%	100%	100%	97%	56%	0%	0%
650	37%	89%	84%	97%	98%	99%	55%	97%	80%	62%	0%	0%
650	37%	86%	93%	90%	98%	99%	97%	92%	88%	52%	0%	0%
650	27%	33%	96%	78%	84%	70%	93%	94%	88%	44%	0%	0%
650	27%	71%	90%	97%	82%	88%	100%	83%	42%	38%	0%	0%
800	0%	0%	55%	44%	22%	93%	97%	77%	82%	0%	0%	0%
800	7%	83%	48%	62%	100%	49%	80%	45%	44%	78%	45%	0%
1000	40%	33%	96%	94%	87%	98%	55%	70%	80%	63%	0%	0%
1000	80%	67%	75%	84%	89%	92%	37%	35%	79%	57%	0%	0%
1000	70%	100%	93%	92%	98%	79%	65%	76%	71%	100%	18%	0%
1000	60%	81%	99%	56%	100%	100%	100%	100%	21%	37%	0%	0%
1000	67%	63%	58%	51%	96%	91%	98%	38%	100%	94%	2%	0%
1000	7%	41%	99%	97%	96%	93%	97%	88%	88%	17%	0%	0%
1000	0%	32%	83%	95%	96%	98%	78%	100%	98%	21%	0%	0%
2300	97%	100%	100%	100%	100%	97%	90%	82%	74%	90%	94%	20%
2300	97%	98%	91%	84%	91%	91%	80%	61%	97%	83%	97%	29%

Table 20: Machine utilization after optimization method

We clearly see that the production runs after the optimization are more spread out than before. The runs that can start later are moved to a later time in the schedule and with that, the inventory costs are reduced. This leads to a less full schedule in the first half of the season and a more stable production rate during the whole season. When a machine breaks down or raw material is not delivered on time, there is more room for error in the production schedule after the optimization. A delay of one production run will not immediately lead to a completely new production schedule since there are more possibilities to reschedule a single production run.

Table 21 and Table 22 show the average utilization per machine group respectively before and after the optimization method. In these overviews, it is clear as well that the utilization of the machines is more spread out over the season after the utilization method. We also see that the machine group of the 2300 ton machines have the highest occupancy rate of on average 91% between August and July. This is very high and therefore risky. If, for some reason, one of the 2300 ton machines cannot produce at the start of the season, a lot of production runs have to be shifted and with that, a lot of orders will be delivered late. This risk is lower with the machines of the other machine groups since their occupancy is lower.

	August	September	October	November	December	January	February	March	April	May	June	July
30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
50	50%	21%	0%	3%	31%	22%	0%	20%	0%	0%	0%	0%
350	68%	88%	97%	99%	94%	94%	93%	94%	71%	0%	0%	0%
650	40%	89%	96%	98%	93%	96%	91%	92%	69%	7%	0%	0%
800	7%	86%	89%	96%	91%	83%	55%	47%	17%	0%	0%	0%
1000	54%	82%	94%	97%	93%	95%	96%	80%	52%	0%	0%	0%
2300	97%	99%	97%	95%	96%	97%	93%	93%	92%	97%	73%	0%

Table 21: Machine utilization per machine group before optimization method

	August	September	October	November	December	January	February	March	April	May	June	July
30	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
50	0%	0%	0%	0%	62%	22%	8%	30%	0%	0%	0%	0%
350	58%	64%	79%	79%	82%	81%	98%	94%	77%	68%	28%	0%
650	41%	76%	88%	85%	90%	92%	90%	92%	74%	50%	0%	0%
800	3%	41%	51%	53%	61%	71%	88%	61%	63%	39%	23%	0%
1000	46%	60%	86%	81%	94%	93%	76%	72%	77%	56%	3%	0%
2300	97%	99%	96%	92%	96%	94%	85%	71%	86%	87%	95%	25%

Table 22: Machine utilization per machine group after optimization method

## 6.3 Mold utilization

Based on the production schedule, an overview can be made of the mold utilization as well. The mold utilization shows per mold what the total proportion of time is that the mold is actively being used on a machine. In total, there are 99 molds that are being used in this season. To show the differences between the mold utilization before and after the optimization method, we choose to show 6 molds of each product group. Table 23 shows the mold utilization before the optimization method and Table 24 shows the utilization after the optimization method.

Garden furniture	Pet Life		B2B									
	August	September	October	November	December	January	February	March	April	May	June	July
442009	20%	56%	74%	78%	16%	82%	52%	52%	14%	0%	0%	0%
442010	0%	63%	74%	83%	22%	76%	62%	42%	14%	0%	0%	0%
442016	0%	40%	62%	75%	100%	100%	100%	100%	86%	0%	0%	0%
442023	0%	40%	51%	0%	89%	100%	100%	100%	100%	29%	0%	0%
29209598	0%	33%	67%	68%	100%	40%	0%	33%	0%	0%	0%	0%
29209600	40%	32%	59%	84%	36%	67%	63%	20%	0%	0%	0%	0%
442056	63%	100%	70%	11%	58%	0%	72%	100%	32%	0%	0%	0%
442057	53%	51%	67%	0%	42%	6%	0%	47%	76%	21%	0%	0%
442058	63%	21%	48%	27%	0%	0%	37%	17%	50%	0%	0%	0%
442059	73%	22%	74%	41%	0%	0%	37%	44%	77%	0%	0%	0%
442061	43%	33%	49%	16%	16%	0%	2%	50%	52%	0%	0%	0%
442066	53%	6%	0%	0%	0%	0%	0%	0%	15%	0%	0%	0%
441541	0%	0%	0%	0%	0%	0%	0%	61%	55%	0%	0%	0%
450019	90%	57%	30%	33%	16%	27%	18%	32%	32%	33%	64%	0%
450192	0%	0%	0%	16%	0%	0%	0%	0%	0%	27%	26%	0%
450195	0%	11%	13%	0%	0%	0%	0%	0%	17%	0%	0%	0%
450305	90%	100%	100%	100%	100%	37%	25%	52%	62%	48%	45%	0%
450306	0%	0%	49%	10%	0%	0%	0%	30%	30%	0%	0%	0%

Table 23: Mold utilization before optimization method

Garden furniture	Pet Life		B2B										
	August	September	October	November	December	January	February	March	April	May	June	July	
442009	20%	52%	39%	100%	40%	34%	100%	48%	14%	27%	0%	0%	
442010	20%	54%	58%	62%	36%	62%	90%	48%	12%	14%	0%	0%	
442016	0%	6%	80%	84%	100%	100%	100%	100%	50%	43%	0%	0%	
442023	0%	2%	86%	0%	82%	100%	100%	100%	97%	37%	0%	0%	
29209598	0%	33%	46%	63%	91%	28%	0%	48%	0%	33%	0%	0%	
29209600	40%	27%	49%	49%	71%	58%	80%	21%	0%	21%	0%	0%	
442056	33%	100%	83%	0%	22%	26%	32%	100%	68%	0%	0%	0%	
442057	40%	56%	68%	0%	9%	22%	0%	29%	53%	63%	0%	0%	
442058	33%	35%	45%	30%	0%	0%	0%	11%	39%	2%	48%	0%	
442059	63%	27%	0%	81%	0%	29%	0%	36%	41%	57%	23%	0%	
442061	43%	33%	49%	0%	0%	14%	7%	15%	36%	11%	41%	0%	
442066	33%	16%	0%	0%	0%	0%	0%	0%	0%	16%	0%	0%	
441541	0%	0%	0%	0%	0%	0%	0%	0%	2%	100%	18%	0%	
450019	90%	57%	30%	33%	2%	33%	18%	32%	32%	25%	41%	29%	
450192	0%	0%	0%	16%	0%	0%	0%	0%	0%	11%	41%	0%	
450195	0%	2%	22%	0%	0%	0%	0%	0%	0%	17%	0%	0%	
450305	90%	100%	100%	100%	100%	37%	25%	45%	42%	27%	70%	20%	
450306	0%	0%	36%	24%	0%	0%	0%	0%	30%	30%	2%	0%	

Table 24: Mold utilization after optimization method

Also in these overviews, we see that the production runs are more spread out after the optimization method. Most of the production runs that are finished in May before the optimization are finished in June after the optimization, so their total production amount is distributed over a longer time period. We also see that some parts will have very long production runs. The parts '442016' and '450305' have a production run of more than 4 months straight.

Table 25 and Table 26 show a more detailed look of the production per product group. The top three rows show the number of kilograms ( $\cdot 10^3$ ) produced per month per machine group and the last row shows the total number of kilograms produced each month as a proportion of the total amount of the season. Table 25 represents the situation before the optimization and Table 26 represents the situation after the optimization. We see again that the production per month is more spread out after the optimization. We also see that January will be the busiest month. The reason for this is that the weekends of the month January are available for production. We also see that the total number of kilograms of garden furniture is the largest group with over 5 million kilograms of finished products. Thereafter, B2B products has the largest proportion and then the pet life products. Pet life products



are significantly lighter than garden furniture products so an equal number of finished products would still lead to a lot less kilograms of finished products.

	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Total
Garden furniture	32,8	576,7	616,5	734,1	419,0	1155,6	687,3	462,7	276,5	103,3	14,2	0,0	5079
Pet Life	38,7	54,9	51,9	7,8	23,3	1,8	27,5	62,8	44,5	4,7	0,0	0,0	318
B2B	152,6	252,5	272,8	237,7	160,4	162,9	79,6	270,4	302,0	153,6	197,7	0,0	2242
Total per month	3%	12%	12%	13%	8%	17%	10%	10%	8%	3%	3%	0%	100%

Table 25: Kilograms ( $\cdot 10^3$ ) produced per month per product group before optimization

	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Total
Garden furniture	30,0	418,5	554,7	575,8	499,1	1011,2	631,4	504,7	510,6	242,5	59,6	0,0	5079
Pet Life	30,1	57,8	54,0	4,2	7,3	24,7	11,4	48,9	51,0	24,2	4,4	0,0	318
B2B	152,6	250,0	263,2	249,8	131,4	171,2	79,4	137,8	183,7	286,8	255,7	80,7	2242
Total per month	3%	10%	11%	11%	8%	16%	10%	9%	10%	7%	4%	1%	100%

Table 26: Kilograms ( $\cdot 10^3$ ) produced per month per product group after optimization

## 6.4 Verification and validation

The verification and validation process lead to more confidence and helps with the decision making regarding the implementation of the model. Subsection 6.4.1 discusses the verification of the model and Subsection 6.4.2 discusses the validation.

### 6.4.1 Model verification

The model verification checks whether the model functions like it is supposed to. The model can be verified by comparing the results of the model to the expected results. These expected results are provided by the planner and the plant manager who have a lot of experience in the production planning and can make good expectations regarding number of kilograms to produce, machine utilization, and mold utilization.

The total kilograms of finished products to be sold in the season is estimated to be approximately 8 million kilograms. The production schedule has scheduled production runs with a total of approximately 7.6 million kilograms. Together with the inventory at the start of the season, this will be close to the expected 8 million kilograms. So, the BOM seems correct and the scheduling method seems to schedule all required parts for the season

We also checked the distribution of the number of kilograms over the season, which is quite similar with the distribution in the past seasons and seems correct. The utilization of the 2300 ton machines is larger than last years and the reason for this is the large increase in demand of a product of a B2B customer that is produced on the 2300 machine. Finally, the mold utilization also seems correct when comparing these with the expectation of the planner. However, there are some differences with the current situation. For example, the planner schedules for a certain part the production always in two production runs, but the model uses four production runs. Using four mold changes leads to more mold change costs but less inventory costs and more flexibility. However, future will tell if four production runs is indeed the better option. Another difference is that in the current situation, some parts are scheduled simultaneously, and in the model, this is not always the case. When two parts are scheduled simultaneously, they can be assembled immediately after production. This is easier than producing them separately and later assemble the two parts.

Overall, the model seems to be correct and all required parts for the season seems to be scheduled correctly while delivering at least 98% of the orders on time. To check whether the model is indeed a good model and an improvement for the current situation, we must validate the model. Subsection 6.4.2 explains this process.



#### 6.4.2 Model validation

The model validation checks whether the model is indeed a good model. To validate the model, we want to look for the differences and the comparisons between the model and the current situation. When looking at the differences and the comparisons, we can check whether the differences proposed by the model can indeed lead to a better output than the current situation. Unfortunately, we cannot compare the model for the whole season because the production scheduling process is only done for two months in advance. We can also not compare the model with the production schedule of last year because the data of the preliminary forecast and the ready to produce amounts are updated when the customers place their orders. So, there is no data available of all forecasts and customer orders of the past.

To be able to validate the model, we decide to make an instruction manual, so that the model can be validated during the season. The model has to be used simultaneously with the current scheduling method to check whether the model provides good decisions. Based on these results, the decision can be made whether to implement the model in its current form or that first some changes have to be made. The main production plant in Tilburg is also interested in the model and when it shows good results in Hengelo, they also want to introduce the model in their production plant. The next section elaborates on the instruction manual for the implementation.

#### Instruction manual

To be able to use the capacity planning model in the company, an instruction manual is written (see Appendix C). This instruction manual consists of 80 detailed steps which guides the user to get the production schedule and the results overview. The model that is built requires five overviews that are made using SAP which have to be exported to Excel. These overviews show the routing data, the BOM, the price per product, the number of parts per pallet, and the forecast and orders for each product. After these overviews are exported to Excel, four steps have to be taken to get the results of the production schedule model (Figure 22 of Appendix C). You can use the data of SAP or use your own data set to see the results. Step 3 automatically performs simulated annealing on the production schedule and the results show a clear overview of the production schedule and the utilization overview for the machines, machine groups, and molds (Figure 23 and Figure 24 of Appendix C).

When an extra machine is added or removed or when for a certain weekend is set to be available for production, this can easily be added in the model as well, so the model is adaptable to different situations. Also, the season, the storage costs per pallet, the inclusion of preliminary forecast, the efficiency, the safety compensation for the forecast, the number of shifts needed per machine group to change a mold, and the duration of the simulated annealing step can easily be changed in this model (Figure 21 of Appendix C).

After the production schedule is made, it can be used side by side with the 'color image' and the current scheduling method. The planner can look at the differences between the schedule of the method and the way he would schedule the orders. Based on the differences, the planner can try to evaluate whether the schedule of the model is actually a better schedule than the current schedule. Because seasonality plays a huge role it is recommended to do these comparisons for the whole season before a conclusion is drawn whether to implement the model in its current form or that first some changes have to be made to the model.

#### 6.5 Conclusions

After the serial schedule generation scheme using the earliest due date priority rule is made, we see that the average production run is ready a few weeks before its due date. This leads to a lot of inventory costs. The simulated annealing optimization method tries to improve the production schedule by

minimizing the objective function. That is, minimizing the sum of the CSL-level penalty costs, the inventory costs, and the mold change employee costs. The optimization method of 25 minutes and 3000 iterations led to a reduction of the objective value of 15.5% while keeping the CSL-level penalty cost equal, reducing the inventory costs with 29.2% and increasing the mold change employee costs with 8.4%.

The production schedule after the optimization shows a more spread out machine and mold utilization over the season. This leads to a more flexible production schedule since a delay does not immediately lead to a completely new production schedule because there are more possibilities to reschedule a single production run.

We also see that the 2300 ton machines have a very high occupancy rate during the whole season. The reason for this is that a B2B customer has largely increased their demand of a product that is made on a 2300 ton machine. However, a CSL-level of 98% is still possible using this production schedule.

To verify whether the model functions like it is supposed to, the results of the production schedule and utilization overview are compared with the expected results by the planner and the plant manager. The values in the model and the output all seemed to be correct. To validate the model, we have made an instruction manual that can be used for implementing the model and using it for one season side to side with the current method to check for the differences and comparisons. Based on the results of the model, a conclusion can be drawn whether to implement the model in its current form or that first some changes have to be made before its implementation.



## 7 Conclusions and Recommendations

This last chapter finalizes the research by drawing some conclusions and giving some recommendations regarding the research. Section 7.1 draws conclusions regarding the used methods and their results. Section 7.2 discusses the recommendations for Taman concerning the current situation and the use of the model.

### 7.1 Conclusions

Taman wants to improve their customer service level from 95.4% to 98%. Using a problem cluster, we found three potential core problems of which we choose the one with the most effect and the smallest amount of costs. Our research goal is: “use a tactical and operational planning technique to create a production planning method that leads to an increase of orders being delivered on time from 95.4% to 98%, while minimizing the total costs”.

At this moment, the production process consists of four steps: S&OP, MPS, ‘color image’, and scheduling. The step ‘color image’ and scheduling are manual processes and take a very long time to execute. Changes in the planning are made frequently which lead to changes in the ‘color image’ and scheduling process. These processes should be automated using a model, since it requires a lot of time to make these changes in the color image and the scheduling process. It is also difficult to evaluate different situations using the current scheduling method.

We first made a feasible production schedule. To do so, we automated the process after the MPS, this includes adding an MRP and choosing what kind of model to implement. We decide to use the serial schedule generation scheme since there is no limitation of the order of the jobs and this method leads to better results and has less computation time compared to the parallel schedule generation scheme (Kim & Ellis Jr, 2010). Our goal is to increase the CSL so therefore we choose the earliest due date priority rule since this priority rule is known for minimizing lateness.

This feasible production schedule made using SSGS is not optimal while it can be improved. To optimize this production schedule, we use simulated annealing. Simulated annealing selects one neighbor per iteration and searches for a global optimum instead of a local optimum, therefore this method is suitable for this research. By using a rule of thumb, we calculated the start temperature of 1268. Based on the duration of one iteration and the total available time, we calculated the maximum number of iterations, which is set at 3000. Then, we do some experiments to see from which temperature, no significant improvements were made, and we set this stop temperature to 8. Now we tested three different ratios of decreasing factor and markov chain length to find the best one. This was respectively 0.9 and 62.

To check whether the optimization method improved the initial production schedule made using the serial schedule generation scheme, an objective function is used. This function includes the CSL-level penalty costs, inventory costs, and mold change employee costs. After the simulated annealing optimization method, the objective value is decreased with 15.5%, while the CSL-level penalty costs remain the same, the inventory costs decreased with 29.2% and the mold change employee costs increased with 8.4%.

Finally, we see that the utilization of the machines and the molds is more spread out after the optimization method compared to the situation before this method. This means that this schedule is more adaptable to changes, because changes have less impact on the whole schedule. Using verification, we tested the model by comparing its output against expected results and the model seemed to be correct. To validate the model, we made an instruction manual on how to use the model. The results of this model can be compared with the results of the current situation. Based on these

results, a decision can be made whether to implement the model in its current form or that first some changes have to be made.

## 7.2 Recommendations

When a customer does not change its preliminary forecast or 'ready to produce' forecast into a customer order at least three months before the planned delivery date, the customer should be contacted. He should be given the choice of either removing the preliminary forecast or 'ready to produce' forecast or by changing this forecast into a customer order.

Some B2B customers send their forecast and their orders by email to Taman. To have a good view of all orders during a certain period, it is necessary that these customers also place their forecast and orders in SAP. In this way, these forecasts and orders are also automatically shown in the MPS overview of the model, so they do not have to be manually added. Also, when a customer places an order, this amount cannot be automatically deduced from the total forecast but has to be deduced from the customer specific forecast. In the current situation, a customer can place orders that are larger than their own forecast. Later in the season, there can be a shortage for other customers who did place orders equal to their forecast. If all orders are deduced from the forecast of the customer that places the order, this problem is solved.

The location of all machines and molds should be updated regularly. Some customer orders are still open for Hengelo while the mold belonging to this product is already moved to another production location. This can lead to miscommunication and not being able to deliver on time. Besides, we advise to use less variations on a certain product. At this moment, a customer can ask for a certain sticker on the box, another pallet, another type of cushion and for all these different customer preferences, Taman introduces a new material number. For some products, we have more than 80 different versions. These different versions make Taman less adaptable. When there is a surplus for the production for one customer and a shortage for the production of another customer, the product first has to be repacked before it can be delivered to the other customer. This process is very time consuming.

At this moment, it is not possible to run in SAP an overview per day of all forecasts and customer orders of the coming year. This can only be run for the coming 52 days. The data is available because in product specific overviews, we can find the data for each day of the coming year. When this feature is added in SAP, the production scheduling process can become more detailed because the delivery dates are not set at the first day of the week but at the actual delivery day.

Based on the utilization overviews, it is clear that some of the machines are very busy during a few months of the year. We recommend Taman to think about the possibility to add a machine to their inventory of the machine group that is going to be the most busy for the months September until April. Between May and August, this machine can be moved to another production location of Retek that needs this machine for these months.

We also recommend Taman to base the purchase process on the production schedule. This production schedule shows when a certain production run starts, so also sets the deadline for the delivery of the raw materials and other required materials.

Furthermore, we recommend doing frequent checks of the functioning of the machines and molds. Especially the machines with high occupation should get preventive maintenance regularly. When such a machine breaks down, a lot of orders will be delayed, leading to orders not being delivered on time. When this delay takes long, a new production schedule is required. Besides, ad-hoc decisions regarding

purchasing, warehousing, and logistics have to be made. Preventive maintenance can decrease the possibility of unexpected failure of the machines.

We also recommend to use the model for checking the effect of accepting or declining an order. When a customer places a large order, the model can be used to analyze the effect of accepting or declining the order regarding the machine and mold utilization. Based on these results, a good decision can be made whether the order is accepted, adjusted or declined.

Finally, in future research, the model can be improved by fully using all available shifts. A mold change always happens in the second shift and a run can always start in the third shift. Then, a production run must be 2, 5, 8 etc. runs long to have the most efficient production schedule. Besides, the model can be further improved by giving certain production runs that run simultaneously a reward. This encourages the production planning process to keep these runs simultaneous. Simultaneous production runs of certain parts have the advantage of being assembled immediately after production instead of first being stored and later moved back for the assembly process.





## 8 Bibliography

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## 9 Appendix

### A. Flowcharts of optimization methods

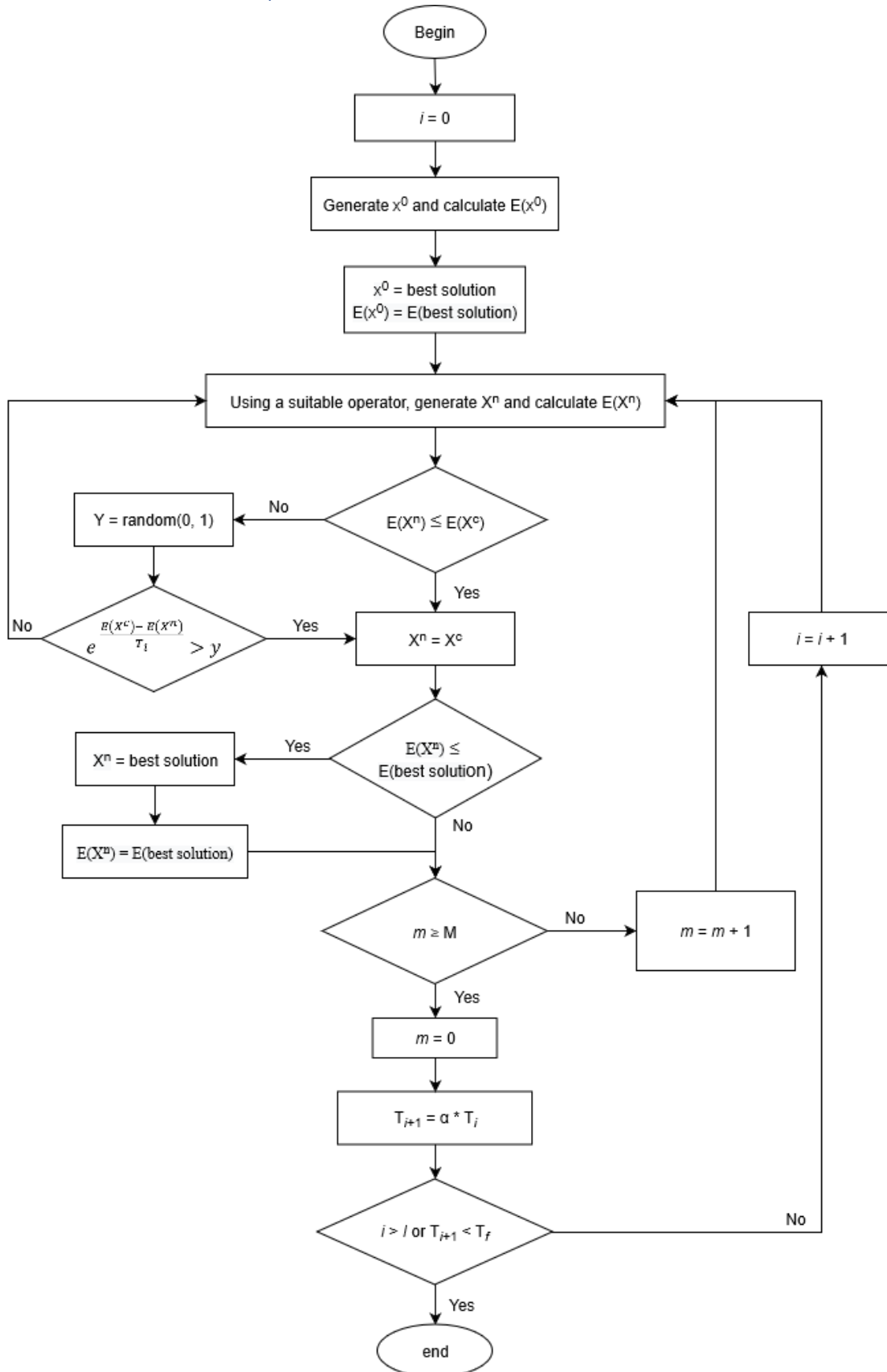


Figure 18: Flowchart simulated annealing

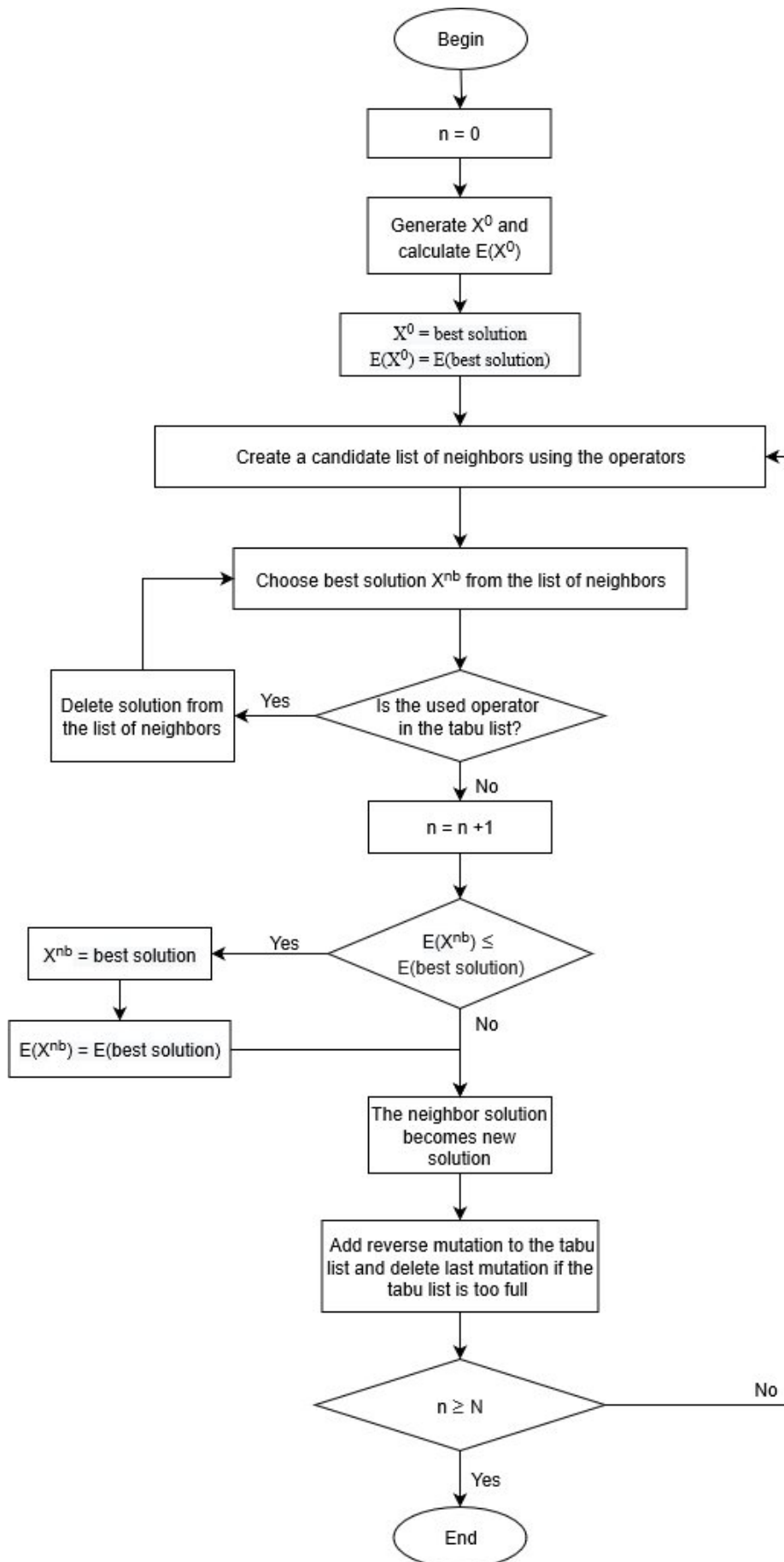


Figure 19: Tabu search flowchart

B. Flowchart of serial schedule generation scheme

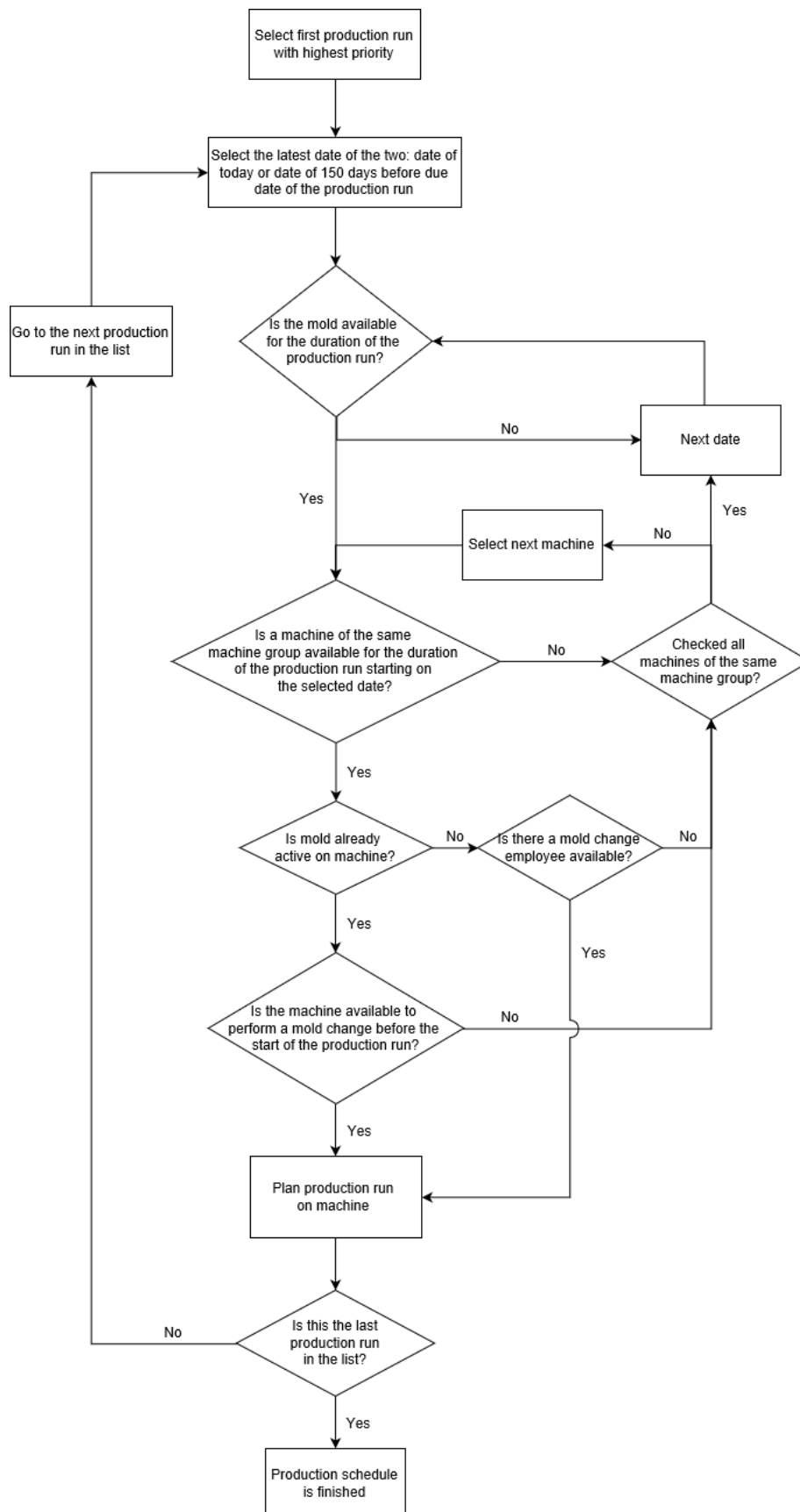


Figure 20: Flowchart of serial schedule generation scheme using the earliest due date priority rule

## C. Instruction manual

### Points to keep in mind

- *If a step mentions to paste a table in Excel, always paste the table in the most top left corner (Cell A1).*
- *Step 1 until 35 has only to be carried out when new products are being added. Normally, these steps only have to be executed once at the start of the season. If these steps are already executed, go to step 36.*
- *If you paste a new table in a certain tab in Excel, make sure the whole tab is completely empty before pasting.*
- *Do not change any data in the tabs where no data has to be pasted except the third and fourth column of the "Input Data" tab.*

1. Open ZCA02
2. Open variant "/Casper 45"
3. Run Variant
4. Export as spreadsheet
5. Copy whole table (including headers)
6. Paste whole table in the Excel file in tab "ZCA02"
  
7. Go to the Excel file in tab "ZCS12" and press the button: "Get material numbers"
8. Go to "ZCS12" in SAP and fill in at 'Application': BEST
9. Click on the arrow besides Material
10. Click on "Import from text file" (Shift + F11)
11. Look for the text file we have saved at the same location as the Excel file
12. Click on file: "Actual Material Numbers" and press F8
13. Run ZCS12 (This can take up to 3 minutes)
14. When you get the screen: "Override Data with Change Numbers", just click continue a few times. (This can take up to 2 minutes)
15. Click "Select Layout" and choose "/Casper 45"
16. Click on "Spreadsheet ..." (Ctrl + Shift + F7)
17. Export the spreadsheet (second icon)
18. Copy whole table (including headers)
19. Paste whole table in the Excel in tab "ZCS12"
  
20. Open YQ\_CD in SAP
21. Open variant "/Casper 45"
22. Run variant
23. Export as spreadsheet
24. Copy whole table (including headers)
25. Paste whole table in the Excel file in tab "YQ\_CD"
  
26. Open ZMM\_PIM in SAP
27. Click on the arrow besides "Material"
28. Click on "Import from Text file" (Shift + F11)
29. Look for the text file we have saved at the same location as the Excel file
30. Click on file: "Actual Material Numbers" and press F8
31. In "Layout" choose "/Casper 45"

32. Execute ZMM\_PIM
33. Click on List -> Export -> Spreadsheet... (or Shift F9)
34. Copy whole table (including headers)
35. Paste whole table in the Excel file in tab "ZMM\_PIM"
  
36. Open ZMD07\_P in SAP
37. Open variant "Casper 45 (1)"
38. Click on the arrow besides Material
39. Click on "Import from text file"
40. Click on file: "Actual Material Numbers" and press F8
41. Run variant
42. Export as spreadsheet
43. Copy whole table (including headers)
44. Paste whole table in the Excel file in tab "ZMD07\_P (1)"
  
45. Open ZMD07\_P in SAP
46. Open variant "Casper 45 (2)"
47. Click on the arrow besides Material
48. Click on "Import from text file" (Shift + F11)
49. Click on file: "Actual Material Numbers" and press F8
50. Run variant
51. Export as spreadsheet
52. Copy whole table (including headers)
53. Paste whole table in the Excel file in tab "ZMD07\_P (2)"
  
54. Open ZMD07\_P in SAP
55. Open variant "Casper 45 (3)"
56. Run variant
57. Export as spreadsheet
58. Copy whole table (including headers)
59. Paste whole table in the Excel file in tab "ZMD07\_P (3)"

*If there are products that have to be made but do not have customer orders in SAP, follow the next 5 steps, otherwise continue from step 67.*

60. Go to the ZMD07\_P (1) for a customer order within 52 days and to ZMD07\_P (2) tab for all other customer orders
61. Go to the last row and insert a new row
62. Fill in column 'A' the material number
63. Columns 'B' and 'C' can be left empty
64. Fill in column 'D' whether it is a 'Reqmts' or a 'PldIndReqs'
65. Fill in columns 'E' to 'BE' the number of finished products that are required for each week. There is no need to fill in 'O' for the weeks no deliveries are planned
  
66. Go to the Excel file in tab "Input Data"
67. In row 4, you can fill the season for which the production schedule is made
68. In row 7, you can change the storage costs per pallet per week
69. In row 8, you can change the transport costs per pallet
70. In row 9, you can choose to include or exclude the preliminary forecasts

71. In row 10, you can set the yield of the production. (What percentage of the production time the products are produced. This is standard set to 90%.)
72. Row 11, you can set the safety forecast compensation. (What percentage the preliminary forecast is increased or decreased. This is standard set to 0%.)
73. Row 12 until 19, show the machines that are available for the production. The first column shows the tonnage of the machine, the third column shows the quantity of machines available and the fourth column shows the number of mold change employee shifts needed for a mold change
74. Rows 20 and down shows the days that no production can take place. These days include most weekends and the holidays.

*All input is now gathered, and the production schedule can be made.*

75. Fill in your preferences for the model in the tab "Input Data" of the Excel file (Figure 21)
76. You can now start with running the model. Press "Step 1 for forecast based on SAP" if you want to get the results based on the input data of SAP. Press "Step 1 for own forecast to check results" if you want a quick check to see the model for a certain input you made yourself for example when SAP is not completely filled yet, predictions you make can be evaluated using this button.
77. After the step is finished, a pop-up appears with the running time. Close this pop-up and press the second button.
78. After step 2 is finished, you can start step 3. In the row "Duration of run" you can choose for how long the optimization will last. The optimization model is tested for a duration of 30 minutes.
79. When step 3 is finished, click on step 4.
80. When the whole model is finished, you can save the document and look at the results.
81. Go to the tab "Capacity Plan" and here you can see all scheduled production runs, the mold changes and the machines on which the runs are scheduled (Figure 23)
82. Go to the tab "Capacity Utilization" and here you can see an overview of the machine utilization, machine group utilization, mold utilization, and kilograms produced per month (Figure 24)

Here you can find input data which you can change and the model will use the new values immediately				
What	Detail	Value		
Season	Season for planning	2019-2020		
Day	Today	18-9-2019		
Day of start scheduling for own forecast	Date of start schedule	19-8-2019		
Duration of run (longer run -> better results)	Time in minutes	30		
Path	Location of output text file	C:\Users\User\Dropbox\Afstuderen\Data\Project\29-05-2019		
Storage costs	Storage costs per pallet/week	€ 0,69		
Transport costs	per pallet (33 pallets/transport)	€ 194,04		
Include forecasts	Include YKF and ZSF in planning?	NO	YES	
Efficiency	In percentage	90%	%	
Forecast compensation	Percentage extra above forecast	0%	%	
	30 # machine tonnage/staff	1	0	
	50 # machine tonnage/staff	1	0	
	350 # machine tonnage/staff	4	0,35	
	550 # machine tonnage/staff	1	0,5	
	650 # machine tonnage/staff	6	0,5	
	800 # machine tonnage/staff	2	0,6	
	1000 # machine tonnage/staff	7	0,8	
	2300 # machine tonnage/staff	2	1	
No Production #1	Date when no production takes place	24-8-2019		
No Production #2	Date when no production takes place	25-8-2019		

Figure 21: Run the model



