Master’s Thesis

Industrial Engineering and Management

IMPROVING THE MEDIUM-TERM AND SHORT-TERM PRODUCTION PLANNING PROCESS OF SEMI-FINISHED PRODUCTS AT A CABLE MANUFACTURING COMPANY

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September 14, 2022

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Management Summary

We perform this research at TKF in Haaksbergen. TKF is a cable manufacturing company that develops, produces, installs and checks cables and cable solutions. TKF is a subsidiary of TKH and was founded in 1930. TKF has grown into a leading and innovative company in the international market, specializing in three market segments, which are Telecom, Building and Industrial Solutions. The production of cables is split into roughly four departments, which are DRAFA, Multi Conductor, Energy and Installation. In our research, we focus on the production planning process of the DRAFA that processes the copper and aluminium into different wire sizes and conductors. Based on the use of the cable, the DRAFA supplies the semi-finished products to one of the three other departments that produce the cables from them. The main problem encountered by TKF is the low delivery reliability of semi-finished products from the DRAFA. In this research, we aim to find an answer to the following main research question:

"How can the DRAFA automate their medium-term and short-term production planning process to improve the delivery reliability of semi-finished products to the next departments in the production process?"

Current situation and problem description

The DRAFA produces according to MTO and MTS. The current inventory methodology used to produce MTS products is based on static minimum and maximum inventory levels. As a result, the capacity planner is not able to react adequately to uncertainties and fluctuations in daily product requests from the departments Multi Conductor, Energy and Installation. For 36.7% of the MTS products, the current ready rate is below the target value for the delivery reliability of 95%. In addition, the medium-term production plan currently does not take into account the available resource capacity. This leads to a lack of insight into whether medium-term production orders can be realized with the available capacity and whether the capacity planner should take action to prevent future capacity problems from occurring. Furthermore, the current production planning process is executed manually by the capacity planner on a daily basis. The capacity planner uses the expected demand and inventory information to make decisions based on knowledge, expertise and intuition about what and how much to produce in which sequence and on which machine.

To conduct this research, we use a stepwise approach throughout the research. The first step is to improve the current inventory management of the MTS products by coping with uncertainties and fluctuations in the expected demand. The second step is to provide insight into the medium-term production plan of the semi-finished products several weeks ahead, while taking into account the number of production hours available per machine per week. The third step is to generate the short-term production schedule of the semi-finished products several days ahead, while taking into account sequence-dependent setups.

Method

From our literature review, we find methods to integrate inventory control and lot sizing decisions into the production planning process. In this research, we face a medium-term production planning problem where products have to be planned over a finite planning horizon with limited resource capacity and where multiple products can be produced per week. Therefore, the medium-term production planning problem at the DRAFA can best be described as a capacitated lot sizing problem (CLSP) that can be modelled by an MILP model. The objective is to minimize production, setup and inventory holding costs over all products and all weeks.

However, because the classical CLSP does not fully cover the problem context at the DRAFA, we make four extensions to the model. First, the number of production hours available each week should be separated per machine. Second, we define product-component relationships among the products in the production process, because some products require multiple operations. Third, we include backorders by allowing the model to produce orders after their due data at a given penalty cost. Fourth, we take into account that only a selection of machines can be used to produce a product when assigning products to machines for production.

To model the short-term production planning problem, we make three additional extensions to the medium-term model. First, we take into account the supply lead time of a product to determine the timing of production

to meet demand, because demand for a product on a given day cannot be satisfied through production on the same day. Second, we include setup carry-overs to ensure that a machine is able to carry over its setup state between days. A setup carry-over implies that the last product produced on a day can be produced the next day without an additional setup. Third, we include sequence-dependent setup times and costs, because both depend on the sequence of the products planned on a machine.

TKF can reduce the effect of demand uncertainty by implementing the (s, nQ)-policy in the MILP models for the MTS products to achieve production and inventory management goals in the production planning process. We use the safety stocks as minimum inventory levels to reduce the risk of a product being out of stock due to uncertainty in the demand and the storage capacity as maximum inventory levels. We force the model to increase the inventory level by scheduling production when it is expected to reach the safety stock level.

Results

We conclude that our medium-term model reduces inventory holding costs and increases the delivery reliability when using the newly defined inventory parameters (i.e. new safety stock levels) instead of the old inventory parameters (i.e. static min/max levels) based on the stock movements of the MTS products. In addition, a correct determination of the unit holding costs as input for the model is important for TKF. When using higher unit holding costs (25% instead of ± 5.6% of the cost price), we see that the sum of the production, setup and inventory holding costs almost doubles as the model aims to minimize backorders by increasing production. Furthermore, our model increases the average utilization per machine and, as a result, the delivery reliability as the target fill rate increases. We also conclude that our model performs well for different problem instances, such as an increase in the resource capacity, low or high initial inventory levels, low or high expected demand rates and different product portfolios due to an increase in the number of products produced by a group of machines. Finally, we conclude that our model works as desired for future-oriented growth scenarios, even for an extreme scenario in which we double both the number of products and machines.

After running the short-term model, a problem arises that is related to the fixed resource capacity for each machine on a day, along with the requirement to produce completely filled packaging units for MTS products. To solve this problem, we allow the model to carry over the remaining resource capacities to the next production day. Because this extension of the model leads to a production schedule in which we exceed the resource capacities, we developed a backwards-oriented post-processing step. The objective is to resolve the capacity exceedance for each machine and each day in the planning horizon by moving production orders backwards. Our resulting model minimizes setup times and costs for the Middentrek and Fijntrek machines based on the sequence of the products. The model also helps the capacity planner in making purchasing-related decisions, as the Gantt chart visualizes how occupied the machines are according to the production schedule. We achieved a cost reduction of almost 7% from € 89,983 to € 83,805 compared to the manual production schedule, as our model decides not to schedule production when the inventory positions and the expected purchase orders to be received are sufficient to meet the expected demand, while the planner schedules production for MTS products based on static min/max levels.

Recommendations

First, we recommend TKF to implement both the medium-term and short-term prototype planning tool as a support tool rather than replacing the current production planning process. We recommend installing Python and purchasing the Gurobi Optimizer licence that we also used in this research. The implementation plan discusses how the proposed medium-term and short-term planning tools can be integrated and implemented in practice. Second, we recommend TKF to implement the (s, nQ)-policy for the MTS products by means of a dynamic dashboard in Excel and to update the safety stock levels on a weekly basis as input for both planning tools. Third, we recommend TKF to improve the data registration in Navision, as the quality of our planning tools is determined by the quality of the input data. Finally, we recommend TKF to improve the short-term model results by further researching machine and product characteristics that can be considered by the model when determining the sequence of products on the machines.

Preface

In front of you lies my master thesis ‘Improving the medium-term and short-term production planning process of semi-finished products at a cable manufacturing company’, with which I acquire my master’s degree in Industrial Engineering and Management at the University of Twente. With this thesis, I finalize my time of being a student. I would like to thank several people who have contributed to this thesis.

First of all, I would like to thank Bettina Plomp for giving me the opportunity to do my graduation project at TKF. Thank you for your supervision and all our weekly meetings. I appreciate the useful feedback and criticism you gave me to take this thesis to a higher level. I would also like to thank my colleagues from TKF, who helped me during this project by sharing their knowledge and expertise with me. I really enjoyed working at the company and I learned a lot during my graduation project about planning and scheduling, mathematical modelling and operations research in production environments. The afternoon walks were a nice way to discuss problems I encountered during my research with other employees of TKF.

Furthermore, I would like to thank my first supervisor Matthieu van der Heijden from the University of Twente. Thank you for always finding time to discuss my thesis and to answer my questions. I have experienced the guidance as positive. Your extensive feedback and helpful insights helped me to conduct this research. I would also like to thank my second supervisor Marco Schutten for his support. Thank you for your useful advice and feedback that I could use to further improve my thesis.

Finally, I would like to thank my girlfriend, family and friends for their support. You were the people who supported me during my project and helped me through ups and downs. This really motivated me to get the most out of this project.

I hope you enjoy reading this report.

Justin Boomers

Haaksbergen, September 2022

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1 Introduction

The research for this thesis on inventory management and improving the production plan of semi-finished products at the DRAFA, which stands for "draadfabriek" in Dutch, takes place at the Twentsche Kabelfabriek (TKF) in Haaksbergen. We conducted this research as a graduation project for the master's program in Industrial Engineering and Management at the University of Twente. Confidential information, such as article numbers or descriptions, has been removed from the public version or replaced by "X" or "Y".

1.1 About TKF

TKF is a cable manufacturing company that develops, produces, installs and checks cables and cable solutions. TKF is a subsidiary of TKH Group NV (TKH) and was founded in 1930. The growth of TKH is concentrated in Europe, North America and Asia. TKF has grown into a leading and innovative company in the international market, specializing in three market segments, which are Telecom, Building and Industrial Solutions. Since the foundation of TKF in 1930, the company has developed from a cable manufacturer into a technologically leading supplier of connectivity solutions. With a broad portfolio of cables, systems and services, TKF offers worldwide customers solutions for creating safe and reliable energy and data connections.

1.1.1 DRAFA department

The production of cables is split into roughly four departments, which are DRAFA, Multi Conductor, Energy and Installation. The DRAFA processes the copper and aluminium into different wire sizes and conductors. Based on the use of the cable, the DRAFA supplies the semi-finished products to one of the three other departments (Multi Conductor, Energy or Installation) that produce the cables from them. The process steps required within the DRAFA depend on the type of semi-finished product. Wire drawing is always done to reduce the cross section of a wire by pulling it through a series of dies to obtain the desired thickness. In addition, the need to perform the bunching and stranding process within the DRAFA depends on the desired flexibility of the cable. Wire drawing, bunching and stranding mean "draadtrekken", "vlechten" and "samenslaan" in Dutch, respectively.

1.1.2 Production process

The process steps that are carried out to produce a cable depend on the use and the required thickness of the cable. In addition, the material requirements differ for different applications of the cable. As a result, different production processes are performed within the TKF factory. Figure 1.1 shows the standard production process at TKF. We have discussed examples of differences in the process steps that are carried out to produce a cable after the description of the standard production process at TKF.

Often the process starts with the purchase of large reels with copper or aluminium wire. The DRAFA processes the copper or aluminium into different wire sizes and conductors by means of wire drawing, bunching and stranding. Within the Multi Conductor, Energy and Installation departments, the conductors are isolated by an insulation layer for protection. Since a large part of the cables consists of several conductors, a stranding process is performed. Depending on the type of cable, an inner cable sheath is added during the first sheathing process to serve as a starting point for further operations such as armouring. A sheath is a visible layer that covers all previous operations and provides mechanical, flame and chemical protection. For the cable with an inner cable sheath, a braiding, armouring or screening process is performed. The braiding process is a process in which small bunches of steel wire are woven together on top of the inner cable sheath for added protection. The armouring process is a process in which layers of steel wires or metal tape are applied over the inner cable sheath to ensure that the cables are not vulnerable to damage during excavation work. The screening process is a process of incorporating a metallic earth screen construction to ensure that if the cable is cut or damaged, the short-circuit current automatically grounds to earth. The final production step is the second sheathing process that is performed for all cables for which the stranding process is performed after isolation. This sheathing process is needed to prevent dirt and water from entering the cable from the outside by means of an outer cable sheath. Finally, the quality of the cable is checked for, among other things, conductor resistance, shield resistance and water blocking, after which the cable is transported to the customer.

The first difference in the way a cable is produced is based on the type of metal used as a conductor. The difference between aluminium and copper wire is largely in the conductivity, weight and cost. Copper wires have a higher conductivity than aluminium wires, while aluminium wires are lighter and cheaper than copper wires. Second, for cables with an inner cable sheath, a braiding process provides a higher flexibility of the cable compared to an armouring process. Finally, the steps that are carried out to produce a cable depend on the guidelines per country and on properties such as flame retardancy, smoke production and the extent to which the emission of the cable is halogen-free.

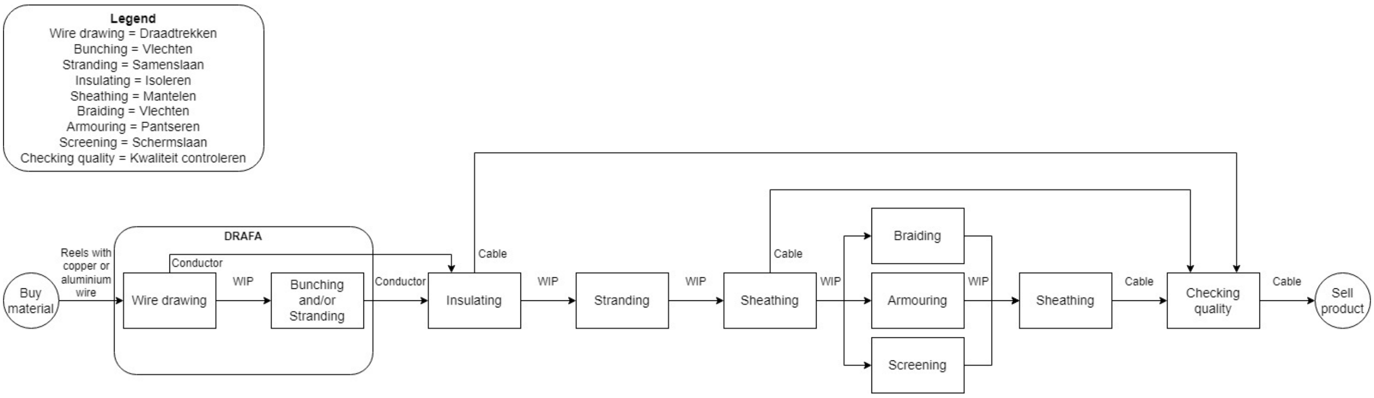

Figure 1.1 - Production process at TKF.

1.2 Research motivation

The DRAFA produces according to Make to Order (MTO), based on orders from the departments Multi Conductor, Energy and Installation, and Make to Stock (MTS). Unless otherwise stated, MTO and MTS products refer to the semi-finished products produced within the DRAFA. The MTS products are placed in stock within the DRAFA after production of the semi-finished products. The production of both MTO and MTS products is triggered by the demand of the next department in the production process. As a result, the customer order decoupling point is at the next department. The difference is that an MTO product is directly related to an order from the next department, while this is not the case for an MTS product. The departments Multi Conductor, Energy and Installation produce cables as finished products according to MTO, based on orders from customers of TKF, and MTS. However, an MTO product for these departments is not by definition an MTO product for the DRAFA, nor is it for MTS products.

The methodology used to produce MTS products within the DRAFA is called Kanban. However, the steps taken to produce MTS products are not well aligned with the Kanban methodology. Currently, there is an inventory list available of MTS products with a minimum and maximum inventory level. The capacity planner monitors when the inventory position of an MTS product falls (almost) below the minimum inventory level and then assigns the product to the appropriate machine for production. In addition, the capacity planner determines the sequence of MTS and MTO products per machine based on expertise and intuition, which is a time-consuming process.

The main problem encountered by TKF is the low delivery reliability of semi-finished products from the DRAFA to the departments Multi Conductor, Energy and Installation. To quantify the current performance of the DRAFA, we made a distinction between the analysis of MTS and MTO products produced within the DRAFA. As we discuss later in Section 2.5.1, the ready rate is calculated separately for each MTS product and provides insight into the fraction of time in which the DRAFA is able to deliver semi-finished products to the departments Multi Conductor, Energy and Installation. For 36.7% of the MTS products that are supplied to one of the three other departments after production in the DRAFA, the current ready rate is below the target value of 95%. As we discuss later in Section 2.5.2, a total of 34.6% of all MTO products produced within the DRAFA are delivered late in the period from 01-02-2021 to 31-01-2022. As a result, the current delivery reliability of the MTO products produced within the DRAFA is approximately 65.4%.

The low delivery reliability is due to the lack of an optimal production plan at the DRAFA and leads to production downtime and production inefficiency in the departments Multi Conductor, Energy and Installation. Production downtime occurs when there is no stock available of certain semi-finished products at the DRAFA and when the next department is not able to produce another production order instead. Production inefficiency occurs when the DRAFA is not able to meet the desired demand of the next department, leading to sub-optimal clustering at the next department. If possible, the next department clusters a group of similar end products to reduce machine setup times. In addition, the low delivery reliability of semi-finished products from the DRAFA can lead to delays in the desired delivery dates of semi-finished products at the departments Multi Conductor, Energy and Installation.

Currently, the inventory methodology used to produce MTS products within the DRAFA is not able to react to uncertainties and fluctuations in daily demand. This problem arises because the current inventory methodology is based on static minimum and maximum inventory levels of MTS products. This makes it difficult for the DRAFA to react adequately to uncertainties and fluctuations in daily product requests from the departments Multi Conductor, Energy and Installation. For example, it may be that there is sufficient stock of a certain semi-finished product, according to the determined minimum inventory level, and that the next day there is suddenly no more stock of that semi-finished product.

1.3 Problem statement

We presented the problems that are encountered by TKF at the start of the research visually in a problem cluster in Figure 1.2. The green box is the central problem. The white, red and orange boxes are causes, core influenceable problems and core non-influenceable problems, respectively. With the help of a problem cluster, we identified connections between problems through causal links between the various problems. The core problems are the root causes of the observed main problem (Heerkens & van Winden, 2017). The numbers in the problem cluster correspond to the numbers in the text below to improve readability.

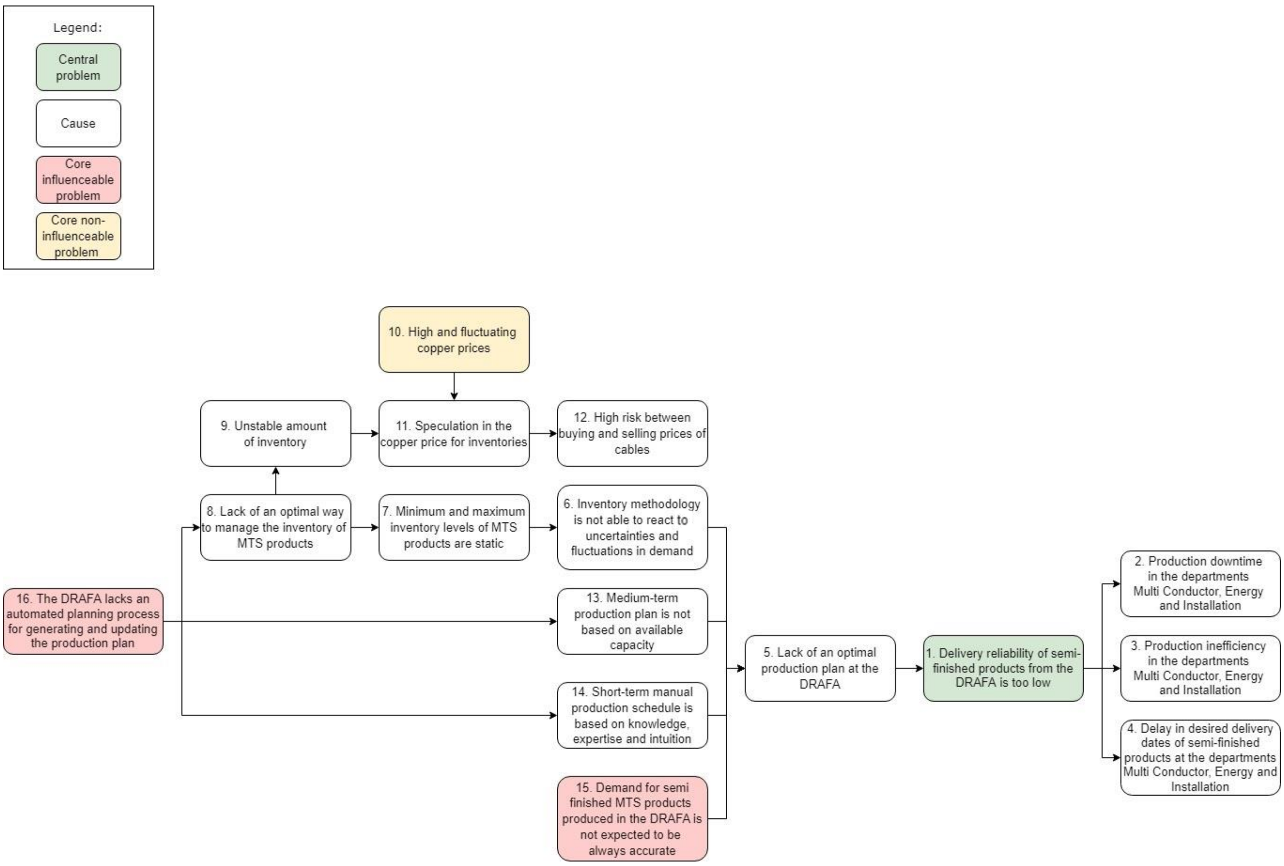

Figure 1.2 - Problem cluster.

The central problem (1) in this research is marked green. At TKF, the delivery reliability of semi-finished products from the DRAFA is too low. This leads to production downtime (2) and production inefficiency (3) in the departments Multi Conductor, Energy and Installation and to delays in the desired delivery dates of semi-finished products for those departments (4). The low delivery reliability of semi-finished products from the DRAFA is the result of multiple causes and sub-causes.

First, the low delivery reliability of semi-finished products from the DRAFA is caused by the lack of an optimal production plan at the DRAFA (5). The production plan at the DRAFA is not optimal because the current inventory methodology, used to manage the inventory of MTS products and required as input to produce MTS products, is not able to react to uncertainties and fluctuations in daily demand (6). The capacity planner of the DRAFA knows about five weeks in advance which quantities of which products have to be produced, given the delivery time of 7 to 11 weeks from placing the order until delivery to the end customer. However, uncertainties and fluctuations in the daily demand occur due to changes in the short-term production schedule of the departments Multi Conductor, Energy and Installation, which are the customers of the DRAFA. For example, when a department clusters a group of similar end products that require a large quantity of the same semi-finished products produced within the DRAFA. Due to the static minimum and maximum inventory levels of MTS products (7), the DRAFA is not always able to deliver the fluctuating amount of semi-finished products as requested by the departments Multi Conductor, Energy and Installation. This means that these inventory levels were once determined, but it is not known whether those inventory levels are still relevant to the current situation. Having static values for the minimum and maximum inventory levels that are not up to date is due to a lack of an optimal way to manage the inventory of MTS products (8).

A lack of an optimal way to manage the inventory of MTS products also results in an unstable amount of inventory (9). Together with high and strongly fluctuating copper prices (10), it leads to speculation in the copper price for inventories of semi-finished products containing copper (11) and therefore to a high risk between the buying and selling price of cables made up of copper (12). To reduce the risk between the buying and selling prices, it is desirable to have low and stable stock levels. Since the high and strongly fluctuating copper prices cannot be influenced, it is a non-influenceable core problem.

Furthermore, the medium-term production plan generated several weeks ahead currently does not take into account the available capacity in terms of the number of production hours per machine per week (13). The capacity planner therefore lacks insight into whether medium-term orders can be realized with the available capacity. As a result, orders are postponed in the short-term due to capacity constraints, which leads to a lower delivery reliability of semi-finished products from the DRAFA. Moreover, the production plan at the DRAFA is not optimal because for the short-term production schedule, each production order currently has to be scheduled manually by the capacity planner based on knowledge, expertise and intuition (14).

Finally, the production plan at the DRAFA is not optimal because the demand for semi-finished products from the departments Multi Conductor, Energy and Installation as input for the production plan at the DRAFA is not expected to be always accurate (15). Given the delivery time of 7 to 11 weeks from placing the order until delivery to the end customer, the capacity planner of the DRAFA knows in time which semi-finished products have to be produced. In determining the expected production of semi-finished MTO and MTS products per week, the Enterprise Resource Planning (ERP) system Navision does not take capacity limitations into account. The expected production for several weeks in the future is not feasible when the workload at the DRAFA exceeds the capacity and must then be postponed by the capacity planner. In addition, incorrect buffer lead times (as we explain later in Section 2.2) can cause the expected production of semi-finished MTO and MTS products to be postponed. To clarify, if the buffer lead time of an operation performed at Installation is too high, the product demand from Installation may arrive later than expected by the capacity planner of the DRAFA. For MTS products, TKF recently developed an Excel tool that calculates the expected production of the semi-finished products at the DRAFA, based on available data in Navision. The relevant data in Navision relates to the future production of the departments Multi Conductor, Energy and Installation. However, the established expected production of semi-finished MTS products at the DRAFA does not always correspond to the actual production. This problem is partly caused by an incorrect conversion of the available data from

Navision to the expected production of semi-finished products at the DRAFA. Parallel to this research, the capacity planner is analysing the causes and improving the accuracy of determining the demand for semi-finished MTS products produced in the DRAFA as input for the production planning process. Therefore, improving the accuracy of the expected demand for semi-finished MTS products produced in the DRAFA is beyond the scope of this research and has not been selected as a core influenceable problem.

The action problem arising from the problem cluster is that the DRAFA lacks an automated planning process for generating and updating the production plan (16). The problem owner is the DRAFA and the capacity planner of the department. The difference between the norm and reality is that the delivery reliability of semi-finished products from the DRAFA needs to be improved. There is no predefined norm that quantifies the current delivery reliability of semi-finished products from the DRAFA to the departments Multi Conductor, Energy and Installation. Taking all this into consideration, we formulated the problem statement as follows:

"The DRAFA lacks an automated planning process for generating and updating the production plan, which leads to a low delivery reliability of semi-finished products from the DRAFA to the departments Multi Conductor, Energy and Installation".

1.4 Problem approach

To be able to solve the research problem, a prototype planning tool should be developed to automate the process of generating and updating the production plan. The inventory parameter values for the MTS products are required as input for the prototype planning tool. Therefore, an appropriate inventory control policy has to be selected for the MTS products being produced within the DRAFA. As mentioned, fluctuations or peaks occur when the department Multi Conductor, Energy or Installation clusters a group of similar end products that require a large quantity of the same semi-finished products produced within the DRAFA. Based on the degree of uncertainties and fluctuations, MTS products can be grouped according to an appropriate classification scheme (e.g. low versus high fluctuation). Subsequently, an appropriate target fill rate can be selected for each group of MTS products. Constraints on the available physical space and the total length or weight per packaging unit as the minimum production quantity must be taken into account. The goal is to improve the delivery performance of MTS products as expressed in the ready rate.

After determining the appropriate inventory control policy for the MTS products, the production schedule of the MTS and MTO products within the DRAFA should be adjusted accordingly. In the medium-term, several weeks ahead, the prototype planning tool should be able to decide which quantities of which semi-finished products to produce in which week for the next two months. The planning horizon is ± two months, given the delivery time of 7 to 11 weeks from placing the order until delivery to the end customer of TKF. The medium-term production plan is less detailed, but it provides insight into whether the planned production quantities in a week can also be realized with the available capacity and it makes it possible to respond in advance to capacity problems that may arise in the future. In the short-term, several days ahead, the prototype planning tool should be able to decide which quantities of which semi-finished products to schedule in which sequence and on which machine.

The part of the production plan that relates to the production of the MTS products must be based on the parameters of the inventory control policy. The parameters of the inventory control policy that trigger the production planning process depend on the demand of the next department in the production process. In addition, the part of the production plan that relates to the production of the MTO products is directly related to an order from the next department in the production process. The demand of the next department is related to the inventory positions of MTS products at those departments or an agreed delivery date with the customer of TKF and a latest start date for production within the DRAFA for MTO products at those departments.

There are some constraints to consider when generating and updating the production plan. First of all, it must be checked whether the desired production quantities can also be realized with the available capacity in terms of the number of production hours available per machine in each time period. In addition, combining MTS and/or MTO products in the production schedule to reduce machine setup times can also be considered.

1.5 Deliverables

After conducting this research, we provided the following deliverables to the company.

1. A tool in Excel to regularly manage the inventory of the MTS products based on an appropriate inventory control policy.
2. A prototype planning tool in Python to generate and update the medium-term production plan and the short-term production schedule when required by TKF.
3. A manual for TKF for using the tool to regularly manage the inventory of the MTS products and for using the prototype planning tools.
4. A master's thesis report on the execution and results of the research, including the conclusions drawn and the recommendations given to the company.

1.6 Research objective

The aim of this research is based on the problem described in Section 1.3 and is:

"To develop a tool that manages the inventory of the MTS products based on an appropriate inventory control policy and prototype planning tools to generate and update the medium-term production plan and the short-term production schedule accordingly, to improve the delivery reliability of semi-finished products from the DRAFA to the departments Multi Conductor, Energy and Installation".

Due to time restrictions, we have determined the scope of the research. First, since the DRAFA is the problem owner of the research, their view is used as a guideline and the results mainly contribute to their department. Second, the research is restricted to generating and updating the medium-term production plan and the short-term production schedule of the MTS and MTO products produced in the DRAFA. Finally, improving the accuracy of the expected demand for semi-finished MTS products produced in the DRAFA is beyond the scope of this research. As mentioned, the capacity planner is currently analysing the causes and improving the accuracy of the expected demand for semi-finished MTS products produced in the DRAFA as input for the production planning process parallel to this research.

1.7 Research questions

After defining the objective of this research, we formulated a number of research questions. To achieve the research objective, we answered the research sub-questions one by one, after which we answered the main research question. The main research question is related to the research objective as defined in Section 1.6. We formulated the main research question as follows:

"How can the DRAFA automate their medium-term and short-term production planning process to improve the delivery reliability of semi-finished products to the next departments in the production process?"

To answer the main research question, we have defined six research sub-questions. The first sub-question is related to the understanding of the current process. The second sub-question is related to the proposed methods in the literature to manage the inventory of MTS products and to gain insight into the medium-term production plan and the short-term production schedule of MTO and MTS products, when taking into account capacity constraints. The information obtained from the literature provides insight into solution approaches suitable for solving the problem at the DRAFA. The third sub-question is related to the design of the model. The fourth sub-question is related to the performance of the medium-term and short-term prototype planning tool. The fifth sub-question is related to the implementation plan. Finally, the sixth sub-question is related to the conclusions drawn and the recommendations given to the company. We further elaborate on the research sub-questions below.

1. How is the production planning process of semi-finished products at the DRAFA currently performed?
    - 1.1. What are the characteristics of an MTO product and an MTS product?
    - 1.2. How is the inventory of MTS products currently managed?
    - 1.3. What decisions are made by the capacity planner in the current production planning process?
    - 1.4. What are production planning constraints and requirements?

1.5. What data is available at TKF about the demand for semi-finished products produced in the DRAFA?
1.6. What data is available at TKF about the delivery of semi-finished products to the next departments in the production process?
1.7. Which KPIs are most important to the DRAFA?
1.8. What are the target values of those KPIs?

The first sub-question focuses on the current production planning process of the semi-finished products produced in the DRAFA and helps to understand the problem context. To gain insight into the current production planning process, we conducted interviews with different employees from different departments of TKF. In this phase of the research, we have made a more detailed distinction between the characteristics of MTO and MTS products. Furthermore, we collected and analysed available data regarding the demand for semi-finished products produced in the DRAFA and the delivery of semi-finished products from the DRAFA. This phase of the research also covers how the inventory of MTS products is managed according to the current inventory methodology. We have identified additional information that is required regarding decisions made by the capacity planner, constraints and requirements that should be taken into account and relevant KPIs and their target values.

2. What can we learn from the literature about integrating inventory control and lot sizing decisions into the production planning process, while minimizing costs and taking capacity constraints into account?
   2.1. What classification schemes have been proposed to group products?
   2.2. What inventory control policies have been proposed to manage inventory for groups of products?
   2.3. How can the parameters of the inventory control policies be determined?
   2.4. What lot sizing models have been proposed to model the medium-term production planning problem at the DRAFA that integrates inventory control decisions?
   2.5. What model extensions have been proposed in the literature to generate the short-term production schedule of MTO and MTS products?

The second sub-question focuses on identifying and understanding possibilities proposed in the literature for integrating inventory control decisions for MTS products and lot sizing decisions for both MTO and MTS products into the production planning process of the DRAFA. This phase of the research contains various classification schemes for grouping products and common types of inventory control policies to manage inventory. Furthermore, it discusses the parameters of the inventory control policies and explains how to calculate the parameter values. This phase of the research also describes lot sizing models that can be used to model the medium-term production planning problem at the DRAFA. In addition, it focuses on extensions to the model needed to generate the short-term production schedule of MTO and MTS products, while taking the determined inventory parameter values of the MTS products as input. To conclude this phase of the research, we described a preferred solution approach adapted to the problem context.

3. How should the prototype planning tool be designed for automating the production planning process of MTO and MTS products, while integrating inventory control and lot sizing decisions?
   3.1. What requirements and assumptions do we take into account in our model?
   3.2. What lot sizing model is suitable to represent the medium-term production situation of the DRAFA?
   3.3. What inventory control policy is appropriate for the MTS products?
   3.4. How can we integrate inventory and lot sizing decisions into one prototype planning tool?
   3.5. How should we extend the model to provide insight into the short-term production schedule of MTO and MTS products?

The third sub-question focuses on designing and developing the prototype planning tool for automating the production planning process of MTO and MTS products and therefore solving the problem. We describe the requirements that we set and the assumptions that we make in our model. Based on these requirements and assumptions and a description of the model in words, we decide on what lot sizing model proposed in the literature fits the problem context. We designed the lot sizing model to decide which quantities of which semi-finished products to produce in which week, known as the medium-term production plan. This phase of the research also describes the mathematical formulation of the model, including necessary model extensions and an explanation of the determination of the cost parameters. In addition, we present an appropriate inventory control policy that we implement in the lot sizing model to reduce the effects of demand uncertainty by integrating inventory control and lot sizing decisions. Finally, we further extended the model by incorporating positive supply lead times, setup carry-overs and sequence-dependent setup times to model the short-term production planning problem.

4. How does the medium-term and short-term prototype planning tool perform?
    4.1. How do we verify the planning model and validate the model results with the real world problem at the DRAFA?
    4.2. What input data is required for the medium-term and short-term planning tool?
    4.3. Which experimental setup do we use to model different settings of the input data?
    4.4. How can the performance of both planning tools be measured?
    4.5. How does the medium-term planning tool perform under different experimental settings?
    4.6. What is the quality of our short-term planning tool compared to the current planning method?
    4.7. What similarities and differences do we get when we compare the operational production schedule with the tactical production plan per machine?

The fourth sub-question focuses on the experimentation and evaluation after we have developed a prototype planning tool. This phase of the research starts with a verification of the planning model and a validation of the model results with the real world problem at the DRAFA. In addition, we describe the input data that is required for the medium-term and short-term planning tool. Furthermore, this sub-question focuses on the experimental setup that we use to model different settings of the input data and the KPIs based upon which the performance of the planning tool can be measured for both the medium-term and the short-term. We evaluated the performance of the medium-term planning tool for different settings of the input data. Furthermore, we evaluated the quality of our short-term planning tool by comparing the model results with the operational production schedule based on static minimum and maximum inventory levels for the MTS products, which is created manually by the planner. Finally, we made a comparison between the operational production schedule and the tactical production plan per machine.

5. How can the proposed medium-term and short-term planning tools be integrated and implemented in practice?

The fifth sub-question focuses on the implementation plan. This phase of the research describes how to implement the medium-term and short-term planning tool in practice and provides insight into the integration of both tools. We also advise on the frequency with which both tools should be used.

6. What are the conclusions drawn and the recommendations given to the company?
    6.1. What can be recommended to the company based on the results of the research?
    6.2. What further research can be done in line with the results of the research?

We have structured the master’s thesis report as follows. Chapters 2 to 6 provide an answer to research sub-questions 1 to 5, respectively. Chapter 7 answers research sub-question 6 and contains the conclusions drawn and the recommendations given to the company. Chapter 7 also includes a discussion and possibilities for further research in line with the results of the research.

2 Current situation

This chapter answers the first research question stated in Section 1.7 and is related to understanding the current production planning process of the semi-finished products at the DRAFA. To answer the first research question, we combined insights from interviews with employees from different departments of TKF, observations of the production process within the TKF factory and data analysis. The first research question is formulated as follows:

1. How is the production planning process of semi-finished products at the DRAFA currently performed?

Section 2.1 provides a more detailed description of the production process at the DRAFA. Section 2.2 introduces the portfolio of semi-finished products produced in the DRAFA and provides a distinction between the characteristics of MTO and MTS products. Section 2.3 describes how the inventory of the fast-moving MTS products is managed according to the current inventory methodology. Section 2.4 provides insight into the decisions made by the capacity planner of the DRAFA and the production planning constraints and requirements. Section 2.5 discusses the current performance of the DRAFA expressed in the delivery reliability of semi-finished products. Section 2.6 identifies the KPIs that are most important to the DRAFA and their target values. Section 2.7 describes the stepwise approach that we use in this research to solve the three main problems arising from the current situation, after which Section 2.8 concludes the chapter.

2.1 Production process at the DRAFA

Section 1.1.2 described the standard production process of cables within TKF. This section provides a more detailed description of the production process at the DRAFA. As shown in Figure 1.1, the process steps carried out within the DRAFA are wire drawing, bunching and stranding.

2.1.1 Wire drawing

The first process step carried out within the DRAFA is wire drawing to reduce the cross section of a wire to obtain the desired diameter. The purchased reels with copper or aluminium wire arrive at the DRAFA in bundles with a diameter of 8 and 9.5 mm, respectively (Figure 2.1 a). For the wire drawing process, a distinction is made between "Groftrek", "Middentrek" and "Fijntrek" in Dutch.

In the wire drawing process, the wire is transported in a bath with emulsion (water and oil) over increasingly faster rotating discs (Figure 2.1 b). As the wire is pulled through the drawing die, the volume remains the same and as a result, the diameter decreases and the length increases. After the wire drawing process, the copper or aluminium is made soft again by means of annealing.

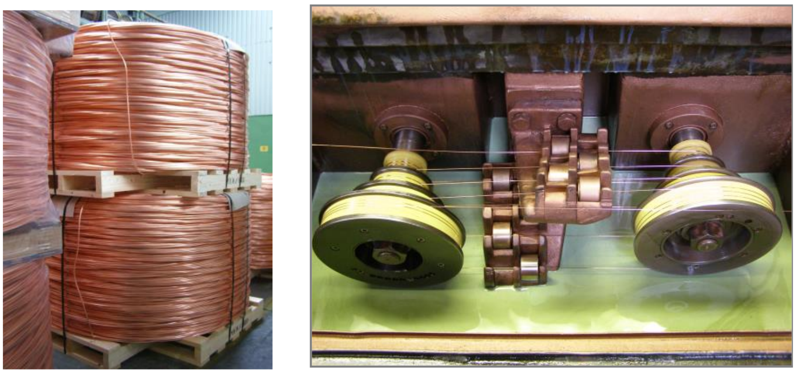

Figure 2.1 - a) Purchased bundle of copper wire, b) Wire drawing concept.

2.1.2 Bunching

The second process step carried out within the DRAFA is bunching to produce bunches or conductors consisting of multiple wires. The machine twists multiple individual wires into a bundle. A motor in the machine pulls the wires out of the baskets (Figure 2.2 a) or from the reels (Figure 2.2 b). Then a bracket gives the wires a double twist. The rotational speed of the bracket in relation to the pull-through speed determines the stroke length (Figure 2.2 c).

Figure 2.2 - a) Baskets with copper wire, b) Reels with copper wire, c) Bunch consisting of several wires.

2.1.3 Stranding

The third process step carried out within the DRAFA is stranding to produce large-sized conductors consisting of multiple layers of copper or aluminium wires. In this process step, rotating reels of wire twist each layer in the opposite direction around a core wire (Figure 2.3 a). The machine ensures that the resulting conductor is transported at a constant speed to be spooled on a large reel (Figure 2.3 b). The rotational speed of the reels in relation to the pull-through speed determines the stroke length. Using a rolling operation, it is possible to produce a compact stranded conductor.

Figure 2.3 - a) Rotating reels of wire, b) Conductor that is spooled on a large reel.

Table 2.1 provides an overview of the machines used for the part of the production process of cables at the DRAFA, including a description of the use of the machine. A more detailed explanation of the properties per machine can be found in Appendix A.

Table 2.1 - Machines used within the DRAFA.

Process step	**Machine**	**Description**
1. Wire drawing	Groftrek 1	Used to reduce the diameter of copper wire with an initial diameter of 8 mm.
	Groftrek 2	Used to reduce the diameter of aluminium wire with an initial diameter of 9.5 mm.
	Middentrek 1	Used to reduce the diameter of copper wire with a diameter of ± 3 mm which has undergone the wire drawing operation on Groftrek 1.
	Middentrek 2	
	Middentrek 3	
	Fijntrek 1	Used to reduce the diameter of copper wire with a diameter of ± 1.8 mm which has undergone the wire drawing operation on Groftrek 1.
	Fijntrek 2	
	Fijntrek 3	
2. Bunching	Vlechtdraad 1	Used to produce medium-sized conductors consisting of multiple wires.
	Vlechtdraad 2	Used to produce small-sized conductors consisting of multiple wires.
	Vlechtdraad 3	Used to produce bunches consisting of multiple wires.
	Vlechtdraad 4	
3. Stranding	Samenslaglijn 1	Used to produce large-sized conductors consisting of multiple layers of copper wires.
	Samenslaglijn 2	Used to produce large-sized conductors consisting of multiple layers of aluminium wires.

Figure 2.4 provides insight into the flow of semi-finished products through the DRAFA. This flow helps to understand the predecessor or successor of a particular machine. Together with Appendix A, it also makes clear to what extent products can be switched between machines, which is relevant to take into account when generating the production schedule. To clarify, each machine in Figure 2.4 can be the final production step of a semi-finished product in the DRAFA, after which it is forwarded to the next department. For example, after performing the operation at Fijntrek 1, some products are ready to be supplied to the next department.

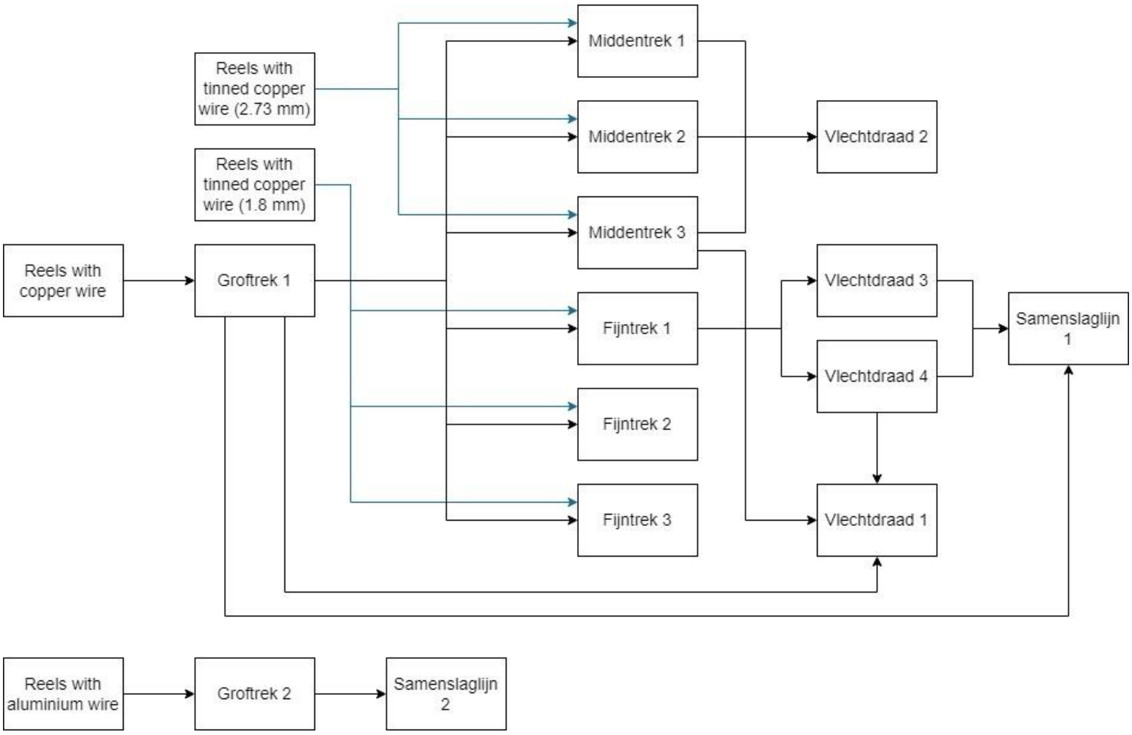

Figure 2.4 - Flow of semi-finished products through the DRAFA.

2.2 Characteristics of MTO and MTS products

As mentioned in Chapter 1, the DRAFA supplies the semi-finished products to one of the three other departments (Multi Conductor, Energy or Installation) that produce the cables from them. For the semi-finished products produced within the DRAFA, a distinction is made between MTO and MTS products.

2.2.1 MTO products

The first group of semi-finished products produced within the DRAFA are the MTO products. The MTO products are directly related to orders from the departments Multi Conductor, Energy or Installation, which are the customers of the DRAFA. When an MTO product is requested by one of the three departments, a production order is registered in the list of production orders for the DRAFA in Navision. To produce an MTO product, a latest start date for production within the DRAFA is determined and a buffer ratio is calculated. The buffer ratio indicates the ratio between the predetermined lead time and the time remaining to complete the production of the MTO product. As the latest start date for production within the DRAFA approaches, the buffer ratio increases and the production order becomes more urgent. The buffer lead time, which is included in the buffer ratio, differs per product produced within the DRAFA. Based on the analysis of the buffer lead times of the products supplied to one of the three other departments, the average buffer lead time is approximately five days. Given that each product produced within the DRAFA can be produced within one day, the extra margin is approximately four days on top of the processing time. Taking into account the buffer ratio, the production order of the MTO product is allocated to the appropriate machine by the capacity planner. For MTO products, the exact length or weight of that production order is scheduled for production.

2.2.2 MTS products

The second group of semi-finished products produced within the DRAFA are the MTS products. The MTS products refer to the semi-finished products that are placed in stock after production. According to Rajagopalan (2002), making a product to stock increases inventory for that product, but can lead to fewer setups and thus lower capacity utilization. We make a distinction between fast-moving and slow-moving MTS products. The DRAFA does not use quantitative criteria to determine whether an MTS product belongs to the group of fast movers or slow movers. However, the main guideline to approach an MTS product as a fast mover is a large number of production requests. In addition, the main guideline to approach an MTS product as a slow mover is a small number of production requests combined with a high product complexity, leading to high setup times. This makes it cost-effective to produce slow-moving MTS products in one batch based on the expected demand over the next five weeks. The period of five weeks is because the capacity planner of the DRAFA knows about five weeks in advance which quantities of which products have to be produced.

Based on intuition, the capacity planner of the DRAFA can add or remove products from the inventory list and can adjust the minimum and maximum inventory levels. The current inventory list consists of 47 fast-moving MTS products produced within the DRAFA. For fast-moving MTS products, it is desirable to always have a certain amount in stock. A minimum and maximum inventory level are assigned to each MTS product on the inventory list. When the inventory position of an MTS product falls (almost) below the minimum inventory level, a production order of the MTS product is allocated to the appropriate machine for production by the capacity planner. In other words, the capacity planner of the DRAFA uses an (R, s, S)-policy for the fast-moving MTS products. The capacity planner checks the inventory position on a daily basis, which is the review period R. If the inventory position drops to or below the minimum inventory level s, a replenishment is made to raise the inventory position to the maximum inventory level S (Silver, Pyke, & Thomas, 2017). For fast-moving MTS products, the capacity planner determines which length or weight of that product is scheduled for production when taking into account the maximum inventory level.

In addition, 11 slow-moving MTS products are produced within the DRAFA, which are not on the inventory list. For slow-moving MTS products, it is not necessary to always have a certain amount in stock due to the low stock movement. Therefore, there is no minimum and maximum inventory level for those products. The slow-moving MTS products differ from MTO products as follows. First, for slow-moving MTS products, it is cost-effective to produce the expected future demand about five weeks in advance because of the high setup costs. Therefore, slow-moving MTS products are (partially) placed in stock after production, while for MTO products the exact length or weight is produced and delivered to the next department as quickly as possible. Second, when combining the production of slow-moving MTS products for more than five weeks in advance, the capacity planner also takes into account the average historical demand of the other three departments over the past three months. Third, the capacity planner often tries to plan complete packaging units (reels, baskets, etc.) for slow-moving MTS products and adjusts the planned length or weight accordingly. For slow-moving MTS products, the capacity planner determines which length or weight of that product is scheduled for production based on both historical demand and expected future demand as registered in Navision.

2.2.3 Distribution of the production time used per product group

Figure 2.5 shows the distribution of the total production time used per product group within the DRAFA over a time period of one year from 01-02-2021 to 31-01-2022. As shown in Figure 2.4, part of the production process at the DRAFA consists of MTO products made up of aluminium that are successively produced on Groftrek 2 and Samenslaglijn 2. These semi-finished products are delivered to TKF's production location in Lochem, where subsea cables are produced. Because the process steps that are carried out in Lochem are very specific, the DRAFA produces and delivers the semi-finished products according to the production plan made in Lochem. From a planning perspective, the production plan of Groftrek 2 and Samenslaglijn 2 is controlled by the production plan made in Lochem and can therefore not be influenced. As a result, the products produced on Groftrek 2 and Samenslaglijn 2 are labelled as non-relevant MTO products in Figure 2.5. It becomes clear that the majority of the production time across all machines within the DRAFA is used to produce fast-moving MTS products.

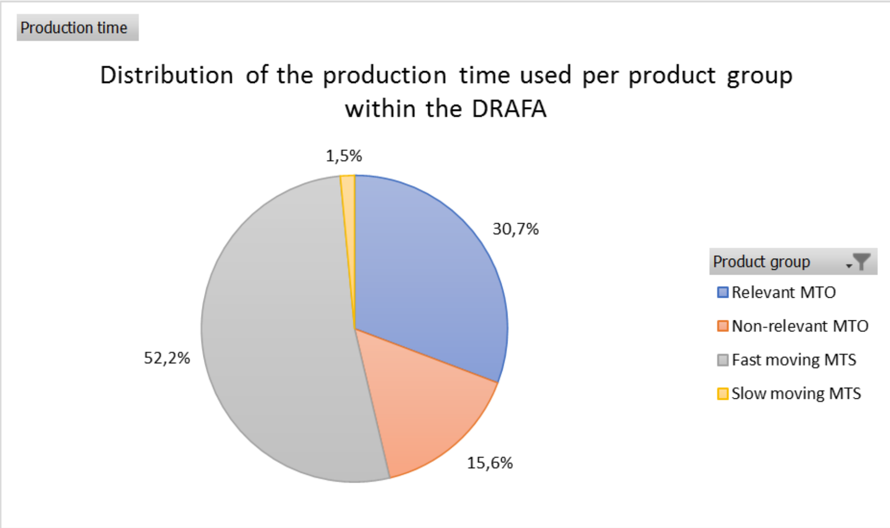

Figure 2.5 - Distribution of the production time used per product group within the DRAFA.

2.3 Inventory management of the fast-moving MTS products

The inventory of the fast-moving MTS products is currently managed according to an inventory list that contains the minimum and maximum inventory levels and the current inventory position per MTS product. The minimum and maximum inventory levels were once determined based on insights from the capacity planner of the DRAFA. Currently, the minimum and maximum inventory levels are static and not updated based on changes in the production quantities of the fast-moving MTS products. As discussed in Section 1.3, uncertainties and fluctuations in daily demand arise as a result of changes in the short-term production schedule of the departments Multi Conductor, Energy and Installation. During the day, the inventory positions increase due to production within the DRAFA and decrease due to production within the other departments. After production within the DRAFA, two methods are used by TKF to increase the inventory position in Navision. For the MTS products produced in relatively small lengths, a separate reference number is generated for each new length that is produced to monitor the inventory position of each specific length. For the MTS products produced in relatively long lengths, only one reference number is generated to monitor the inventory position. Once a new production order of that MTS product is produced, the produced length is added to the total inventory position of that MTS product. We take both methods into account when determining the stock movements to quantify the current delivery reliability of MTS products in section 2.5.

The inventory list is generated once a day at 00:00 am (1) and communicated to the capacity planner of the departments DRAFA, Multi Conductor, Energy and Installation. The capacity planners of all four departments schedule production based on the information on the inventory list during the morning at ± 11:00 am (2) for more than one day ahead until ± 06:00 pm the next day (5). Figure 2.6 shows a timeline to visualize how the inventory of the fast-moving MTS products is managed according to the current inventory methodology. If the capacity planner of a department other than the DRAFA requests a product from the DRAFA that reduces the inventory position of that product, the capacity planner of the DRAFA notices this the next morning production is scheduled (4) based on the information on the new inventory list (3). If needed according to the minimum inventory level of that product, the capacity planner of the DRAFA can schedule new production on the machines after 06.00 pm (5) at the earliest, as scheduled production is fixed until this time. In other words, the inventory position of an MTS product can decrease from point (1) on the timeline due to product requests from the departments Multi Conductor, Energy and Installation and can be replenished after 06.00 pm the next day (5) at the earliest, which is equal to a period of 1.75 days.

To replenish the inventory position of an MTS product, the response time of the DRAFA must be taken into account. The response time consists of the speed at which an MTS product can be put into production, depending on the available production capacity and the workload at that moment, and the setup time plus the production time of that MTS product. Since the response time varies per MTS product, the lead time from the decrease of the inventory position of an MTS product until replenishment also varies per product. To quantify the current delivery reliability of semi-finished products from the DRAFA in Section 2.5, we have determined the lead time from the decrease of the inventory position of an MTS product (1) until replenishment (6) for each MTS product separately. Because it depends on the availability of the resources whether the capacity planner can schedule production on the machines at 06.00 pm, the following equation is used to compute a lower bound for the lead time per MTS product. In addition, we can add a safety lead time to cope with additional waiting time for production due to limited capacity.

$$Lead\ time = 1.75\ days + \ Response\ time$$

The 1.75 days apply to each product, because if the inventory position falls below the minimum inventory level after point (1) on the timeline, it can be replenished after 06.00 pm the next day (5) at the earliest. In addition, the response time is a variable that largely depends on the production time of the product. For each MTS product, we have based the response time on the setup plus production time of one packaging unit. Based on historical production data over a period of one year from 01-02-2021 to 31-01-2022, the average setup plus production time of one packaging unit of the fast-moving MTS products ranges from 1.95 to 14.01 hours.

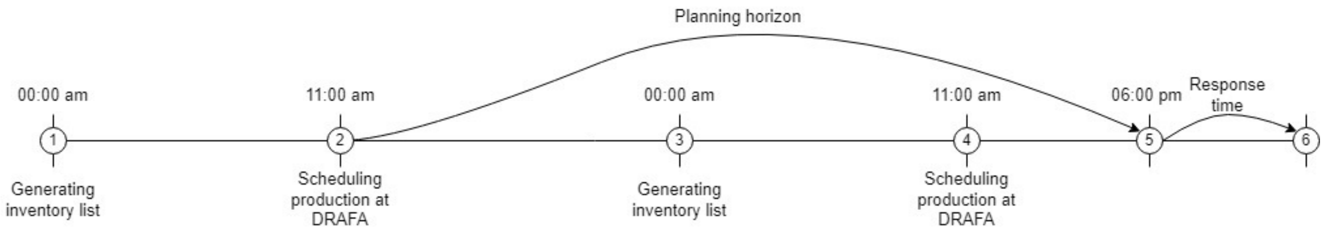

Figure 2.6 - Timeline of the current inventory management of the fast-moving MTS products.

Because the inventory list is generated once a day and is not updated during the day, the DRAFA is not always able to respond in the short-term to changes in the production schedule of the next three departments in the production process. In addition to this inflexibility, the current inventory methodology is based on static minimum and maximum inventory levels. In other words, these inventory levels were once determined, while some of them do not apply to the current situation. Based on historical production data, it became clear that the production quantities of some fast-moving MTS products changed both temporarily and structurally. As a result, we decided to revise the current inventory methodology in the first place based on an appropriate inventory control policy proposed in the literature.

2.4 Production planning process

Currently, a medium-term production plan is generated in Navision for several weeks ahead based on the list of production orders for the DRAFA. The medium-term production plan currently does not take into account the available capacity in terms of the available number of production hours per machine in a week. As a result, the capacity planner lacks insight into whether medium-term production orders can be realized with the available capacity and is not able to respond in advance to future capacity problems. In addition, the capacity planner of the DRAFA schedules the production of semi-finished products on the appropriate machine for production on a daily basis, known as the short-term production schedule. In the short-term, the capacity planner decides which quantities of which products to schedule in which sequence and on which machine. In Sections 2.4.1 to 2.4.4, we focus on the short-term production schedule, with an explanation of the production planning constraints, the performance analysis and the decisions made by the capacity planner.

2.4.1 Short-term production schedule

The capacity planner schedules production for each machine by integrating the production orders of MTO and MTS products. The sequence in which production is scheduled per machine is determined by the capacity planner and can differ per day. However, the capacity planner often starts with the machines on which a more stable production process is carried out. The capacity planner ensures that sufficient work is scheduled on each machine. As a guideline, the capacity planner aims to schedule production 24 to 48 hours in advance, depending on the availability of production orders for a particular machine.

Based on Section 2.2, 46.3% of the production time used within the DRAFA is spent on the production of MTO products and 30.7% on the production of relevant MTO products whose production schedule can be influenced. For MTO products, the capacity planner takes the buffer ratios into account and schedules the exact length or weight of that product as requested by the other departments. In addition, 52.2% of the production time is spent on the production of fast-moving MTS products. For fast-moving MTS products, the capacity planner monitors when the inventory position falls (almost) below the minimum inventory level and schedules an appropriate length or weight for that product when taking into account the maximum inventory level. Finally, 1.5% of the production time is spent on the production of slow-moving MTS products. For slow-moving MTS products, the capacity planner schedules an appropriate length or weight for that product based on the future and historical production of the other three departments as registered in Navision.

The production schedule of the DRAFA is currently based on two data sources. First, the demand for MTO products and slow-moving MTS products is based on the production schedules of the next departments. Second, the demand for fast-moving MTS products is based on the stock movement relative to the minimum and maximum inventory level.

The flow of semi-finished products through the DRAFA, as shown in Figure 2.4, is taken into account by the capacity planner when scheduling production. This flow provides insight into the preceding or succeeding operation of a particular production order at a particular machine. It is an important requirement to know what the preceding operation is and when it is expected to be completed, because the operation on a particular machine cannot start if the preceding operation has not yet been completed. In addition, it is an important requirement to know what the succeeding operation is, because the time when a particular operation is scheduled influences the time when the succeeding operation can be performed. Appendix A provides insight into the possibilities of switching production orders between machines. For example, switching production orders between Vlechtdraad 3 and Vlechtdraad 4 can be considered as these are identical machines. However, it appears that switching possibilities are limited due to the specific properties of each machine.

2.4.2 Production planning constraints

When scheduling production, some production planning constraints are relevant. The first constraint is related to the latest start date for production within the DRAFA. For MTO products, the capacity planner takes into account the buffer ratio that is based on the latest start date for production. Because of this extra buffer for production within the DRAFA, the latest start date for production within the DRAFA is not a hard constraint. However, exceeding the latest start date can be at the expense of the available buffer for the operations that are carried out in other departments later in the production process. The second constraint is related to the flow of the products through the DRAFA, as some jobs have to undergo multiple operations on a number of different machines and each operation can be performed on a limited number of machines. The third constraint relates to the available personnel on a given day. The DRAFA produces in three shifts (morning, afternoon and night) and five days a week with approximately nine employees per shift. The fourth constraint relates to the available number of production hours per machine on a given day. As mentioned in Section 2.1, 14 machines are used within the DRAFA, each with its own daily production capacity. If the desired production orders cannot be realized with the available capacity, it is possible to purchase semi-finished products from an external production company or to work overtime during the weekends. The fifth constraint relates to preventive maintenance of machines that is planned in advance. There is no possibility to schedule a product on that particular machine when maintenance is performed. The sixth constraint concerns public holidays that are taken into account, as no production takes place on these days.

2.4.3 Performance analysis

The capacity planner, production team leader, process improvement engineer and value stream manager participate in a Lean Daily Management (LDM) meeting. In this daily meeting, the performance of the past day is discussed in the areas of safety, quality, percentage on time, first time right, productivity and production losses. Of course, the aim is to produce according to the schedule. However, due to various circumstances discussed during the meeting, changes to the production schedule must be made. The following circumstances can lead to changes in the production schedule in the short-term, based on insights from the LDM meeting.

- Changes in priorities of orders to be produced, such as rework orders with a high priority.
- Machine failures.
- Illness of production staff.
- No raw materials (reels with copper or aluminium wire) in stock.

2.4.4 Decisions made by the capacity planner

To gain insight into the production planning process of semi-finished products at the DRAFA, the most important decisions made by the capacity planner on a daily basis are discussed. First, the capacity planner determines whether a machine should be shut down in case the number of production orders that can be produced on that machine is limited. A machine shutdown is not always desirable, but early production of semi-finished products that have to be kept in stock for a long time period can lead to high inventory costs and problems with the availability of reels for other production orders. Second, the capacity planner can change the sequence of production orders on the same machine and switch production orders between machines based on personally determined priorities. Adjusting the production schedule of one machine can affect the production schedule of other machines that are used later in the production process. For example, changes in the production schedule of Groftrek 1 affect the production schedule of Samenslaglijn 1. Third, the capacity planner can combine production orders to improve efficiency by making better use of reel availability and by reducing machine setup times. However, this can come at the cost of postponing more urgent production orders. To summarize, most decisions made by the capacity planner of the DRAFA are based on knowledge, expertise and intuition, which is a time-consuming process.

2.5 Current delivery reliability of the DRAFA

As described in Section 1.2, the main problem encountered by TKF is the low delivery reliability of semi-finished products from the DRAFA to the departments Multi Conductor, Energy and Installation. To quantify the low delivery reliability, available data from the ERP system Navision is analysed. In this section, we make a distinction between the current delivery reliability of MTS and MTO products produced within the DRAFA.

2.5.1 Analysis of the MTS products

For the MTS products produced within the DRAFA, we base the quantification of the current delivery reliability on the stock movements of a selection of the fast-moving MTS products that are currently on the inventory list. This selection includes the 30 fast-moving MTS products that are supplied to another department after production, as these products affect the delivery reliability of the DRAFA. The other 17 fast-moving MTS products are input for another production step within the DRAFA and are therefore not supplied to another department. Due to the low stock movement of the slow-moving MTS products, it is not necessary to always have a certain amount in stock for these products. Therefore, we exclude the slow-moving MTS products from the analysis. The stock movements of the 30 selected fast-moving MTS products provide insight into the availability of products for delivery to the departments Multi Conductor, Energy and Installation.

Since TKF currently does not have a method to determine the historical inventory position of a product per department, we have developed an Excel tool that is able to approximate the historical inventory position of a given product at the DRAFA. As discussed in Section 2.3, the capacity planners plan production for a period of more than one day ahead. Therefore, the tool assumes that for any department other than the DRAFA, an amount equal to the average amount requested from the DRAFA per day is stored in that specific department that is needed for production on that day. The tool then calculates the inventory position of a product at the DRAFA by subtracting the inventory positions at the other departments from the total inventory position at the TKF factory.

To gain insight into the current delivery reliability of MTS products from the DRAFA, the ready rate is calculated for each MTS product. According to Teunter, Syntetos and Babai (2017), the ready rate is defined as the fraction of time during which the stock on hand is positive. It is known that for Poisson and normally distributed demand, the ready rate is equivalent to the fill rate. For the MTS products produced within the DRAFA, we defined the ready rate as the fraction of time during which the inventory position at the DRAFA exceeds a certain threshold and the demand of the next departments is filled directly from stock on hand.

Our Excel tool visually displays the stock movement of a given product at the DRAFA over a time period of one year. As explained in Section 2.3, we have determined a lower bound for the lead time from the decrease of the inventory position of an MTS product until replenishment for each MTS product. In addition, we have assumed that in each department other than the DRAFA an amount is stored that is equal to the amount requested on one day from the DRAFA. Therefore, the remaining amount requested during the lead time period from the DRAFA should at least be available as inventory in the DRAFA. As a result, the following equation is used to compute the threshold for each MTS product separately.

$$\begin{aligned}&Amount\ requested\ over\ the\ lead\ time\ period\ from\ the\ DRAFA\\&= \sum_{\substack{All\ departments\\ \neq DRAFA}} Amount\ requested\ on\ 1\ day\ from\ the\ DRAFA, as\ stored\ in\ each\ department + Threshold\end{aligned}$$

To quantify the current delivery reliability, we have assumed that the DRAFA is able to deliver the semi-finished products as requested by the departments Multi Conductor, Energy and Installation when the inventory position at the DRAFA exceeds the threshold. Once the inventory position at the DRAFA drops below the threshold, it is expected that the DRAFA will not be able to deliver according to the request. Figure 2.7 shows the stock movement of one fast-moving product over a time period of one year, including the threshold. The inventory position is expressed in the number of packaging units of that product in stock.

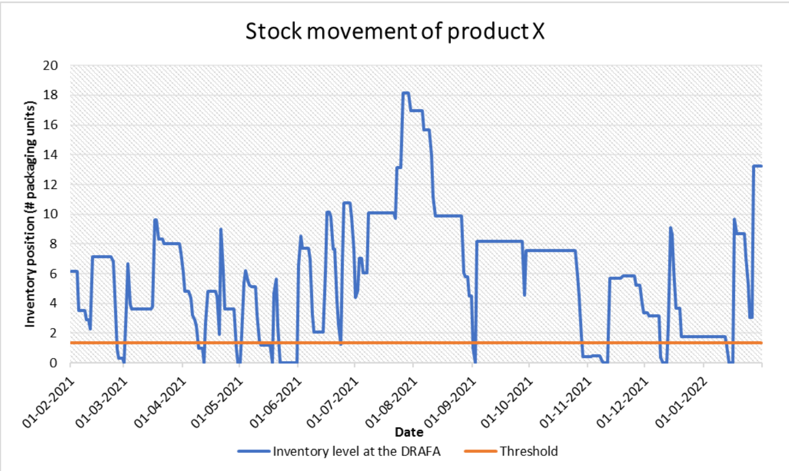

Figure 2.7 - Stock movement of a fast-moving MTS product.

From the analysis, it became clear that the inventory position at the DRAFA of this product falls below the threshold for 54 days over a time period of one year. We determine the ready rate as the number of days that the inventory position at the DRAFA exceeds the threshold for the 30 selected fast-moving MTS products. Figure 2.8 shows a Pareto chart indicating the fraction of time in which the inventory position of each fast-moving MTS product at the DRAFA is below the threshold, which is equal to one minus the ready rate.

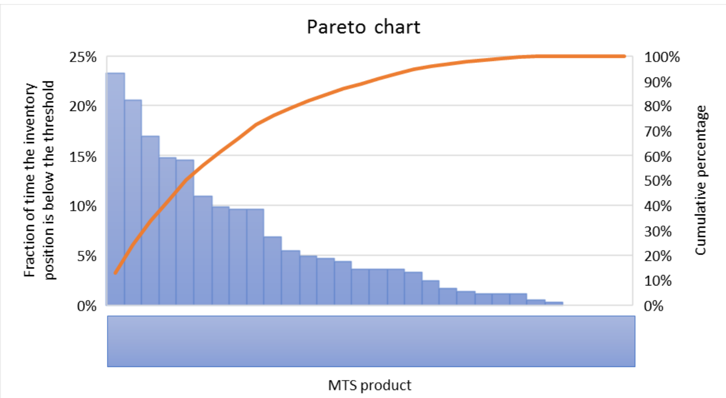

Figure 2.8 - Pareto chart, fraction of time the inventory position is below the threshold.

The Pareto chart provides insight into the current performance of the DRAFA expressed in the fraction one minus the ready rate of the 30 selected fast-moving MTS products. The analysis showed that the current ready rate fluctuates and that the average current ready rate is approximately 94.0%. However, for 36.7% of the fast-moving MTS products (11 out of 30), the current ready rate is below the target value for the delivery reliability of 95%. We discuss this target value later in Section 2.6.

2.5.2 Analysis of the MTO products

For the MTO products produced within the DRAFA, the quantification of the current delivery reliability is based on the difference between the actual completion date and the planned completion date. The actual completion date is the date on which the operation to produce a semi-finished product was actually completed as registered in Navision. After completion, the semi-finished product is ready to be supplied to one of the three other departments. The planned completion date is determined for each operation carried out within the DRAFA and is equal to the date on which a particular operation must be completed in order to meet the desired delivery date of the semi-finished product at the departments Multi Conductor, Energy and Installation. The planned completion date takes into account a buffer lead time per operation, which is included in the buffer ratio as explained in Section 2.2. The buffer lead time per operation is a fixed value that is determined by TKF and allows a few days of slack on top of the expected production time.

Once the date on which the MTO product was actually completed exceeds the planned completion date plus the buffer lead time of that MTO product, this leads to a delay in the desired delivery date of the semi-finished product at the departments Multi Conductor, Energy and Installation. For the analysis, we used historical production data over a period of one year from 01-02-2021 to 31-01-2022. For each MTO product produced within the DRAFA and delivered to the next department in the production process during this period, the following equation is used to calculate the number of days that the MTO product was produced late.

$$Number\ of\ days\ late = Max(Actual\ completion\ date - (Planned\ completion\ date + Buffer\ lead\ time),0)$$

The equation indicates that a product is delivered late if the actual completion date is above the planned completion date, taking into account the buffer lead time of that product. Figure 2.9 shows a distribution of the delivery reliability over the MTO products produced within the DRAFA, expressed in the number of days that the MTO products were delivered late in the period from 01-02-2021 to 31-01-2022.

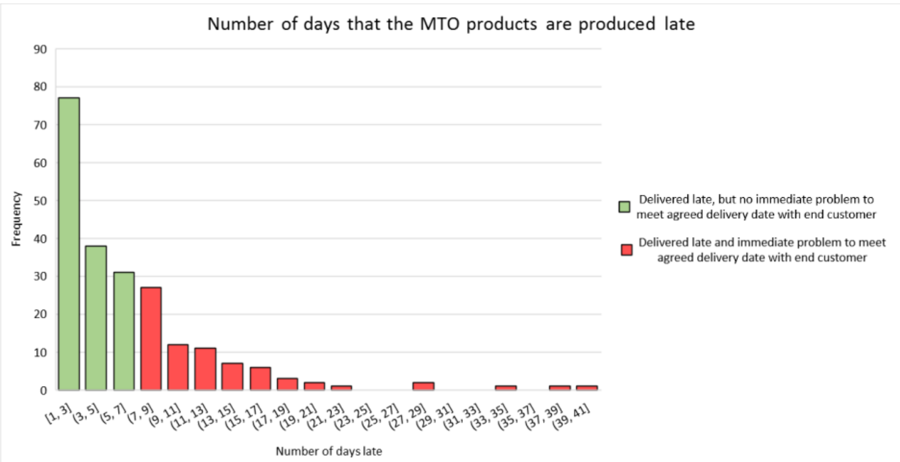

Figure 2.9 - Histogram, number of days that the MTO products are produced late.

In total, 34.6% of all MTO products produced within the DRAFA are delivered late in the period from 01-02-2021 to 31-01-2022. As a result, the current delivery reliability of the MTO products produced within the DRAFA is approximately 65.4%. It becomes clear from the analysis that a majority of 77 MTO orders are between one and three days late for delivery to the departments Multi Conductor, Energy and Installation. Since there is also a buffer lead time per operation performed at the next department in the production process, being a few days late is not an immediate problem in the delivery to the end customer of TKF. The more days the DRAFA is late, the more difficult it becomes for the next department to meet the agreed delivery date with the end customer. Based on consultation with the capacity planners of the three other departments, it became clear that being more than one week late leads to problems in delivering on time to the end customer. Being one to seven days late is not an immediate problem in the delivery to the end customer of TKF. In this situation, the amount of slack available for the next department in the production process shrinks, but it may still be possible for the next department to meet the agreed delivery date with the end customer (green bars in Figure 2.9). If the DRAFA is more than seven days late, this can lead to problems in meeting the agreed delivery date with the end customer for the next departments in the production process (red bars in Figure 2.9).

2.6 KPIs and their target values

To measure the performance of the DRAFA, the capacity planner keeps track of the realized number of production hours per machine on a daily basis. The capacity planner compares this KPI with the associated target value as set by TKF. During the LDM meeting, the performance of the past day is analysed and causes of deviations from the target values are discussed. Table 2.2 shows the target values for the number of production hours per week in each quarter of 2022 for a group of machines.

Table 2.2 - Number of production hours per week in each quarter for a group of machines.

	Group of machines				
Quarter	**Groftrek**	**Middentrek**	**Fijntrek**	**Vlechtdraad**	**Samenslaglijn**
Q1	190	189	120	435	182
Q2	194	193	122	443	185
Q3	198	197	125	580	188
Q4	188	192	123	568	172

The target values are based on the total estimated number of production hours per group of machines. TKF takes into account the amount of semi-finished products that are purchased and therefore do not have to be produced by the DRAFA. It is necessary to purchase some of the semi-finished products because the capacity of the DRAFA is not infinite. To illustrate the calculation of the target values per quarter for a group of machines, we explain this calculation for the Groftrek machines below. Table 2.3 shows the total estimated number of production hours per machine (Groftrek 1 and Groftrek 2), divided over the four quarters. This distribution takes into account the number of production weeks per quarter and the percentage performance improvement per quarter. For the performance improvement, TKF assumes an improvement of 2% per quarter. Because TKF is working on a large project, the production hours for Groftrek 1 are divided into project work and other work. For each quarter, the sum of the total estimated number of production hours per week over the machines gives the target value for the number of production hours for that quarter for a group of machines. The decrease in the target values in quarter 4 is the result of the termination of the project.

Table 2.3 - Target value calculation for the Groftrek machines.

	2022	**Q1**	**Q2**	**Q3**	**Q4**
Groftrek 1 Project [hours in total]	252	90	85	78	-
Groftrek 1 Other [hours in total]	3,950	1,037	1,000	935	978
Groftrek 1 [hours in total]	4,202	1,127	1,085	1,013	978
Groftrek 1 [hours per week]	89	89	90	92	84
Groftrek 2 [hours in total]	4,920	1,292	1,246	1,165	1,218
Groftrek 2 [hours per week]	104	102	104	106	104
Groftrek total [hours in total]	**9,122**	**2,419**	**2,330**	**2,177**	**2,196**
Groftrek total [hours per week]	**192**	**190**	**194**	**198**	**188**

In addition, TKF has set a target value for the delivery reliability of semi-finished products from the DRAFA to the departments Multi Conductor, Energy and Installation. The target values set by TKF for the delivery reliability of MTS and MTO products from the DRAFA are equal to 95% and 90%, respectively.

2.7 Research direction

From the analysis of the current situation, we conclude that we have encountered three major problems. First, the way in which the inventory of the MTS products is currently managed leads to a low delivery reliability as expressed in the ready rate. Second, the medium-term production plan currently does not take into account the available capacity, which leads to a lack of insight into whether medium-term production orders can be realized with the available capacity. Third, the capacity planner currently uses a manual scheduling approach for the short-term production schedule based on knowledge, expertise and intuition.

To address these problems, we searched in three different research directions during the literature review, as described in the next chapter. First, we looked for inventory theory, including inventory control policies to avoid stockouts caused by uncertainties and fluctuations in daily demand. Uncertainties and fluctuations in daily demand are mainly related to changes in the short-term production schedule of the departments Multi Conductor, Energy or Installation. Second, we searched for lot sizing models that can be used to plan production of MTO and MTS products several weeks ahead, while minimizing costs and taking capacity constraints into account. In addition, possibilities are explored to integrate inventory and lot sizing decisions into one planning tool. Third, we focused on model extensions to schedule jobs on machines several days ahead, while taking the inventory parameter values of the MTS products as input.

2.7.1 Stepwise approach

To conduct this research, we used a stepwise approach. As illustrated in Figure 2.10, the first step is to improve the current inventory management of MTS products. In this step, the aim is to better deal with uncertainties and fluctuations in daily demand. Since demand uncertainty is largely unavoidable, we focus on reducing the effects of uncertainty on the production planning process through inventory control decisions. The second step is to provide insight into the medium-term production plan of the semi-finished products produced within the DRAFA several weeks ahead. In this step, the aim is to decide which quantities of which semi-finished products to produce in which week. The focus is on developing a prototype planning tool that integrates inventory control decisions for MTS products resulting from the first step. It provides insight into whether the planned production quantities in a week can be realized with the available capacity and it makes it possible to respond in advance to capacity problems that may arise in the future. The third step is to generate the short-term production schedule of the semi-finished products produced within the DRAFA several days ahead. In this step, the aim is to decide which quantities of which semi-finished products to schedule in which sequence and on which machine on a day. Since the setup and/or production times of semi-finished products produced within the DRAFA are long (multiple hours), we can achieve cost savings by taking into account the characteristics of the products when determining the sequence of the products on a machine. The focus is on developing a prototype planning tool to generate the short-term production schedule of MTO and MTS products, while taking the determined inventory parameter values of the MTS products as input.

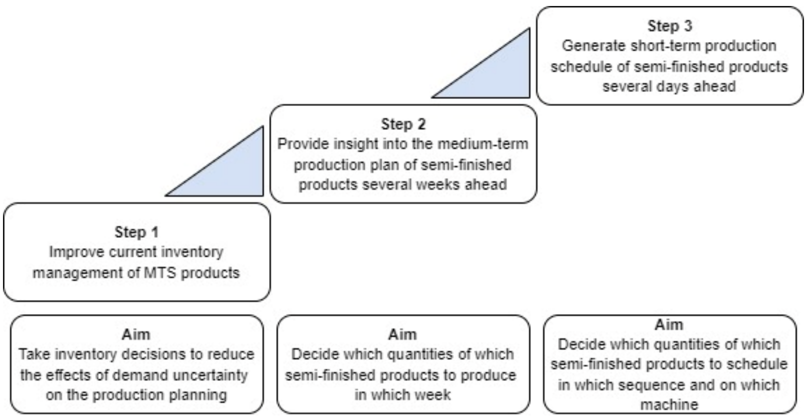

Figure 2.10 - Stepwise approach.

2.7.2 Goals of the solution directions

The aim of focusing on inventory control theory is to improve the ready rate and delivery reliability of MTS products from the DRAFA and to better deal with demand uncertainty or fluctuations in demand. The aim of focusing on the medium-term production planning process is to provide insight into whether medium-term production orders can be realized with the available capacity and to help the capacity planner in responding to future capacity problems. This can be done by purchasing semi-finished products from an external production company or by working overtime during the weekends. The aim of focusing on the short-term production planning process is to help the capacity planner in the day-to-day decision-making process by means of a support tool, rather than replacing the current production planning process.

2.8 Conclusion

In this chapter, we analysed the current situation at TKF. The current inventory methodology is based on static minimum and maximum inventory levels of fast-moving MTS products. As a result, the capacity planner of the DRAFA is not able to react adequately to uncertainties and fluctuations in daily product requests from the departments Multi Conductor, Energy and Installation. For some fast-moving MTS products, this leads to a low delivery reliability as expressed in the ready rate. The current performance of the DRAFA expressed in the fraction one minus the ready rate is visualized in a Pareto chart. For 36.7% of the fast-moving MTS products, the current ready rate is below the target value for the delivery reliability of 95%. The first step of this research is to search in the literature for classification schemes and inventory theory needed to improve the current inventory management of MTS products.

In addition, the medium-term production planning process currently does not take into account the available resource capacity. This leads to a lack of insight into whether medium-term production orders can be realized with the available capacity and whether the capacity planner should take action to prevent future capacity problems from occurring. The second step of this research is to search in the literature for lot sizing models that can be used to plan production several weeks ahead, while minimizing costs and taking into account inventory control decisions and capacity constraints. The most relevant capacity constraint in this research is the number of production hours available per machine per week.

Finally, the current short-term production planning process is executed manually by the capacity planner on a daily basis. The expected demand and inventory information are used to make decisions based on knowledge, expertise and intuition about what and how much to produce in which sequence and on which machine. The third step of this research is to search in the literature for extensions to the lot sizing models that can be used to schedule semi-finished products on machines several days ahead. The literature helps us to design a prototype planning tool that takes the determined inventory parameter values of the MTS products as input. The tool aims to support the capacity planner in the day-to-day decision-making process, rather than replacing the current production planning process.

3 Literature review

This chapter answers the second research question stated in Section 1.7. This research question is related to the identification and understanding of classification schemes and inventory theory proposed in the literature to manage the inventory of the MTS products produced within the DRAFA. In addition, this research question concerns lot sizing models proposed in the literature to plan production several weeks ahead, while minimizing costs and taking into account inventory control decisions and capacity constraints. Finally, this research question is about finding literature that can be used to schedule jobs on machines several days ahead. To answer the second research question, an extensive literature study is performed. The second research question is formulated as follows:

2. *What can we learn from the literature about integrating inventory control and lot sizing decisions into the production planning process, while minimizing costs and taking capacity constraints into account?*

Section 3.1 explains various classification schemes used for grouping products and discusses the most common types of inventory control policies proposed in the literature to manage inventory. This section also covers various cost and service objectives that can be set and the parameters of the inventory control policies. Section 3.2 provides an overview of general production planning models. Section 3.3 focuses on the medium-term production planning problem that integrates inventory control and lot sizing decisions. This section covers the characteristics of the lot sizing problem, a classification of lot sizing models and a mathematical formulation that can be used to model the medium-term production planning problem at the DRAFA. Section 3.4 focuses on extensions needed to model the short-term production planning problem at the DRAFA. This chapter ends with a conclusion describing the preferred solution approach, adapted to the problem context, for answering the second research question in Section 3.5, based on findings from the literature.

3.1 Inventory management and control

As discussed in Section 2.7.1, the first step of the stepwise approach is to improve the current inventory control by implementing an appropriate inventory control policy for the MTS products to reduce the effects of demand uncertainty. As stated by Axsäter (2006), the objective of inventory control is often to balance conflicting goals. According to Silver, Pyke and Thomas (2017), the assumption of deterministic demand is inappropriate in many production situations. Therefore, in the literature study, we focused on control methods capable of dealing with probabilistic demand. A distinction can be made between single- and multi-echelon inventory control methods. As mentioned by Ekanayake, Joshi and Thekdi (2016), single-echelon inventory control problems focus on determining the appropriate inventory level for an individual unit within the supply chain. On the contrary, multi-echelon inventory control problems focus on determining the appropriate inventory levels across the entire supply chain. Since the research is restricted to managing the inventory of the semi-finished products produced within the DRAFA, we focused on single-echelon inventory control methods.

As stated by Silver, Pyke and Thomas (2017), the purpose of a replenishment control system is to resolve the following three problems.

1. How often the inventory status should be determined.
2. When a replenishment order should be placed.
3. How large the replenishment order should be.

Under probabilistic demand, those problems are less trivial and more difficult to solve compared to situations with deterministic demand. To address these three problems, the following four questions can be used to systematically establish an appropriate inventory policy.

1. How important is the product?
2. Can, or should, the stock status be reviewed continuously or periodically?
3. What form should the inventory policy take?
4. What specific cost or service objectives should be set?

Section 3.1.1 discusses a classification to answer the first question. Sections 3.1.2 to 3.1.5 provide answers to the other three questions. Section 3.1.6 indicates how to calculate the inventory control policy parameters. Section 3.1.7 explains the concept of advance demand information (ADI) on customer demand, which is relevant to the DRAFA. In this section, we describe the relevance of the literature to this research, while Appendix B contains a more detailed explanation of the literature that is supposed to be known to the reader.

3.1.1 Classification of products

As mentioned by Scholz-Reiter, Heger, Meinecke and Bergmann (2012), a classification of products supports inventory management. There are many different classification schemes in the literature that can be applied depending on the objective. According to Teunter, Babai and Syntetos (2010), the most important reason for companies to apply a classification scheme is that the number of Stock Keeping Units (SKUs) is too large to select and implement SKU-specific inventory control policies. The DRAFA produces many different semi-finished products, making it necessary to classify products and determine an appropriate inventory control policy for each class of products. In Appendix B, we discuss three classification schemes, which are the ABC classification, the XYZ classification and the combined ABC-XYZ classification. The appendix also lists the nine classes obtained when combining the ABC and XYZ classification.

3.1.2 Continuous versus periodic review

Before we describe the most common types of single-echelon inventory control policies, we discuss the problem of how often the inventory status should be reviewed. A distinction can be made between a continuous and a periodic review. In a continuous review, the inventory position is continuously tracked and therefore always known. In a periodic review, the inventory position is reviewed at regular points in time (Chopra, 2019). The review period (R) is the time between two consecutive moments at which the inventory status is reviewed (Silver, Pyke, & Thomas, 2017). Currently, the capacity planner of the DRAFA checks the inventory position on a daily basis, which is the review period R. Appendix B discusses the advantages and disadvantages of using a continuous or periodic review.

3.1.3 Inventory control policies

To manage the inventory of the MTS products produced within the DRAFA, an appropriate inventory control policy should be selected for a group of semi-finished products with similar characteristics. According to Silver, Pyke and Thomas (2017), the inventory control policy specifies when to place a replenishment order and what quantity to order. To clarify, an order refers to a production order for the DRAFA. Table 3.1 shows the most common types of single-echelon inventory control policies. The inventory control policies can be categorized according to two pillars, which are the review period and the lot size. In the case of a fixed lot size, the order quantity is always the same or a multiple of the order quantity. In the case of a variable lot size, the order quantity varies to reach a certain inventory position. Appendix B discusses the advantages and disadvantages of the most common types of single-echelon inventory control policies.

Table 3.1 - Inventory control policies.

	Continuous review	Periodic review
Fixed lot size	(s, Q) or (s, nQ)	(R, s, Q) or (R, s, nQ)
Variable lot size	(s, S)	(R, S) or (R, s, S)

3.1.4 Inventory control policy selection

There is no standard guideline for selecting an appropriate inventory control policy for each product. Instead, Silver, Pyke and Thomas (2017) provided rules of thumb for the selection of an appropriate inventory control policy, based on the review period and the class of the ABC classification as shown in Table 3.2. According to the ABC classification, class A products are the most important products in terms of the annual dollar usage. Because class A items are often expensive, it is not desirable to order a fixed quantity Q or to raise the inventory position every R units of time to the order-up-to-level S, as this can lead to unnecessary inventories and therefore high inventory costs. Instead, it is desirable to only replenish the inventory position when it reaches a certain minimum level (the reorder point s).

Table 3.2 - Rules of thumb for the selection of an appropriate inventory control policy (Silver, Pyke, & Thomas, 2017).

	Continuous review	Periodic review
A items	(s, S)	(R, s, S)
B items	(s, Q)	(R, S)

It can be noted that class C products are not included in Table 3.2. According to Silver, Pyke and Thomas (2017), companies can use a more manual and simple approach to manage the inventory of class C products. For such an approach, a simple (s, Q)-policy or (R, S)-policy requiring less effort is equivalent, because the potential cost savings are small.

3.1.5 Cost and service objectives

As discussed by Silver, Pyke and Thomas (2017), there are different perspectives on how to balance the probability of stockouts and inventory costs as explained in Appendix B. In this research, the objective is to improve the delivery reliability of semi-finished products to the next departments in the production process. As a result, we focus on the method where the safety stock is based on customer service. When focusing on this method, Beerens and Kusters (2015) mention that the service level is used as input for calculating the optimal safety stock. There are several ways to define customer service targets. Each customer service target leads to a different safety stock level. The four most common customer service targets discussed in Appendix B are Cycle Service Level (CSL), fill rate, ready rate and Time Between Stockout Occasions (TBS).

In Chapter 2, the delivery reliability is expressed in the ready rate. The ready rate is a service level and is defined as the fraction of time during which the stock on hand is positive (Teunter, Syntetos, & Babai, 2017). As noted by Silver, Pyke and Thomas (2017), finding the optimal inventory policy is more complex when using the ready rate as the service measure. However, it is known that for Poisson and normally distributed demand, the ready rate is equivalent to the fill rate. If it is not possible for the DRAFA to immediately satisfy the customer demand due to a low inventory position, it is allowed to produce orders at a later point in time at a given penalty cost. The goal is to meet the desired fraction of the demand that can be filled directly from stock and can best be measured by the fill rate. So we use the fill rate as the service measure to calculate the optimal safety stock for each MTS product.

3.1.6 Parameter calculation

Depending on the selected inventory control policy, the corresponding parameters should be determined. Appendix B describes the parameters of the most common types of single-echelon inventory control policies discussed in Section 3.1.3 and explains how to calculate the parameter values. These parameter calculations are based on the assumption that products can be stored indefinitely because there is no perishability or obsolescence. The review period (R), the order quantity (Q), the reorder point (s) and the order-up-to-level (S) are covered.

As discussed in Section 3.1.5, the safety factor k is determined based on the desired customer service target. The formulas for calculating the fill rate and the corresponding formula for calculating the safety factor k are given below. In the formulas below, $ESPRC$ is the expected shortage per replenishment cycle and $G(k)$ is the standard normal loss function (van der Heijden, 2020c).

$$Fill\,rate = 1 - \frac{ESPRC}{Q} = 1 - \frac{\sigma_{L+R} G(k)}{Q}$$

$$G(k) = \frac{Q(1 - Fill\,rate)}{\sigma_{L+R}}$$

3.1.7 Inventory modelling

The standard modelling assumption in the analysis of inventory systems implies that customer demand is random with a known probability distribution and has to be satisfied immediately (Wijngaard & Karaesmen, 2007). If it is not possible to satisfy the customer demand immediately, the system will incur a penalty, such as backorder costs. However, in several industrial environments, there may be ADI on customer demand, such as early customer orders with specified due dates. As discussed in Section 2.2.2, the capacity planner of the DRAFA knows about five weeks in advance which quantities of which products have to be produced because of ADI. However, it is uncertain on which day these quantities will be requested. Due to a planning horizon of approximately one day at all departments, the capacity planner of the DRAFA knows which products will be requested for the next 24 hours. Hariharan and Zipkin (1995) concluded from their analysis that demand lead times are the opposite of supply lead times. This means that a supply lead time increases uncertainty about the future, while a demand lead time reduces it. The demand lead time is the time from a customer's order until the due date and the supply lead time is the time required to fill a replenishment order. As a result, the lead time L can be modelled as the supply lead time L^S minus the demand lead time L^D.

Currently, the capacity planner uses an (R, s, S)-policy for the fast-moving MTS products. If the inventory position drops to or below the minimum inventory level s, a replenishment is made to raise the inventory position to the maximum inventory level S. However, using static minimum and maximum inventory levels in combination with uncertainties and fluctuations in daily demand leads to a low delivery reliability. In addition, the current inventory methodology is not able to make replenishment decisions based on ADI. Therefore, a dynamic inventory control policy is preferred, where the inventory parameter values depend on the expected demand of the next departments in the production process. The expected daily demand can be based on the production schedules of the next departments. The supply lead time for replenishing varies per MTS product. The setup and production time of a product determine the supply lead time of a product and are fixed. In addition, a safety lead time can be added to cope with additional waiting time for production due to limited capacity (van Kampen, van Donk, & van der Zee, 2010). We therefore assume that the supply lead time per product varies over time. In addition, we assume that the demand lead time is equal to one day for each MTS product, since the capacity planner knows which products are requested for the next 24 hours.

3.2 Production planning models

According to Karimi, Fatemi Ghomi and Wilson (2003), production planning focuses on making the best use of resources to achieve production goals over the planning horizon. Production planning distinguishes between three planning horizons for decision-making, namely long-term, medium-term and short-term. In long-term planning, the focus is on strategic decisions, such as product, equipment and process choices. In medium-term planning, the focus is often on material requirements planning decisions and determining production quantities or lot sizing over the planning period. The objective is to minimize overall costs, while meeting demand requirements and satisfying capacity constraints. In short-term planning, the focus is on daily scheduling decisions, such as job sequencing.

In addition to the planning horizon, manufacturing systems can be characterized by a variety of factors, such as the number of machines and their characteristics. The differences in these characteristics lead to a large number of different planning and scheduling models. One class relevant to this research are the lot scheduling models, which are often used for medium-term production planning. Lot scheduling models are applicable when there is a variety of different products. A changeover or setup cost is incurred when a machine switches from one product to another. The objective of the lot scheduling model is usually to minimize overall costs, consisting of inventory and changeover costs (Pinedo, 2009). As mentioned by Karimi, Fatemi Ghomi and Wilson (2003), the lot sizing decision is related to the problem of determining when and how much of a product to produce so that setup, production and holding costs are minimized.

3.3 Medium-term production planning

In this research, the second step of the stepwise approach focuses on providing insight into the medium-term production plan of the semi-finished products produced within the DRAFA several weeks ahead. The most important decision is which quantities of which semi-finished products to produce in which week. Capacity constraints should be taken into account to gain insight into whether the planned production quantities in a week can be realized with the available capacity. The capacity planner can decide to purchase products externally or to have employees work overtime if it is expected that the available capacity is insufficient to realize the desired production. The problem can best be described as a lot sizing problem.

3.3.1 Characteristics of the lot sizing problem

Karimi, Fatemi Ghomi and Wilson (2003) describe eight characteristics that affect the complexity of lot sizing decisions. The first characteristic is the planning horizon, which is the time interval on which the production plan extends into the future and can be finite or infinite. If the demand pattern is dynamic, a finite planning horizon is often used. If the demand pattern is stationary, an infinite planning horizon is used. In this research, a finite planning horizon applies since the demand pattern is dynamic. Lot sizing problems can be divided into large and small bucket problems. For large bucket problems, the planning horizon is long enough to produce multiple products per time period. For small bucket problems, only one product can be produced per time period. In this research, the planning horizon for the medium-term is 10 weeks with time buckets of 1 week. Since multiple products can be produced per week, the problem is a large bucket problem.

The second characteristic is the number of levels. In single-level systems, the final product is often simple because a single operation is used to convert the raw materials into the final product. The product demand is based on customer orders and is known as independent demand. In multi-level systems, there is a parent-component relationship among the products, because several operations are used to convert the raw materials into the final product. In other words, semi-finished products are produced and the output of one operation is input for another operation. The product demand at one level depends on the demand at the next production step and is therefore known as dependent demand. In this research, a multi-level production system applies as several operations are used within the DRAFA to produce some semi-finished products.

The third characteristic is the number of products. The number of products in a production system also affects the modelling and complexity of production planning problems. Production systems can be divided into two types based on the number of products. In single-item production planning, there is only one product for which the planning activity must be executed. In multi-item production planning, there are multiple products for which production must be planned. In this research, multi-item production planning applies as the DRAFA produces a large number of semi-finished products.

The fourth characteristic is the capacity constraints. In a production system, capacities are personnel, machines and physical space. If there is no restriction on the available capacity, the problem is called uncapacitated. If capacity constraints are explicitly stated, the problem is called capacitated. In this research, the number of available production hours per machine in a week is considered the most relevant capacity constraint.

The fifth characteristic is the deterioration of products. In some practical situations, deterioration of products is possible. In this research, deterioration of products is not relevant because semi-finished products produced within the DRAFA can be stored for a long time period without loss of quality.

The sixth characteristic is the demand. A distinction can be made between static and dynamic demand. Static demand means that the demand is the same for each time period, while dynamic demand means that the demand pattern changes over time. If the demand is known in advance, it is called deterministic. However, if the demand is based on some probabilities and not exactly known in advance, it is called probabilistic. In this research, the demand is dynamic. In addition, demand forecasts are assumed to be known in advance. However, to reduce the effects of demand uncertainty, we need to consider safety stocks for the MTS products.

The seventh characteristic is the setup structure. A production changeover on a machine between different products can incur setup time and thus setup costs. In the short-term, the setup structure at the DRAFA is complex because the setup time depends on the sequence of the products. Karimi, Fatemi Ghomi and Wilson (2003) describe this type of complex setup structure as a family setup, because combining products with similarities in the production process influences the required setup time. However, because job sequencing is not relevant to the medium-term production planning process, a simple setup structure can be used.

The eighth characteristic is the inventory shortage. In the backlogging case, it is allowed to satisfy the demand of the current period in future periods. In the lost sales case, it is allowed that some of the demand may not be satisfied at all. Allowing shortages usually introduces a shortage cost in the objective function. In this research, the backlogging case is relevant because it is allowed to produce orders after their due date.

3.3.2 Classification of lot sizing models

There are many variants of the lot sizing problem discussed in the literature. Ramya, Rajendran, Ziegler and Ganesh (2019) developed a classification of different variants of lot sizing models, as shown in Figure 3.1. The large bucket lot sizing problem with capacity restrictions is called the capacitated lot sizing problem (CLSP). According to Karimi, Fatemi Ghomi and Wilson (2003), the classical CLSP determines the lot sizes for multiple products with known dynamic demand that are produced on a resource with limited capacity over a finite planning horizon and with no backlogs. In the classical CLSP, the setup costs may vary per product and per period but are sequence-independent. The setup to produce a product involves a setup cost and consumes a certain part of the available capacity. The objective is to determine a production plan that minimizes the total costs, consisting of production costs, setup costs and inventory holding costs. The production plan contains the amount and timing of production in the planning horizon, limited by capacity constraints. The CLSP best describes the medium-term production planning problem at the DRAFA.

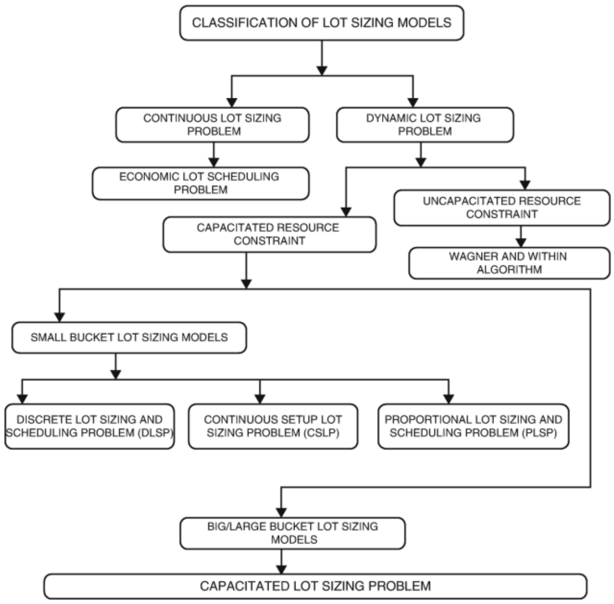

Figure 3.1 - Classification of lot sizing models (Ramya, Rajendran, Ziegler, & Ganesh, 2019).

3.3.3 Mathematical model formulation

Now we have obtained insight into the characteristics of the medium-term production planning problem at the DRAFA, we provide the mathematical formulation of the classical CLSP formulated by Karimi, Fatemi Ghomi and Wilson (2003).

Sets

i	Product with $i = 1, \ldots, N$
t	Time period with $t = 1, \ldots, T$

Parameters

N	Number of products
T	Number of time periods in the planning horizon
R_t	Available resource capacity in period t
d_{it}	Expected demand for product i in period t
C_{it}	Unit production costs of product i produced in period t
S_{it}	Setup costs incurred if product i is produced in period t
h_{it}	Unit holding costs of product i at the end of period t
a_i	Unit resource consumption for product i
M	Sufficiently large number

Decision variables

X_{it}	Number of products of product i produced in period t
I_{it}	Inventory of product i at the end of period t
Y_{it}	Binary variable that is equal to 1 if product i is produced in period t and 0 otherwise

Objective function

$$\text{Min} \sum_{i=1}^{N} \sum_{t=1}^{T} C_{it}X_{it} + S_{it}Y_{it} + h_{it}I_{it}$$

Constraints

$\sum_{i=1}^{N} a_i X_{it} \leq R_t \qquad \forall t \in T \qquad (3.1)$
$X_{it} + I_{i,t-1} - I_{it} = d_{it} \qquad \forall i \in N, \forall t \in T \qquad (3.2)$
$X_{it} \leq M\, Y_{it} \qquad \forall i \in N, \forall t \in T \qquad (3.3)$
$X_{it} \geq 0, I_{it} \geq 0, Y_{it} \in \{0,1\} \qquad \forall i \in N, \forall t \in T \qquad (3.4)$

The objective function is to minimize the total costs over all products and all time periods in the planning horizon, consisting of production costs, setup costs and inventory holding costs. Constraint (3.1) indicates that the total production time used in period t should be smaller than or equal to the available machine capacity in that period. The inventory balance constraint (3.2) ensures that all demand is met from the inventory of the previous period $t-1$ and the production in period t. The remaining quantity is placed in stock in period t. Constraint (3.3) makes sure that if a product is produced in period t, the binary variable Y is set to 1 and a setup is incurred in that period. Constraint (3.4) ensures that the number of products produced and the inventory are always greater than or equal to 0 and that the binary variable Y can only take values 0 and 1.

The unit resource consumption for product i (a_i) can be defined as the sum of the unit production time for product i (PT_i) and the setup time for product i (ST_i). In this research, the setup times of the semi-finished products produced within the DRAFA are long (multiple hours) and consume a significant part of the machine's capacity. Then constraint (3.1) can be replaced by constraint (3.5) as follows.

$\sum_{i=1}^{N} PT_i\, X_{it} + ST_i Y_{it} \leq R_t \qquad \forall t \in T \qquad (3.5)$

To model the medium-term production planning problem at the DRAFA, we make four extensions to the classical CLSP using the literature found. First, the available resource capacity in each time period, expressed in the number of available production hours, should be separated per machine. The lot sizing problem with multiple constrained resources can be modelled by adding a machine index to the resource capacity parameter (Katok, Lewis, & Harrison, 1998). We also add a machine index to the production and setup parameters and decision variables. Second, as mentioned in Section 3.3.1, the multi-level production system is a relevant extension for this research, because the production of some products within the DRAFA requires multiple operations. According to Kuik and Salomon (1990), the parent-component relationship among the products in the production process can be modelled by integer numbers a_{ij}, where i and j range over the products. The meaning of a_{ij} is that the production of one unit of product j requires a_{ij} units of product i. Third, the backlogging case is a relevant extension, because it is allowed to produce orders after their due date at a given penalty cost. As mentioned by Zangwill (1969), the concept of backlogging can be modelled by allowing the inventory to become negative. We define I_{it}^{+} as the amount of inventory of product i at the end of period t and I_{it}^{-} as the amount of inventory shortage or the number of backorders of product i at the end of period t. Fourth, only a selection of machines can be used to produce a product within the DRAFA. A product is not pre-assigned to a machine and therefore the prototype planning tool should assign a product to a machine for production. The four extensions in the mathematical formulation are as follows.

Set

m	Machine with m = 1,…, V

Parameters

V	Number of machines
R_{mt}	Available resource capacity for machine m in period t
a_{ij}	Number of units of component i required to produce one unit of parent j
$B1_i$	Shortage costs for backlogging one unit of product i
v_{im}	Binary parameter that is equal to 1 if product i can be assigned to machine m for production and 0 otherwise

Decision variables

X_{imt}	Number of products of product i produced on machine m in period t
I_{it}^{+}	Inventory of product i at the end of period t

I_{it}^{-}	Number of backorders of product i at the end of period t
Y_{imt}	Binary variable that is equal to 1 if product i is produced on machine m in period t and 0 otherwise

Objective function

$$\text{Min} \sum_{i=1}^{N} \sum_{m=1}^{V} \sum_{t=1}^{T} C_{im}X_{imt} + S_{im}Y_{imt} + h_i I_{it}^{+} + B1_i I_{it}^{-}$$

Constraints

$$\sum_{i=1}^{N} PT_{im}\, X_{imt} + \sum_{i=1}^{N} ST_{im}Y_{imt} \le R_{mt} \qquad \forall m \in V, \forall t \in T \qquad (3.6)$$

$$\sum_{m=1}^{V} X_{imt} - \sum_{j=1}^{N} \sum_{m=1}^{V} a_{ij}X_{jmt} + I_{i,t-1}^{+} - I_{it}^{+} + I_{it}^{-} - I_{i,t-1}^{-} = d_{it} \quad \forall i \in N, \forall t \in T \qquad (3.7)$$

$$X_{imt} \le M\, Y_{imt} \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (3.8)$$

$$X_{imt} = 0 \qquad \forall i \in N, \forall m \in V, \forall t \in T, v_{im} = 0 \quad (3.9)$$

$$X_{imt} \ge 0, I_{it}^{+} \ge 0, I_{it}^{-} \ge 0, Y_{imt} \in \{0,1\} \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (3.10)$$

The objective function is to minimize the total costs over all products and all time periods in the planning horizon, including now the penalty costs for having backorders. Constraint (3.6) is unaltered compared to the classical CLSP. However, the available resource capacity in each time period is now separated per machine. The inventory balance constraint (3.7) allows to meet demand in future periods and takes into account the amount of production of a product required to satisfy the production of its successors. Constraint (3.8) is equivalent to the classical CLSP. Constraint (3.9) ensures that products can only be assigned to a selection of machines for production. Constraint (3.10) now also ensures that the number of backorders is always greater than or equal to 0.

The mathematical model can be used to find an optimal solution to the medium-term production planning problem with integrated inventory control decisions. Chen and Thizy (1990) showed that the multi-item CLSP is strongly NP-hard, making it unlikely to find an optimal solution to the problem in a reasonable time. As a result, in Chapter 5 we determine whether the problem can be solved within a reasonable time using a mathematical model or whether a heuristic should be used.

3.4 Short-term production schedule

In this research, the third step of the stepwise approach focuses on generating the short-term production schedule of the semi-finished products produced within the DRAFA. To model the short-term production planning problem, we make three additional extensions to the model formulated in Section 3.3.3.

3.4.1 Supply lead times

First, the supply lead times at the DRAFA are longer than one day. As a result, the demand for a product on a given day cannot be satisfied through production on the same day. In addition, a production order may take longer than one day, causing the production order to be spread over several days without an additional setup. In the CLSP, positive supply lead times can be modelled by shifting production quantities backward (Buschkühl, Sahling, Helber, & Tempelmeier, 2010). In other words, the timing of production must be realized for at least a period equal to the supply lead time plus the safety lead time earlier than the due date. Positive supply lead times can be incorporated into the model by adding a parameter L_i that represents the supply lead time of product i and by modifying constraint (3.7) as follows to get constraint (3.11). The constraint takes into account the supply lead time of a product to determine the timing of production to meet demand.

$$\sum_{m=1}^{V} X_{im,t-L_i} - \sum_{j=1}^{N} \sum_{m=1}^{V} a_{ij}X_{jmt} + I_{i,t-1}^{+} - I_{it}^{+} + I_{it}^{-} - I_{i,t-1}^{-} = d_{it} \quad \forall i \in N, \forall t \in T \qquad (3.11)$$

3.4.2 Setup carry-over

Second, the setup structure at the DRAFA is complex when scheduling on a daily basis, because a machine is able of carrying over its setup state between periods. In practice, a setup may often be performed within a period and the setup state of machines can be preserved over idle time (Haase, 1996). While the standard CLSP implies a setup for each product produced per period, a setup carry-over implies that the last product produced in a certain period can be produced without an additional setup in the next period. The following parameters, decision variables and constraints are required to include setup carry-over, also known as the capacitated lot sizing problem with linked lot sizes (CLSPL).

Additional parameters

α_{im}^0	Initial setup state of product i on machine m at the beginning of the planning horizon (α_{im}^0 = 1, if machine m is initially set up for product i)

Additional decision variables

β_{imt}	Binary variable that is equal to 1 if the setup state for product i on machine m is carried over from period t to period t + 1 and 0 otherwise

Additional constraints

$$X_{imt} \leq M\ (Y_{imt} + \beta_{im,t-1}) \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (3.12)$$

$$\sum_{i=1}^{N} \beta_{imt} = 1 \qquad \forall m \in V, \forall t \in T \qquad (3.13)$$

$$\beta_{imt} - Y_{imt} - \beta_{im,t-1} \leq 0 \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (3.14)$$

$$\beta_{im,t-1} + \beta_{imt} + Y_{jmt} - Y_{imt} \leq 2 \qquad \forall i,j \in N \ if\ i \neq j, \forall m \in V, \forall t \in T \qquad (3.15)$$

$$\beta_{im0} = \alpha_{im}^0 \qquad \forall i \in N, \forall m \in V \qquad (3.16)$$

$$\beta_{imt} \in \{0,1\} \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (3.17)$$

Constraint (3.12) replaces constraint (3.8) formulated in Section 3.3.3. The constraint ensures that product i can only be produced on machine m in period t if either a setup for product i is performed on machine m in period t (i.e. Y_{imt} = 1) or machine m carries over a setup state for product i from period t – 1 to t (i.e. $\beta_{im,t-1}$ = 1). Constraint (3.13) implies that machine m can only carry over a setup for one product at the end of period t to the next period t + 1. The "=" sign forces the model to always carry over the setup state of a machine at the end of the day to the next day, regardless of whether that product is also scheduled for production the next day. Constraint (3.14) ensures that if machine m carries over a setup state for product i from period t to period t + 1 (i.e. β_{imt} = 1), there must be a setup for product i on machine m in period t (i.e. Y_{imt} = 1) or the setup state has been carried over from period t – 1 to t (i.e. $\beta_{im,t-1}$ = 1). Constraint (3.15) is required to deal with a specific situation. If machine m carries over a setup state for product i from period t – 1 to t (i.e. $\beta_{im,t-1}$ = 1) and also from period t to t + 1 (i.e. β_{imt} = 1), and a setup for another product j is performed on the same machine in period t (i.e. Y_{jmt} = 1), then we need to re-set up this machine to product i in period t (i.e. Y_{imt} = 1). Constraint (3.16) initializes the setup carry-over variables for all products. Finally, constraint (3.17) makes the setup carry-over variables binary.

3.4.3 Sequencing

Third, the setup structure at the DRAFA is complex when scheduling on a daily basis, because the setup times and costs depend on the sequence of the products. We want to determine the sequence of all products produced on a particular machine and on a particular day. The capacitated lot sizing problem with sequence-dependent setups (CLSD) is a variant of the CLSPL (Quadt & Kuhn, 2008). The following model characteristics are required to include sequence-dependent setup times and costs.

Additional parameters

S_{ijm}	Setup costs while changing over from product i to product j on machine m
ST_{ijm}	Setup time while changing over from product i to product j on machine m

Additional decision variables

Y_{ijmt}	Binary variable that is equal to 1 if a setup is performed from product i to product j on machine m in period t and 0 otherwise
γ_{jmt}	Sequencing variable that indicates the position of product j on machine m in period t (the larger γ_{jmt}, the later product j is scheduled for production on machine m in period t)

Objective function

$$\text{Min} \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{m=1}^{V} \sum_{t=1}^{T} C_{jm} X_{jmt} + S_{ijm} Y_{ijmt} + h_j I_{jt}^{+} + B1_j I_{jt}^{-}$$

Additional constraints

$\sum_{j=1}^{N} PT_{jm} X_{jmt} + \sum_{i=1}^{N} \sum_{j=1}^{N} ST_{ijm} Y_{ijmt} \leq R_{mt}$	$\forall m \in V, \forall t \in T$	(3.18)
$X_{jmt} \leq M \left(\sum_{i=1}^{N} Y_{ijmt} + \beta_{jm,t-1}\right)$	$\forall j \in N, \forall m \in V, \forall t \in T$	(3.19)
$\sum_{i=1}^{N} Y_{ijmt} + \beta_{jm,t-1} = \sum_{k=1}^{N} Y_{jkmt} + \beta_{jmt}$	$\forall j \in N, \forall m \in V, \forall t \in T$	(3.20)
$\gamma_{jmt} \geq \gamma_{imt} + 1 - N\left(1 - Y_{ijmt}\right)$	$\forall i, j \in N, \forall m \in V, \forall t \in T$	(3.21)
$Y_{ijmt} \in \{0,1\}$	$\forall i, j \in N, \forall m \in V, \forall t \in T$	(3.22)
$\gamma_{jmt} \geq 0$	$\forall j \in N, \forall m \in V, \forall t \in T$	(3.23)

The objective function is slightly modified so that sequence-dependent setups are taken into account. Constraints (3.18) and (3.19) replace constraints (3.6) and (3.12), respectively, and take into account the setups from all possible preceding products i to product j on machine m (i.e. $\sum_{i=1}^{N} Y_{ijmt}$). In addition, the setup carry-over constraints (3.14) and (3.15) of the CLSPL in Section 3.4.2 are replaced by constraints (3.20) and (3.21), respectively. Constraint (3.20) ensures that if machine m is set up to product j in period t (i.e. $\sum_{i=1}^{N} Y_{ijmt}$ = 1) or a setup carry-over from period t – 1 to t is used for product j (i.e. $\beta_{jm,t-1}$ = 1), then the machine must be set up from product j to another product k (i.e. $\sum_{k=1}^{N} Y_{jkmt}$ = 1) or carry over the setup state for product j from period t to t + 1 (i.e. β_{jmt} = 1). Constraint (3.21) generates the production sequence per machine and per period and thus eliminates subtours. When a setup is performed from product i to product j (i.e. Y_{ijmt} = 1), then $N\left(1 - Y_{ijmt}\right)$ equals zero and $\gamma_{jmt} \geq \gamma_{imt} + 1$ must hold. This means that product j is scheduled after product i. Finally, constraint (3.22) makes the setup variables binary and constraint (3.23) makes the sequencing variables non-negative, which automatically become integers through constraint (3.21).

3.5 Conclusion

In this chapter, we performed an extensive literature study on inventory control and production planning to find out how to integrate inventory control and lot sizing decisions. Several inventory control policies are available in the literature to determine when to place a replenishment order and what quantity to order. To reduce the effects of demand uncertainty, we consider safety stocks while achieving the desired customer service targets. For the DRAFA, the goal is to meet the desired fraction of the demand that can be filled directly from stock and can best be measured by the fill rate. We use the combined ABC-XYZ classification to determine which service level target to use for which class of semi-finished products.

Many variants of the lot sizing problem exist. The medium-term production planning problem at the DRAFA can best be described as a CLSP, because a finite planning horizon applies, capacity constraints are relevant and multiple semi-finished products can be produced per week. The objective of the classical CLSP is to minimize the total costs, consisting of production costs, setup costs and inventory holding costs. However, the classical CLSP does not fully cover the problem context at the DRAFA. Therefore, we make the following four extensions to the model in the solution design in Chapter 4 to model the medium-term production planning problem: separated available resource capacity per machine, the concept of a multi-level production system, the concept of backlogging and limited possibilities in the allocation of products to the machines.

To improve the current inventory management of MTS products, an appropriate inventory control policy can be implemented in the lot sizing model. This can be done by adding a constraint that ensures that the inventory levels of the MTS products do not fall below the calculated safety stocks. When implementing inventory control policy parameters in the model, ADI on customer demand should be taken into account. In the next chapter, we present a Mixed Integer Linear Programming (MILP) model that fits the medium-term production planning problem. We further extend the model by incorporating positive supply lead times, setup carry-overs and sequence-dependent setup times to model the short-term production planning problem.

4 Solution design

This chapter answers the third research question stated in Section 1.7 and focuses on the design and development of a prototype planning tool for automating the production planning process of MTO and MTS products. To answer the third research question, we use information from the analysis of the current situation and the literature. In addition, we expand the stepwise approach provided in Section 2.7.1 and use it as a guideline for this chapter. The third research question is formulated as follows:

3. *How should the prototype planning tool be designed for automating the production planning process of MTO and MTS products, while integrating inventory control and lot sizing decisions?*

This chapter is structured as shown in the flowchart in Figure 4.1. Section 4.1 elaborates on the solution direction based on the problem context discussed in Chapter 2 and the relevant literature found in Chapter 3. Section 4.2 describes the requirements that we set and the assumptions that we make in our model. Based on these requirements and assumptions, we describe the problem in words in Section 4.3. The mathematical formulation of the MILP model is provided in Section 4.4, including necessary model extensions and an explanation of the determination of the cost parameters. Section 4.5 is part of the first step of the stepwise approach with the aim to improve the current inventory management of the MTS products. This section is also part of the second step of the stepwise approach with the aim to integrate inventory control and lot sizing decisions to provide insight into the medium-term production plan. Section 4.6 is part of the third step of the stepwise approach with the aim to generate the short-term production schedule. In this section, we extend the MILP model by incorporating positive supply lead times, setup carry-overs and sequence-dependent setup times. The chapter ends with a conclusion in Section 4.7.

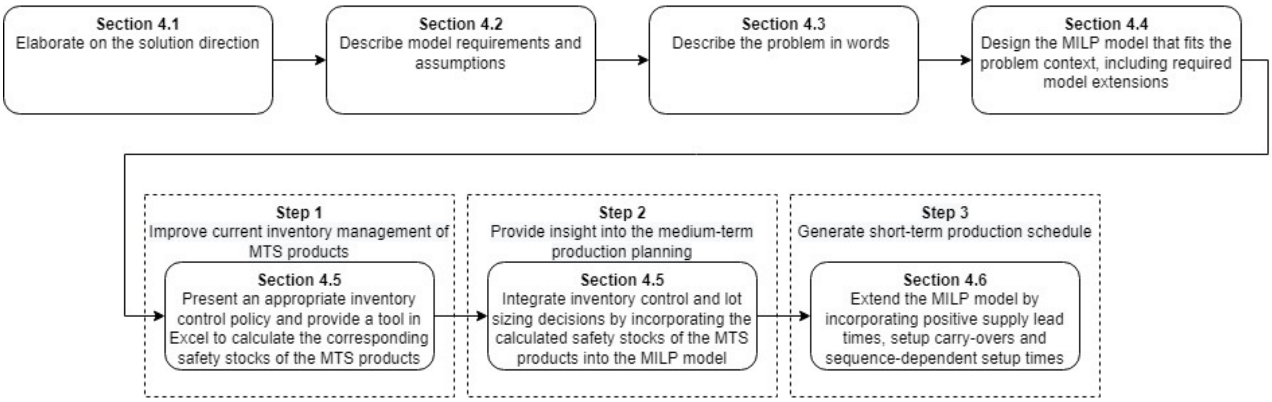

Figure 4.1 - Flowchart of the solution design.

4.1 Solution direction

Based on the problems identified in Chapter 2, the way in which the inventory of the MTS products is currently managed leads to a low delivery reliability. This problem occurs due to a lack of insight into the correct production quantities and timing of production of MTS products. In addition, the medium-term production plan currently does not take into account the available capacity, which leads to a lack of insight into whether medium-term production orders can be realized with the available capacity. When capacity problems occur, the capacity planner does not know which products should be prioritized and which products should be backordered so that the total costs are minimized.

Both problems can be solved by developing a prototype planning tool that integrates inventory control decisions for MTS products and lot sizing decisions for both MTO and MTS products. As noted during the literature review, many variants of the lot sizing problem exist. We use the CLSP to model the medium-term production planning problem at the DRAFA, because a finite planning horizon applies, capacity constraints should be taken into account and multiple semi-finished products can be produced per time period. Based on the characteristics of the CLSP, a mathematical optimization model can be developed to determine a production plan that minimizes the total costs. The MILP model determines the amount and timing of production of products in the planning horizon under capacity constraints.

With the prototype planning tool, we want to gain insight into the impact of the *resource capacity* and the *inventory control policy*. First, for production within the DRAFA, the resource capacity is limited and can be expressed in the number of production hours available per machine in each time period. We want to gain insight into whether the planned production quantities in a week can also be realized with the available capacity. Second, to reduce the effects of demand uncertainty, an appropriate inventory control policy can be implemented. When calculating the safety stock, ADI on customer demand should be taken into account.

For the short-term, we want to gain insight into the impact of the *supply lead time* and the *sequence of jobs*. First, the supply lead time is also known as the setup plus production time required for production within the DRAFA. In addition, a safety lead time can be added to cope with additional waiting time for production due to limited production capacity. The supply lead time is relevant when scheduling on a daily basis. Because supply lead times at the DRAFA are longer than one day, the demand for a product on a given day cannot be met through production on the same day. The timing of production must therefore be realized for at least a period equal to the supply lead time plus the safety lead time earlier than the due date. When using time buckets of 1 week, it is possible to satisfy the demand for a product in a week through production in the same week. In this case, there is no need to model positive supply lead times. Second, job sequencing is not relevant to the medium-term. In the short-term, however, the capacity planner currently determines how much to produce in which sequence and on which machine based on knowledge, expertise and intuition. We design a short-term planning tool that supports the capacity planner in the day-to-day decision-making process and that combines jobs based on setup time data to reduce machine setup times.

4.2 Requirements and assumptions

Based on consultation with the capacity planner of the DRAFA, we set the following requirements and make the following assumptions in our model in order to develop an MILP model that fits the medium-term problem context. In Section 4.6, we discuss the requirements and assumptions that are relevant for the short-term.

4.2.1 Requirements

- Weeks are used as the unit of time over a period of 10 weeks (1).
- Multiple products can be produced per week at the DRAFA (2).
- Production of some products requires multiple operations, hence parent-component relationships exist among the products in the production process (3).
- Production capacity set in a particular week for a particular machine may not be exceeded (4).
- Orders produced after their due date are backordered at a given penalty cost (5).
- Production of each MTS product is constrained by a minimum production quantity that is based on the total length or weight per packaging unit (6).
- Production quantity of each MTS product must be a multiple of the minimum production quantity (7).
- Inventory of each MTS product is constrained by a maximum storage quantity that is based on the limited stock capacity allocated to each MTS product by TKF (8).

4.2.2 Assumptions

- Planning horizon is finite and consists of T weeks (1).
- Expected demand ($d_t,\ t = 1, \ldots, T$) is dynamic and demand forecasts are assumed to be known in advance (2).
- Supply lead times, including an approximation of the safety lead time, are known (3).
- Expected production and setup times/costs are known (4).
- Variable unit production times and costs are independent of the production quantity (5).
- Setup times and costs for each production lot are constant over time (6).
- Inventory holding costs are linear and are charged at the end of the week (7).
- Sufficient raw materials are available to realize production according to the plan (8).
- Products produced within the DRAFA can be stored for a long time period without loss of quality (9).
- Possible failures during production are included in determining the available resource capacity (10).

4.3 Model description

Before we formulate the MILP model, we describe the problem in words. The DRAFA uses 14 machines for the first part of the production process of cables. Each machine can produce a specific set of semi-finished products. Therefore, only a selection of machines can be used to produce a specific semi-finished product within the DRAFA. After each operation, a product with a separate article number is produced. Currently, the DRAFA produces ± 200 different MTO products with a positive demand over the past year. In addition, the DRAFA produces 47 fast-moving MTS products and 11 slow-moving MTS products. The ERP system Navision indicates per semi-finished product which machines can be used for production. We consider a finite planning horizon consisting of T weeks. As mentioned in Section 4.2.1, the planning horizon of the medium-term prototype planning tool is equal to 10 weeks with time buckets of 1 week.

The production of some products within the DRAFA requires multiple operations. This makes the production context of the DRAFA a multi-level production system. For example, to produce a conductor at Samenslaglijn 1, a certain amount of wire with a corresponding diameter must first be produced at Groftrek 1. To model these parent-component relationships among the products in the production process, the production of a wire (component) is input to produce a conductor (parent) in the same week. The expected demand for product i in week t (d_{it}) is equal to the product requests from the departments Multi Conductor, Energy and Installation. As a result, production of the wire is required to satisfy the expected demand for the conductor. This is illustrated with a numerical example in Figure 4.2, which only explains the concept of a multi-level production system. Suppose that we expect demand for product 2 of 1000 meters (m) in a given week. In addition, suppose that 0.3 kilograms (kg) of product 1 is required to produce one m of product 2. Then 300 kg of product 1 must be produced in order to be able to produce 1000 m of product 2 and to satisfy the demand.

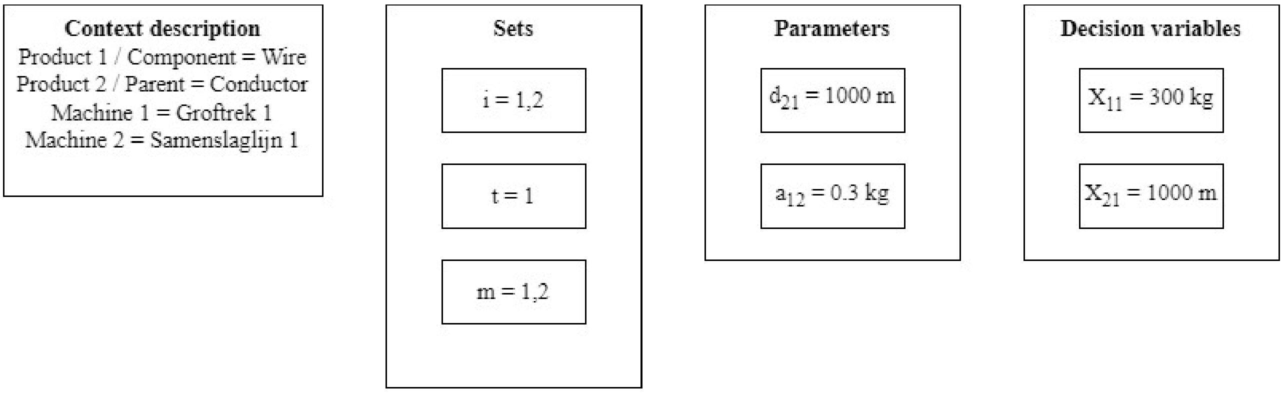

Figure 4.2 - Numerical example for a multi-level production system.

The objective function is to minimize the total costs, consisting of production costs, setup costs, inventory holding costs and backorder costs. We want to gain insight into the stock movements of the MTS products. Based on the planned purchase quantity, the production quantity and the expected demand for a product in a given week, the model should determine the inventory level of that product at the end of the week and the associated inventory holding costs. In addition, the backlogging case is relevant to the DRAFA. If production cannot be finished before the specified due date, orders will not be lost to the system. Instead, it is allowed to produce orders after their due date at a given penalty cost. The due date is equal to the week in which the demand is expected.

Currently, TKF does not forecast demand for the products produced within the DRAFA. To determine the expected demand for each product on a weekly basis, we distinguish between MTO and MTS products. For MTO products, we know approximately for the next five weeks which quantities of which products should be produced before which due date because of ADI. For weeks 6 to 10 of the planning horizon, we base the expected demand on a weekly average of the historical demand data from the past year. For MTS products, we further distinguish between MTS products that are supplied to another department after production in the DRAFA and MTS products that are input for another production step within the DRAFA. For the MTS products that are supplied to another department, we also know approximately which quantities of which products should be produced in which week for the next five weeks. In addition, for weeks 6 to 10 of the planning horizon, we use historical demand data from the past year, as we do for the MTO products. However, there is no external demand for the MTS products that are input to another production step within the DRAFA. As a result, the expected demand for these MTS products is zero and is derived from the expected demand for the parent in a given week. We use a rolling horizon planning concept, because ADI on customer demand gradually becomes known.

The expected demand for each product in a week is expressed in the total weight in kg or total length in m. For MTS products, the capacity planner of the DRAFA only produces complete packaging units. Therefore, the production of each MTS product is constrained by a minimum production quantity. The production quantity of each MTS product must be a multiple of the weight or length per packaging unit. In addition, there is a limited stock capacity for the storage of MTS products. As a result, the inventory of each MTS product is constrained by a maximum storage quantity.

Finally, the production capacity of each machine must be taken into account, which is determined by the number of production hours available each week. We consider multiple constrained resources by separating the available resource capacity in each week per machine. The production capacity per machine is affected by preventive maintenance that is planned in advance or by public holidays on which no production takes place. In addition, TKF takes into account possible failures that may occur during production in terms of an Overall Equipment Effectiveness (OEE) percentage. By adding capacity constraints, we gain insight into whether the planned production quantities in a week can also be realized with the available capacity.

4.4 Mathematical model formulation

Recall from the literature review in Chapter 3 that we have described the mathematical formulation of the classical CLSP. However, the classical CLSP does not fully cover the requirements and assumptions described in Section 4.2. To model the medium-term production planning problem at the DRAFA, we make four model extensions. First, we separate the available resource capacity per machine by adding a machine index to the resource capacity parameter and the production and setup decision variable. Second, we extend the classical CLSP by taking into account the parent-component relationships among the products in the production process, which is required for a multi-level production system. Third, we model the concept of backlogging by allowing the inventory to become negative. Fourth, we model that products can only be assigned to a selection of machines for production.

4.4.1 MILP model

In this section, we develop an MILP model that incorporates the four model extensions that are relevant for the medium-term. To model different situations, adaptations can be made to this model. This can be done by experimenting with changes in the inventory control policy or model parameters to gain insight into the impact of these adjustments on the production plan. We first introduce and describe the *sets*, followed by the *parameters* and *decision variables*. Finally, the MILP model, including the *objective function* and *constraints*, is formulated and explained afterwards. All product units are expressed in kilograms or meters, depending on the standard unit of measure and all time-related parameters are expressed in minutes.

Set	**Description**
i	Product with i = 1,…, N
j	Product with j = 1,…, N
m	Machine with m = 1,…, V
t	Week with t = 1,…, T

Parameters	**Description**
N	Number of products
V	Number of machines
T	Number of weeks in the planning horizon
$IntI_i$	Initial inventory of product i in m/kg

$IntB_i$	Initial number of backorders of product i in m/kg
R_{mt}	Available resource capacity for machine m in week t in minutes
Pur_{it}	Planned purchase quantity for product i to receive in week t in m/kg
d_{it}	Expected demand for product i in week t in m/kg
C_{im}	Unit production costs of product i on machine m in euros per m/kg
S_{im}	Setup costs for product i on machine m in euros per setup
h_i	Unit holding costs of product i in euros per m/kg per week
$B1_i$	Shortage costs for backlogging one unit of product i in euros per m/kg per week
PT_{im}	Unit production time for product i on machine m in minutes per m/kg
ST_{im}	Setup time for product i on machine m in minutes per setup
M	Sufficiently large number
a_{ij}	Number of units of component i required to produce one unit of parent j
v_{im}	$\begin{cases} 1, \text{if product } i \text{ can be assigned to machine } m \text{ for production} \\ 0, \text{otherwise} \end{cases}$

Decision variables	**Description**
X_{imt}	Number of units of product i produced on machine m in week t
I_{it}^{+}	Inventory of product i at the end of week t
I_{it}^{-}	Number of backorders of product i at the end of week t
Y_{imt}	$\begin{cases} 1, \text{if product } i \text{ is produced on machine } m \text{ in week } t \\ 0, \text{otherwise} \end{cases}$

Objective function

$$\text{Min} \sum_{i=1}^{N}\sum_{m=1}^{V}\sum_{t=1}^{T} C_{im}X_{imt} + \sum_{i=1}^{N}\sum_{m=1}^{V}\sum_{t=1}^{T} S_{im}Y_{imt} + \sum_{i=1}^{N}\sum_{t=1}^{T} h_i I_{it}^{+} + \sum_{i=1}^{N}\sum_{t=1}^{T} B1_i I_{it}^{-}$$

Subject to

$$\sum_{i=1}^{N} PT_{im}\, X_{imt} + \sum_{i=1}^{N} ST_{im}Y_{imt} \le R_{mt} \qquad \forall m \in V, \forall t \in T \qquad (4.1)$$

$$Pur_{i1} + \sum_{m=1}^{V} X_{im1} - \sum_{j=1}^{N}\sum_{m=1}^{V} a_{ij}X_{jm1} + IntI_i - I_{i1}^{+} + I_{i1}^{-} - IntB_i = d_{i1} \quad \forall i \in N \qquad (4.2)$$

$$Pur_{it} + \sum_{m=1}^{V} X_{imt} - \sum_{j=1}^{N}\sum_{m=1}^{V} a_{ij}X_{jmt} + I_{i,t-1}^{+} - I_{it}^{+} + I_{it}^{-} - I_{i,t-1}^{-} = d_{it} \quad \forall i \in N, t = 2,..T \qquad (4.3)$$

$$X_{imt} \le M\, Y_{imt} \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (4.4)$$

$$X_{imt} = 0 \qquad \forall i \in N, \forall m \in V, \forall t \in T, v_{im} = 0 \qquad (4.5)$$

$$I_{it}^{-} = 0 \qquad \forall i \in N \; if \; \textstyle\sum_{j=1}^{N} a_{ij} > 0, \forall t \in T \qquad (4.6)$$

$$X_{imt} \ge 0 \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (4.7)$$

$$I_{it}^{+} \ge 0 \qquad \forall i \in N, \forall t \in T \qquad (4.8)$$

$$I_{it}^{-} \ge 0 \qquad \forall i \in N, \forall t \in T \qquad (4.9)$$

$$Y_{imt} \in \{0,1\} \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (4.10)$$

We want to use the model to determine which quantities of which products to produce in which week and on which machine. In addition, we want to gain insight into the stock movements of the MTS products and the number of units that are produced after their due date, expressed in the number of backorders. Finally, the model provides insight into whether a product should be produced in a certain week so that a setup must be performed. The objective function is to minimize the total costs, consisting of production costs, setup costs, inventory holding costs and backorder costs. The objective function is minimized over N products, T weeks and V machines.

Constraint (4.1) ensures that the total production plus setup time used on machine m in week t should be smaller than or equal to the available machine capacity in that week. We decided to define the unit resource consumption for product i (a_i) used in the classical CLSP as the sum of the unit production time for product i (PT_{im}) and the setup time for product i (ST_{im}) on machine m. The parameter R_{mt} is related to the first model extension and is used to separate the available resource capacity per machine by adding a machine index.

The first inventory balance constraint (4.2) is related to the first week of the planning horizon and takes into account the initial inventory level and the initial number of backorders for all products to meet the demand in that week. In addition, the second inventory balance constraint (4.3) is related to the remaining weeks in the planning horizon and ensures that all demand is met from planned purchase orders to be received in week t, production in week t, inventory of the previous week $t-1$ or by postponing demand to future weeks at a given penalty cost. The parameter a_{ij} is related to the second model extension and is used to model the parent-component relationships among the products in the production process. The third part of both constraints takes into account the amount of production of a product that is required to satisfy the production of its successors. The parameter $B1_i$ is related to the third model extension and is used in the objective function to model the concept of backlogging. Constraints (4.2) and (4.3) determine the number of backorders of a product by assigning a value to the decision variable I_{it}^{-}.

Constraint (4.4) makes sure that if a product is produced on machine m in week t, the binary variable Y is set to 1 and a setup is incurred in that week. Because part of the objective is to minimize the total setup costs, the binary variable Y is always equal to 0 if the number of units produced (X) equals 0.

The parameter v_{im} is related to the fourth model extension and is used in constraint (4.5) to ensure that products can only be assigned to a selection of machines for production.

Constraint (4.6) ensures that it is not possible to backorder the components. This constraint prevents the model from backordering components if the parent is planned for production. In other words, this constraint ensures that sufficient units of the components must be available to produce the parent, while the demand for the parent can still be backordered. There is no demand for components until the parent is planned for production. To be able to produce the parent in a certain week, the demand for the components must be met and therefore cannot be backordered.

Constraints (4.7), (4.8) and (4.9), respectively, ensure that the number of units produced, the amount of inventory and the number of backorders are always greater than or equal to 0. Constraint (4.10) ensures that the binary variable Y can only take values 0 and 1.

4.4.2 Determining the cost parameters

This section briefly explains how we determine the cost parameters of the MILP model. A more detailed explanation of the calculation of the cost parameters can be found in Appendix C. These parameters are quantities that are used as input and that influence the output of the model. As mentioned in Section 4.4.1, the objective of the model is to minimize the total costs, consisting of production costs, setup costs, inventory holding costs and backorder costs. Because some parameters are not defined by TKF, we define them in cooperation with the capacity planner of the DRAFA, the logistics manager and the finance department.

First, to determine the unit production costs of product i produced on machine m (C_{im}), we multiply the production time for one kg or m of a product by the machine production costs. Second, to determine the setup costs for product i produced on machine m (S_{im}), we multiply the setup time for a product by the machine setup costs. Third, a common method used in practice to determine the inventory holding costs is to divide it into the following three cost components: cost of capital, cost of inventory storage and handling and cost of risk (Durlinger, 2014). There is not one general percentage for the inventory holding costs. However, in collaboration with the logistics manager and the finance department, we use this method to determine the inventory holding costs per product produced within the DRAFA. Based on the calculations, the inventory holding costs range from € X to € X per m/kg per week. Because TKF currently does not have a method to determine the exact costs of inventory storage and handling, we experiment with different values for the inventory holding costs in Chapter 5. Fourth, to determine the shortage costs for backlogging one unit of product i per time period (B_i), we use the inventory holding costs of product i (h_i). In addition, we select an appropriate target fill rate. In Chapter 5, we experiment with different levels of the target fill rates and thus varying shortage costs per product. It is interesting to understand the impact of different service levels on the production plan and the stock movements of the MTS products.

4.5 Incorporating inventory control decisions

As we concluded from Chapter 2, the use of static minimum and maximum inventory levels for the MTS products in combination with uncertainties and fluctuations in daily demand leads to a low delivery reliability. In addition, the current inventory methodology is not able to make replenishment decisions based on ADI on customer demand that gradually becomes known. In this section, we present an appropriate inventory control policy that can be used to improve the inventory management of MTS products.

4.5.1 Appropriate inventory control policy

There are several inventory control policies available to determine when to place a replenishment order and what quantity to order. To clarify, an order refers to a production order for the DRAFA. It is important to emphasize that an inventory control policy only applies to the MTS products produced within the DRAFA. The MTO products are produced when requested by the next departments in the production process and are produced in the requested quantities. Our main goal concerning inventory management is to protect against uncertainties in demand. These demand uncertainties are mainly related to changes in the short-term production schedule of the departments Multi Conductor, Energy or Installation.

Because of ADI on customer demand, a dynamic inventory control policy is preferred that makes the inventory parameter values dependent on the expected demand of the next departments in the production process. In the production context of the DRAFA, the production quantity of an MTS product is always a multiple of the minimum production quantity. The production of each MTS product is constrained by both a minimum production quantity and a maximum storage quantity. The minimum production quantity is based on the total length or weight per packaging unit, because it is not efficient to produce half-filled packaging units that are placed in stock. The maximum storage quantity is based on the stock capacity, because it is not possible to produce more packaging units of a product than can be stored for that product in the TKF factory.

In other words, the (R, s, nQ)-policy is an appropriate inventory control policy for the MTS products where a multiple of the minimum production quantity Q is produced whenever the inventory position drops to or below the reorder point s. When determining the reorder point s, the lead time L can be modelled as the supply lead time L^S minus the demand lead time L^D. Due to uncertainties in daily product requests, the capacity planner of the DRAFA should review the inventory position on a daily basis. Therefore, the review period R is equal to one day and we can conclude that the (R, s, nQ)-policy approaches the (s, nQ)-policy. The (s, nQ)-policy should be made dynamic by setting SKU-specific production quantities, reorder points and safety stocks. When determining the quantity to be produced and the reorder point per product, ADI on customer demand should be taken into account. In addition, we need to select an appropriate target fill rate as input for calculating the optimal safety stock for each MTS product to protect against demand uncertainties.

4.5.2 Implementing inventory control policy parameters in the MILP model

The (s, nQ)-policy consists of the following two parameters: the reorder point s and the production quantity nQ. Recall from the literature that a safety stock is required to reduce the risk of a product being out of stock in case of uncertainty in the demand. The quantity to be produced for a product in a given time period is determined by the MILP model. However, we force the MILP model to determine a suitable value for the decision variable X_{imt} which is a multiple n_{imt} of the minimum production quantity Min_i for all MTS products. This can be modelled by replacing constraint (4.7) with constraint (4.11) and adding constraint (4.12).

$$X_{imt} = n_{imt}\, Min_i \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (4.11)$$
$$n_{imt}\ as\ integer \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (4.12)$$

In addition, we incorporate inventory control policy parameters into the MILP model to achieve inventory management goals. For each MTS product, the inventory level should not fall below the safety stock and may not exceed the maximum storage quantity. As a result, we determine a minimum and maximum inventory level for each MTS product. The safety stock is part of the reorder point and is needed to cover higher than expected demand that may arise during the lead time. The lead time can be modelled as the supply lead time minus the demand lead time, due to ADI. We force the MILP model to increase the inventory level of an MTS product by scheduling production when the inventory level at the end of a week is expected to reach the safety stock level SS_i of product i. However, due to limited production capacity, it is not always possible to keep all inventory levels above the calculated safety stock levels. Therefore, we decided to allow the model to have the inventory levels below the safety stock levels at a certain penalty cost $B2_i$. The decision variable SS_{it}^- keeps track of the number of units of product i that are below the safety stock level of that product at the end of week t and is multiplied by the penalty cost $B2_i$ in the objective function. In addition, the inventory level may not exceed the maximum storage quantity Max_i of product i. The inventory control policy parameters can be implemented in the model by adding constraints (4.13), (4.14) and (4.15). Appendix D contains the extended MILP model from Section 4.4.1 that integrates inventory control and lot sizing decisions.

$$I_{it}^+ + SS_{it}^- \geq SS_i \qquad \forall i \in N, \forall t \in T \qquad (4.13)$$
$$I_{it}^+ \leq Max_i \qquad \forall i \in N, \forall t \in T \qquad (4.14)$$
$$SS_{it}^- \geq 0 \qquad \forall i \in N, \forall t \in T \qquad (4.15)$$

There are several ways to calculate the safety stock levels, as it depends on the perspective of the company (Silver, Pyke, & Thomas, 2017). As discussed in Section 3.1.5, we focus on the method where the safety stock is based on the target fill rate as the customer service measure. The safety stock can be computed by multiplying a safety factor k_i based on the target fill rate and the standard deviation of the lead time demand σ_i^L, which is the standard deviation of the demand per period σ_i^D multiplied by the square root of the lead time L_i. When the lead time demand can be modelled by a normal distribution, the formulas for calculating the safety stock and the standard deviation of the lead time demand for product i are as follows.

$$SS_i = k_i * \sigma_i^L$$
$$\sigma_i^L = \sigma_i^D \sqrt{L_i}$$

To determine which target fill rate to use for which MTS product, we use the combined ABC-XYZ classification. The combined ABC-XYZ classification is based on both the annual dollar usage (ABC classification) and the level of demand uncertainty (XYZ classification). Table 4.1 shows the distribution of the MTS products over the classes and shows in brackets which target fill rate can be used for which class. Appendix E provides insight into the calculations of the annual dollar usage values and the coefficient of variations (CoVs) required to classify the MTS products according to the combined ABC-XYZ classification.

Table 4.1 - Classification of the MTS products according to the combined ABC-XYZ classification.

	X	**Y**	**Z**	**Total**
A	0 (97%)	5 (95%)	11 (93%)	16
B	0 (95%)	4 (93%)	13 (90%)	17
C	0 (93%)	0 (90%)	25 (90%)	25
Total	0	9	49	58

As mentioned in Section 3.1.6, the safety factor k can be determined based on the selected target fill rate by using the formula below for the standard normal loss function $G(k)$.

$$G(k) = \frac{Q(1 - Fill\,rate)}{\sigma_{L+R}}$$

We have developed an Excel tool to calculate the corresponding safety stock levels of the MTS products needed to reduce the effects of demand uncertainty. With the help of the dynamic dashboard in Figure 4.3, we calculate the safety stock levels for the MTS products based on the historical demand data per day over the past six months. Appendix F explains how the safety stock levels are calculated by the Excel tool.

Inventory control tool DRAFA - Calculating safety stocks

	Date T periods ago		10-11-2021
	Article		
	Description		
	ABC-XYZ class		AZ
	Target fill rate		93%
	% of days with no demand		2,4%
	Threshold		80%
MPQ	Minimum production quantity		400 [KG]
LSu	Supply lead time		2 [days]
LD	Demand lead time		1 [days]
LSa	Safety lead time		0,5 [days]
L	Lead time (production)	L = [LSu-LD+LSa]+	1,5 [days]
OH	Current on-hand inventory		64.835 [KG]
T	Demand period		182 [days]
D	Historical demand over the period		1.034.317 [KG]
µ	Average historical demand per day	µ = D / T	8.341 [KG]
σD	Standard deviation of historical demand		3.180 [KG]
µL	Mean lead time demand	µL = µ x L	12.512 [KG]
σL	Standard deviation of lead time demand	σL = σD x √L	3.894 [KG]
G(k)	Standard normal loss function	G(k) = MPQ x (1 - Target fill rate) / σL	0,0072
G(k)2	Standard normal loss function 2		0,0073
k	Safety factor		2,0567
SS	Safety stock	SS = k x σL	8.010 [KG]

Cells to be filled in per article
Default parameters
Calculated values

Calculate safety factor

Calculate safety stocks

Historical demand data

#	Date	Day	Quantity	Quantity 2
1	10-11-2021	woensdag	11.618	11.618
2	11-11-2021	donderdag	2.166	2.166
3	12-11-2021	vrijdag	1.736	6.121
4	13-11-2021	zaterdag	878	
5	14-11-2021	zondag	3.507	
6	15-11-2021	maandag	31.084	31.084
7	16-11-2021	dinsdag	1.313	1.313
8	17-11-2021	woensdag	2.580	2.580
9	18-11-2021	donderdag	25.544	25.544
10	19-11-2021	vrijdag	867	3.901
11	20-11-2021	zaterdag	1.728	
12	21-11-2021	zondag	1.305	
13	22-11-2021	maandag	13.691	13.691
14	23-11-2021	dinsdag	3.877	3.877
15	24-11-2021	woensdag	5.514	5.514
16	25-11-2021	donderdag	886	886
17	26-11-2021	vrijdag	4.482	8.001
18	27-11-2021	zaterdag	1.799	
19	28-11-2021	zondag	1.720	
20	29-11-2021	maandag	6.721	6.721
21	30-11-2021	dinsdag	1.790	1.790
22	1-12-2021	woensdag	4.805	4.805
23	2-12-2021	donderdag	5.687	5.687
24	3-12-2021	vrijdag	2.599	6.124
25	4-12-2021	zaterdag	1.755	
26	5-12-2021	zondag	1.770	
27	6-12-2021	maandag	4.391	4.391
28	7-12-2021	dinsdag	1.321	1.321
29	8-12-2021	woensdag	7.074	7.074
30	9-12-2021	donderdag	766	766

Figure 4.3 - Inventory control tool DRAFA for calculating the safety stock levels.

We have excluded public holidays from the analysis, because no production takes place on these days. In addition, the DRAFA was not operational during the weekends, while other departments did produce. The demand on Saturday and Sunday is added to the demand on Friday, because the DRAFA had to ensure that there was sufficient stock on Friday to meet the production at the other departments during the weekends.

Because the current list of MTS products is static and not up to date, we decided to establish a threshold value to determine for each product on the list whether it should still be classified as an MTS product with a safety stock or not. Contrary to the current situation, we have decided to only consider a safety stock for products that are supplied to one of the other departments, because the uncertainty in the demand only applies to those products. In collaboration with the capacity planner, we decided to classify a product as an MTS product with a positive safety stock if on average the product is requested on a weekly basis, given the fraction of periods in which the demand is equal to zero. In other words, products that are requested less than once a week on average are not considered MTS products with a positive safety stock.

Based on the safety stock calculations, we observed that the safety stock level was unrealistically high for one specific product. The reason for this is that the date on which the product is requested by the next department does not always correspond to the date registered in Navision. The capacity planners of the other departments have to process the demand for this product themselves in Navision and sometimes wait several days to register the realized demand over the past few days at once. This leads to large fluctuations in the historical demand and thus to an unrealistically high safety stock. To solve this problem, we decided to remove the outliers from the historical demand data set, after which the safety stock could be calculated. We set the lower bound equal to the first quartile minus 1.5 times the interquartile range and the upper bound to the third quartile plus 1.5 times the interquartile range. To conclude, we obtained a positive safety stock for 24 MTS products.

4.6 Short-term planning model

In this section, we focus on developing the MILP model by incorporating positive supply lead times, setup carry-overs and sequence-dependent setup times to solve the short-term production planning problem at the DRAFA. We set the following requirements and make the following assumptions in our model.

4.6.1 Requirements

Requirements (1), (2) and (4) that we discussed in Section 4.2.1 are different for the short-term and are now as follows.

- Days are used as the unit of time over a period of 10 days.
- Multiple products can be produced per day at the DRAFA.
- Production capacity set on a particular day for a particular machine may not be exceeded.

The other requirements that we discussed in Section 4.2.1 are still valid for the short-term.

4.6.2 Assumptions

Assumptions (1) and (7) that we discussed in Section 4.2.2 are different for the short-term and are now as follows.

- Planning horizon is finite and consists of T days.
- Inventory holding costs are linear and are charged at the end of the day.

The other assumptions that we discussed in Section 4.2.2 are still valid for the short-term. In addition, we make the following assumptions.

- Demand for a product on a given day cannot be met through production on the same day.
- Each machine is initially set up to a product at the beginning of the planning horizon.
- The remaining production quantities of the products that are currently in production on each machine in the DRAFA are planned at the beginning of the planning horizon.
- Each machine carries over a setup for only one product from the end of the day to the next day, i.e. no additional setup is needed the next day.
- Required setup time and associated setup costs can be reduced when switching over from one product to another, depending on the properties of both products (i.e. number of wires and wire diameters).
- On average, the capacity planner schedules production halfway through the day and thus we use half of the resource capacity on the first day of the planning horizon for each machine.

4.6.3 MILP model

Based on the MILP model that we developed for the medium-term in Appendix D and the relevant literature found in Section 3.4, we develop an MILP model that incorporates positive supply lead times, setup carry-overs and sequence-dependent setup times to model the short-term production planning problem. We want to use the model to determine which quantities of which products to produce on which day, in which sequence and on which machine. The objective function is to minimize the total costs over N products, V machines and T days. In this section, we only discuss those parts of the model that deviate from the MILP model developed for the medium-term, while Appendix G contains the complete mathematical formulation of the extended MILP model.

Objective function

$$\text{Min} \sum_{j=1}^{N}\sum_{m=1}^{V}\sum_{t=1}^{T} C_{jm}X_{jmt} + \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{m=1}^{V}\sum_{t=1}^{T} SF_{ij}S_{jm}Y_{ijmt} + \sum_{j=1}^{N}\sum_{t=1}^{T} h_j I_{jt}^{+} + \sum_{j=1}^{N}\sum_{t=1}^{T} B1_j I_{jt}^{-} + \sum_{j=1}^{N}\sum_{t=1}^{T} B2_j SS_{jt}^{-}$$

Subject to

$$\sum_{j=1}^{N} PT_{jm} X_{jmt} + \sum_{i=1}^{N}\sum_{j=1}^{N} SF_{ij} ST_{jm} Y_{ijmt} \leq R_{mt} \qquad \forall m \in V, \forall t \in T \qquad (4.16)$$

$$Pur_{j1} - \sum_{k=1}^{N}\sum_{m=1}^{V} a_{jk} X_{km1} + IntI_j - I_{j1}^{+} + I_{j1}^{-} - IntB_j = d_{j1} \qquad \forall j \in N \qquad (4.17)$$

$$Pur_{jt} + \sum_{m=1}^{V} X_{jmt-L_j} - \sum_{k=1}^{N}\sum_{m=1}^{V} a_{jk} X_{kmt} + I_{j,t-1}^{+} - I_{jt}^{+} + I_{jt}^{-} - I_{j,t-1}^{-} = d_{jt} \quad \forall j \in N, t = 2,..T \qquad (4.18)$$

$$X_{jm1} \leq M \left(\textstyle\sum_{i=1}^{N} Y_{ijm1} + \alpha_{jm}^{0}\right) \qquad \forall j \in N, \forall m \in V \qquad (4.19)$$

$$X_{jmt} \leq M \left(\textstyle\sum_{i=1}^{N} Y_{ijmt} + \beta_{jm,t-1}\right) \qquad \forall j \in N, \forall m \in V, t = 2,..T \qquad (4.20)$$

$$X_{jmt} \geq IntP_{jmt} \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.23)$$

$$\textstyle\sum_{t=1}^{T} X_{jmt} = o_{jm} Pack_j Min_j \qquad \forall j \in N, \forall m \in V \qquad (4.24)$$

$$\textstyle\sum_{j=1}^{N} \beta_{jmt} = 1 \qquad \forall m \in V, \forall t \in T \qquad (4.28)$$

$$\alpha_{jm}^{0} + \textstyle\sum_{i=1}^{N} Y_{ijm1} = \sum_{k=1}^{N} Y_{jkm1} + \beta_{jm1} \qquad \forall j \in N, \forall m \in V \qquad (4.29)$$

$$\textstyle\sum_{i=1}^{N} Y_{ijmt} + \beta_{jm,t-1} = \sum_{k=1}^{N} Y_{jkmt} + \beta_{jmt} \qquad \forall j \in N, \forall m \in V, t = 2,..T \qquad (4.30)$$

$$\gamma_{jmt} \geq \gamma_{imt} + 1 - N\,(1 - Y_{ijmt}) \qquad \forall i,j \in N, \forall m \in V, \forall t \in T \qquad (4.31)$$

In the objective function and constraint (4.16), we multiply a fraction SF_{ij} by the setup costs and time for product j on machine m, respectively, when a setup is performed from product i to product j on machine m on day t (i.e. Y_{ijmt} = 1). This fraction ranges from 0 to 1 and is based on decision rules that we explain in Section 6.1.

The first inventory balance constraint (4.17) is related to the first day of the planning horizon. Because the supply lead times at the DRAFA are longer than one day, the demand for a product on the first day cannot be met through production on that day. As a result, we can only meet this demand through purchase orders that arrive on the first day and inventory that is realized through historical production. This is incorporated into the model by omitting the option to plan production on day 1 to meet demand on that day. The second inventory balance constraint (4.18) is related to the remaining days in the planning horizon. The demand for a product on a given day can be met by shifting production backward by at least a period equal to the supply lead time plus additional safety lead time. The parent-component relationships among the products are valid and are included in constraint (4.18). Suppose the supply lead time of each production step is equal to one day. If there is demand for a parent on day 3, we must produce the parent one day earlier (i.e. day 2). In addition, we have to produce the component one day before we produce the parent (i.e. day 1).

Constraint (4.19) is related to the first day of the planning horizon and ensures that when a product is produced on a particular machine, either a setup is performed for that product on that machine on the first day or the machine is initially set up to that product. If the machine is initially set up to a product, there is no need to set up the machine to that product for production and thus no setup costs are charged. Constraint (4.20) is related to the remaining days in the planning horizon and ensures that when a product is produced on a particular machine, either a setup is performed for that product on that machine on that day or the machine carries over a setup state from the previous day.

Constraint (4.23) forces the model to plan the remaining production quantities of the production orders currently in production at the beginning of the planning horizon. These production orders must first be completed, after which a new order can be produced. The "≥" sign allows the model to produce more of a product than the remaining quantity of the production order that is currently in production. A production order may take longer than one day, causing the order to be spread over several days.

For some products, the production quantity is a fixed number of packaging units. Constraint (4.24) ensures that the total quantity produced in the planning horizon is a multiple o_{jm} of the standard production quantity of a product, being the fixed number of packaging units times the length or weight per packaging unit. To give an example, for some products the standard production quantity is ten times the minimum production quantity of 350 kg per reel to minimize the amount of residual material. Because this takes longer than one day, those products cannot be planned for production due to the limited resource capacity per day. Therefore, constraint (4.24) ensures that for these products the sum of the production quantities over all days in the planning horizon is a multiple of (10 x 350 kg=) 3500 kg.

Constraint (4.28) ensures that each machine carries over a setup for one product from the end of the day to the next day. This constraint gives the possibility to continue with a production order the next day without performing an additional setup. If the situation arises that the machine is currently empty and thus no product is initially set up on that machine, we initially set up the machine to a dummy product (i.e. $\alpha_{jm}^{0} = 1$). If the model decides to switch from the dummy product to another product, the full setup time and costs are included.

Constraint (4.29) is related to the first day of the planning horizon and ensures that when a particular machine is either initially set up to a product or set up to a product from another product, the machine must again switch to another product on the same day or the machine must carry over the setup state to the next day. In other words, this constraint forces the model to make a follow-up decision for each setup state per machine on the first day. Constraint (4.30) is related to the remaining days in the planning horizon. Instead of the possibility that a machine is initially set up to a particular product, for the other days in the planning horizon, the machine may carry over a setup state from the previous day.

Finally, constraint (4.31) becomes relevant when multiple products are planned for production on a particular machine and on a particular day. The constraint generates the production sequence per machine and per day by assigning an integer value to the decision variable γ_{jmt} for each product j. The greater the value of the decision variable, the later product j is planned for production. When a product is not planned for production on a particular machine and on a particular day, the value of the decision variable is zero.

4.7 Conclusion

In this chapter, we designed and developed an MILP model, including four relevant model extensions, that fits the medium-term problem context at the DRAFA, while integrating inventory control and lot sizing decisions. We have developed an appropriate inventory control policy for the MTS products that we implement in our MILP models to achieve both production and inventory management goals in the production planning process. We decided to integrate inventory control and lot sizing decisions by using the (s, nQ)-policy for the MTS products. We use the safety stocks as the minimum inventory levels to reduce the risk of a product being out of stock due to uncertainty in the demand and the storage capacity as the maximum inventory levels. Because it is not always possible to keep all inventory levels above the calculated safety stocks due to limited production capacity, we decided to allow the model to have the inventory levels below the safety stock levels at a certain penalty cost. We further extended the MILP model by incorporating positive supply lead times, setup carry-overs and sequence-dependent setup times to model the short-term production planning problem.

In Chapter 5 we use the extended MILP models to develop a prototype planning tool for both the medium-term and the short-term that meets the assumptions and requirements set in consultation with the capacity planner of the DRAFA. In addition, we analyse the results of the numerical experiments performed, including sensitivity analysis on information that is uncertain, to find out what the impact is on our findings. We experiment with different settings for the inventory control policy parameters, different values for the inventory holding costs and different levels of the target fill rates to understand the impact on the number of backorders and the stock movements of the MTS products. Finally, we compare the results of the short-term production planning model with the current situation and with the results of the medium-term production planning model.

5 Results and analysis – Part I

This chapter and the next chapter answer the fourth research question stated in Section 1.7. To answer the fourth research question, we develop a prototype planning tool for both the medium-term and the short-term that meets the assumptions and requirements set in Sections 4.2 and 4.6, respectively. Chapter 5 focuses on the performance of the prototype planning tool for the medium-term for different settings of the input data, while Chapter 6 elaborates on this by focusing on the performance of the prototype planning tool for the short-term. The fourth research question is formulated as follows:

4. *How does the medium-term and short-term prototype planning tool perform?*

Before implementing the mathematical models provided in Chapter 4, we verify the planning model and validate the model results with the real world problem for one process step carried out within the DRAFA in Section 5.1. The verification and validation focus on the medium-term planning model, because this model is also the basis of the short-term planning model. Section 5.2 elaborates on the setup of the medium-term planning model by an explanation of the data sets that we use as input. Section 5.3 explains the experimental setup and describes the KPIs that we use to analyse the performance for each combination of experimental settings. We discuss the results of the medium-term prototype planning tool in Section 5.4. We analyse what happens to the gap if we increase the computational time limit of the model in Section 5.5. In Section 5.6, we analyse whether the model works as desired for future-oriented growth scenarios to decide whether a heuristic should be used. We end this chapter with a conclusion in Section 5.7.

5.1 Verification and validation

Before we focus on the implementation of the model and the analysis of the model results for the real problem at the DRAFA, we verify the planning model and validate the model results for only one group of machines used within the DRAFA. We decided to focus on one group of machines as this reduces the problem instance and helps to better analyse the results. To verify and validate the model, we focus on the bunching process only. Recall from Chapter 2 that four machines are used in this process step. If the model is valid for this problem instance, it is also valid for the entire real problem instance. This is because all model characteristics described in Section 4.3, such as the inventory control decisions and the presence of parent-component relationships among the products, apply to the bunching process.

After analysing the real problem context at the DRAFA in Chapter 2 and reviewing the relevant literature in Chapter 3, we designed a paper model in Chapter 4. In this chapter, we convert this paper model to a computer model by programming the model in an appropriate programming language. In the verification step, we determine whether the paper model has been correctly translated into a computer model. In the validation step, we determine whether the computer model is an accurate representation of the real system (Law, 2015).

First, we verify the model by checking the input data retrieved from the ERP system Navision and derived from discussions with stakeholders. To verify the input data, we took a sample for each input parameter by randomly selecting 10 products. For each selected product, we compared the value of the input parameter with the value registered in Navision. In discussions with stakeholders, we determined input data that is needed for the model, but that is not registered in Navision. We shared the determined input data afterwards with the stakeholders for verification. Verification of the input data is an important step, because computational errors in determining the input values will lead to wrong decisions of the computer model and thus wrong results.

After verifying the input data, we validated the output data obtained after solving the model. Law (2015) provides several techniques to validate the model. A common technique used in practice is to compare the historical schedule generated by the planner with the schedule obtained after solving the model by using the same historical demand data as input. In our case, however, it is not possible to retrieve the historical schedule, because historical data concerning the production schedule is not stored by TKF. Alternatively, we decided to compare the results of our short-term planning model with the operational production schedule created manually by the planner later in Chapter 6, as our short-term model is derived from the medium-term model.

To validate the output data, we analysed whether the total production quantity over all periods in the planning horizon minus the amount of production of a product that is required to satisfy the production of its successors minus the amount of inventory in the last period plus the number of backorders in the last period equals the total expected demand over all periods. We determined whether this equality applies to all products included in the production schedule. Furthermore, we checked the parent-component relationships among the products by recalculating whether the correct quantity of a component needed to produce the parent in a certain period has been produced. In addition, we checked for all MTS products whether the production quantity is a multiple of the total length or weight per packaging unit and whether the inventory levels are above the calculated safety stocks. Finally, we analysed whether no production or storage capacity is exceeded. For the production capacity per machine, we summed the quantity over all products planned for production in a certain period and compared it to the available resource capacity. For the storage capacity per MTS product, we took the maximum of all inventory levels over all time periods and compared it to the maximum storage quantity.

5.2 Model setup

We discuss the results obtained after solving a toy problem to illustrate the problem and the functionality of the model in Appendix H. Before we implement the mathematical model for the more advanced real problem at the DRAFA, we explain the data sets that we use as input for the model. In Section 4.3, we explained how we determine the expected demand and resource capacity as input for the model. In Section 4.4.2, we explained how we determine the unit production times, setup times and cost parameters. In addition, we use the following input data.

- Initial inventory level and number of backorders

The initial inventory level and number of backorders should be determined prior to the first week of the planning horizon for all products produced within the DRAFA. The initial inventory level represents the current inventory level of a product stored in the facility and is realized through historical production. The initial number of backorders represents the outstanding demand for a product for which the due date has already passed. We need to consider the initial inventory level and number of backorders to ensure that all demand for the first week is met.

- Planned purchase orders

To decide on the production quantities per product and per week, we need to consider the planned purchase orders to be received in a week. All planned purchase orders are registered in Navision with an expected arrival date. This gives the planner the possibility to analyse what happens to the production schedule when a larger quantity of a product is purchased. When the expected arrival date of a purchase order has passed, we add this quantity to the planned purchase orders to be received in the current week.

- Parent-component relationships

To incorporate the parent-component relationships among the products in the production process, we need to examine the product structure of each product produced within the DRAFA. The product configuration of each product provides insight into the quantity of all components that make up a product. The obtained values are the number of units of the component needed to produce one unit of the parent, while taking into account the standard unit of measure as registered in Navision. For example, to produce one m of a particular parent, we need 13.36 m of one component and 24.71 m of another component. In addition, to produce one m of a particular parent, we need 0.0347 kg of a particular component.

- Possible machine assignments

As mentioned in Section 4.3, products can only be assigned to a selection of machines for production. Navision indicates per product which machines can be used for production in the product configuration. We translate this information into a binary number for each product-machine combination. Because the products that are made up of aluminium and that are successively produced on Groftrek 2 and Samenslaglijn 2 are not incorporated into the planning model, we exclude both machines by default by setting the available resource capacity to zero. However, we give the capacity planner the option to indicate per week whether both machines can be used to produce the products that are made up of copper.

- Inventory control policy parameters

As mentioned in Section 4.5.2, we need to determine the value of additional parameters for the MTS products only. First, we determine the minimum production quantity of each MTS product based on the total length or weight per packaging unit to avoid the production of half-filled packaging units. Second, we determine the safety stock level of each MTS product as the minimum inventory level to reduce the risk of a product being out of stock due to uncertainty in the demand. Third, we determine the maximum storage quantity of each MTS product as the maximum inventory level to avoid exceeding the available storage space in the facility. Some MTS products are stored at the same location in the facility. For these MTS products, the sum of the inventory levels of a group of MTS products may not exceed a certain maximum storage quantity.

5.3 Experimental setup and KPIs

To understand the performance of the model, we conducted numerical experiments, including sensitivity analysis on information that is uncertain. In Section 5.3.1, we discuss the experimental setup. In Section 5.3.2, we describe the KPIs that we use to analyse the performance for each combination of experimental settings.

5.3.1 Experimental setup

We experimented with different settings for the inventory control policy and uncertain model parameters to gain insight into the impact of these adjustments on the production plan. The uncertain model parameters are the unit holding costs and the target fill rates. Table 5.1 shows the experimental setup consisting of eight relevant experiments. For the unit holding costs, the average of ± 5.6% of the cost price is based on the method we used in Section 4.4.2 by dividing it into cost of capital, cost of inventory storage and handling and cost of risk. The combination of grey cells indicates which settings have been chosen per experiment. To improve readability in the remainder of this chapter, we base the description of each experiment on an abbreviation of the selected settings. For example, in experiment New_25%_95% (6) we use the new inventory parameters, a holding cost rate of 25% of the cost price and a target fill rate of 95%.

Table 5.1 - Experimental setup.

Description of experiment	Inventory control policy		Unit holding costs		Target fill rate		
1. New_5.6%_95%	Current policy parameters	New policy parameters	On average ± 5.6% of cost price	25% of cost price	90%	95%	99%
2. Old_5.6%_95%	Current policy parameters	New policy parameters	On average ± 5.6% of cost price	25% of cost price	90%	95%	99%
3. Old_25%_95%	Current policy parameters	New policy parameters	On average ± 5.6% of cost price	25% of cost price	90%	95%	99%
4. Old_25%_90%	Current policy parameters	New policy parameters	On average ± 5.6% of cost price	25% of cost price	90%	95%	99%
5. Old_25%_99%	Current policy parameters	New policy parameters	On average ± 5.6% of cost price	25% of cost price	90%	95%	99%
6. New_25%_95%	Current policy parameters	New policy parameters	On average ± 5.6% of cost price	25% of cost price	90%	95%	99%
7. New_25%_90%	Current policy parameters	New policy parameters	On average ± 5.6% of cost price	25% of cost price	90%	95%	99%
8. New_25%_99%	Current policy parameters	New policy parameters	On average ± 5.6% of cost price	25% of cost price	90%	95%	99%

The first experiment describes the combination of settings we found during the research to model the medium-term production planning problem at the DRAFA, while integrating inventory control and lot sizing decisions. In experiment 2, we compare the old inventory parameters with the newly defined inventory parameters, i.e. the new safety stock levels of the MTS products. Due to the uncertainty in the determination of the unit holding costs, we investigate what happens if we use a holding cost rate of 25% of the cost price as a common number used in the literature in experiments 3 to 8 (Durlinger, 2014). The DRAFA has no strong preference for a target fill rate as input for the calculation of the shortage costs. As a result, we use a service level of 90%, 95% and 99% in combination with the old and new inventory parameters in experiments 3 to 8.

5.3.2 KPIs

As we observe from Table 5.1, in each experiment we make only one adjustment relative to another experiment in order to better assess the impact on our findings. For example, the difference between the first two experiments is in the choice of the inventory control policy, while the other settings remain the same. We define the KPIs to analyse the performance for each combination of experimental settings below.

- Production time / production costs

The first KPI is the production time or costs, which is the first part of our objective function. It is directly related to the number of units produced of each product per machine and per week as a decision made by the model. This KPI is influenced by the number of production hours available, but also by the unit holding costs. The higher the unit holding costs, the less likely the model will plan production far in advance.

- Setup time / setup costs

The second KPI is the setup time or costs, which is the second part of our objective function. The number of setups provides insight into the distribution of the products among the machines. For some products, it can be cost-effective to produce one product on several machines at the same time. This leads to higher setup costs, but may be necessary to meet demand and avoid backorder costs. In addition, this KPI provides insight into the distribution of the products among the weeks in the planning horizon.

- Inventory level / holding costs

The third KPI is the inventory level or holding costs, which is the third part of our objective function. With this KPI, we want to gain insight into the stock movements of the MTS products according to the inventory control policy and the corresponding inventory holding costs. This KPI is directly influenced by the inventory control policy and the unit holding costs. Using the old inventory parameters may lead to unnecessary high inventories for some MTS products.

- Service level / backorder costs

The fourth KPI is the service level or backorder costs, which is the fourth part of our objective function. The number of backorders provides insight into the number of products that is produced after their due date. Recall that the due date is equal to the week in which the demand is expected. The service level can be expressed in the delivery reliability and can be computed as follows:

$$\text{Delivery reliability (\%)} = \left(1 - \frac{\text{\# backorders}}{\text{Total expected demand}}\right) * 100\%$$

This KPI is directly related to the target fill rate, because a higher level of the target fill rate leads to higher shortage costs for backlogging products. The higher the target fill rate, the more likely the model will aim to avoid backorders as much as possible by making the best use of the available resource capacity.

- Safety stock backlogs / safety stock backlog costs

The fifth KPI is the number of units of each MTS product below the safety stock level. We measure this KPI in terms of the safety stock backlog costs, which is the fifth part of our objective function. Because it is not always possible to keep all inventory levels above the safety stock levels due to the limited production capacity, we allow the model to have the inventory levels below the safety stock levels at a certain penalty cost. This KPI provides insight into the difference between the desired safety stock level and the realized inventory level per MTS product at the end of each week. Because the unit backorder costs are higher than the unit penalty costs for having the inventory level below the safety stock level, we expect the model to meet the demand first and then use the remaining capacity to increase the inventory levels of the MTS products.

- Resource utilization

The sixth KPI is the resource utilization as a percentage of the available production hours used for production. The utilization rate can be computed as follows:

$$\text{Utilization rate (\%)} = \frac{\text{\# production and setup hours used}}{\text{\# available production hours}} * 100\%$$

We want to gain insight into the utilization per machine and per week to see when the utilization rate is high. As stated by Boucherie, Braaksma and Tijms (2021), above a utilization rate of 80%, the average waiting time increases rapidly. This KPI helps the planner to respond to capacity problems that may arise in the future.

5.4 Model performance analysis medium-term

In this section, we analyse the model results in terms of our KPIs. In Section 5.4.1, we discuss the results obtained by solving the model for the different experiments. In Section 5.4.2, we analyse whether the results are valid for different problem instances. To solve the medium-term production planning problem, we implemented the model provided in Appendix D in Python with the extension module Gurobi.

5.4.1 Different experimental settings

We experiment with different settings for the inventory control policy and uncertain model parameters according to the experimental setup described in Section 5.3.1. Because we performed the experiments on June 17, 2022, the input data and model results correspond to the situation on that day. The problem consists of $N = 187$ products, $V = 14$ machines and $T = 10$ weeks. We analyse the performance of the model by comparing the results in terms of our KPIs and the gaps obtained after a maximum computational time of 10 minutes. Table 5.2 shows the results by means of a cost breakdown into the production, setup and inventory holding costs, which are the relevant cost factors for the performance analysis and the corresponding gap obtained for each experiment. Because the unit holding costs are either ± 5.6% or 25% of the cost price, we normalized the inventory holding costs for all experiments to be able to compare the model results.

First, we compare the impact of using the newly defined inventory parameters instead of the old inventory parameters on the stock movements of the MTS products and thus the inventory holding costs. Using the newly defined inventory parameters leads to lower inventory holding costs, because the new safety stock levels are up to date and not based on static values. When comparing New_25%_95% (6), New_25%_90% (7) and New_25%_99% (8) with Old_25%_95% (3), Old_25%_90% (4) and Old_25%_99% (5) we obtain a reduction in the inventory holding costs of 5.8%, 5.6% and 3.9%, respectively. Second, we compare the impact of using a holding cost rate of 25% of the cost price instead of ± 5.6% according to the method we used in Section 4.4.2. Using higher unit holding costs leads to higher unit backorder costs. As a result, we see that the sum of the production, setup and inventory holding costs almost doubles as the model aims to minimize backorders by increasing production, when comparing New_25%_95% (6) and Old_25%_95% (3) with New_5.6%_95% (1) and Old_5.6%_95% (2). This indicates the importance of a correct determination of this cost factor for TKF, because of the impact on the model decisions. Third, we compare the impact of different target fill rates. Using a higher target fill rate also leads to higher unit backorder costs. When comparing New_25%_90% (7), New_25%_95% (6) and New_25%_99% (8), we obtain an increase in the sum of the production, setup and inventory holding costs of 7.6% and 7.1% as the model increases production and thus inventories to reduce backorders. Finally, the gap varies between the experiments. The model complexity and gap increase when we use higher unit holding costs or when we increase the target fill rate from 90% to 99%.

Table 5.2 - Model results per experiment.

Performance indicator	**1. New_5.6%_95%**	**2. Old_5.6%_95%**	**3. Old_25%_95%**	**4. Old_25%_90%**
Production costs	€ 207.513	€ 206.742	€ 298.998	€ 270.988
Setup costs	€ 46.883	€ 47.157	€ 95.003	€ 76.036
Inventory holding costs	€ 122.554	€ 125.415	€ 152.110	€ 147.191
Σ	**€ 376.950**	**€ 379.314**	**€ 546.111**	**€ 494.215**
Gap	1.25%	0.88%	6.23%	3.21%

Performance indicator	**5. Old_25%_99%**	**6. New_25%_95%**	**7. New_25%_90%**	**8. New_25%_99%**
Production costs	€ 318.995	€ 299.465	€ 278.548	€ 317.283
Setup costs	€ 110.014	€ 94.383	€ 81.622	€ 110.740
Inventory holding costs	€ 153.191	€ 143.317	€ 138.982	€ 147.215
Σ	**€ 582.200**	**€ 537.165**	**€ 499.152**	**€ 575.238**
Gap	6.45%	4.85%	3.48%	8.55%

In addition, we are interested in the delivery reliability per experiment, as shown in Figure 5.1, based on the number of backorders as a fraction of the total expected demand. We note that for all experiments the delivery reliability (i.e. blue bars) does not meet the target fill rate of 90%, 95% or 99% (i.e. orange line) due to the limited capacity for some machines. According to the model results, however, for machines with sufficient capacity and thus a lower utilization rate, the model is able to meet the target fill rate. We see that the delivery reliability increases as the target fill rate increases. When comparing New_25%_90% (7), New_25%_95% (6) and New_25%_99% (8), an increase in the delivery reliability of 2.3% and 1.5% is achieved. In addition, using the new inventory parameters (i.e. new safety stock levels) instead of the old inventory parameters (i.e. static min/max levels) leads to an increase in the delivery reliability. When comparing New_25%_95% (6), New_25%_90% (7) and New_25%_99% (8) with Old_25%_95% (3), Old_25%_90% (4) and Old_25%_99% (5) an increase in the delivery reliability of 0.8%, 1.2% and 1.8%, respectively, is achieved.

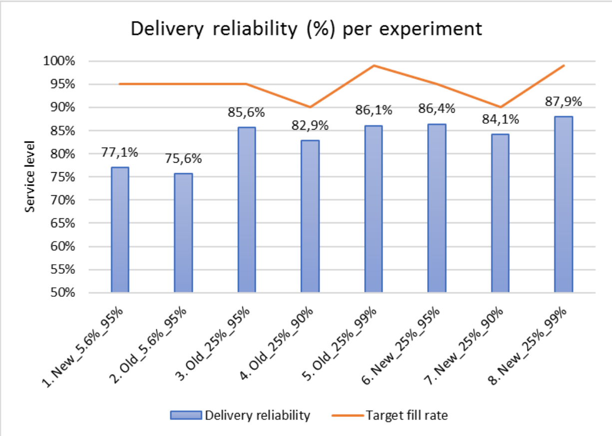

Figure 5.1 - Delivery reliability (%) per experiment.

The last KPI we are interested in is the impact of different target fill rates on the resource utilization. Figure 5.2 shows the average utilization per machine over the planning horizon for three different target fill rates. When comparing New_25%_90% (7), New_25%_95% (6) and New_25%_99% (8), we notice that the average utilization per machine increases as the target fill rate increases. As mentioned, a higher target fill rate leads to higher unit backorder costs. As a result, the model tries to avoid backorders as much as possible by making maximum use of the resource capacity. To clarify, our planning tool does not plan the entire 24 hours of production per day, but takes into account a lower number of available production hours due to possible efficiency losses. This ensures that the utilization rates of the machines are realistic and often do not exceed 80%. The relatively low utilization rates of Fijntrek 2 and 3 are remarkable. One reason for this is the low flexibility of Fijntrek 2 and 3 in combination with the changing product portfolio of TKF, which means that fewer end products require semi-finished products produced on these machines.

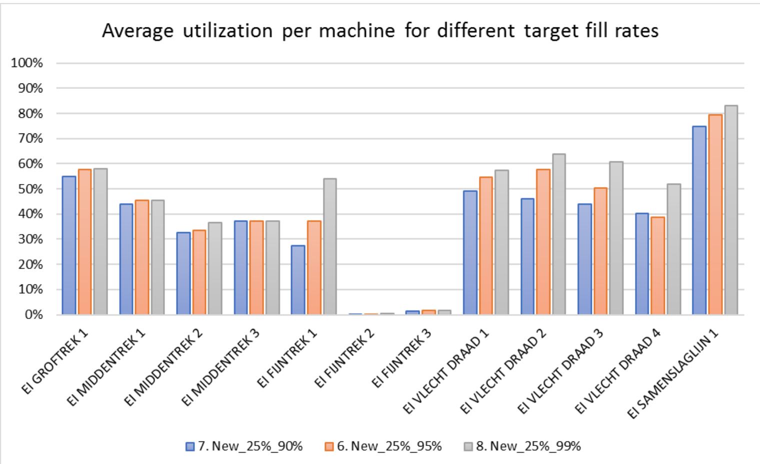

Figure 5.2 - Average utilization per machine for different target fill rates.

5.4.2 Different problem instances

The analysis of the model results in Section 5.4.1 corresponds to the situation on June 17, 2022. However, we want to test whether the model performs well and whether the results are valid for other problem instances. Therefore, we decided to run the model about two months later based on the input data collected on August 15, 2022. In addition, we randomly generated eight problem instances by using a random instance generator. Table 5.3 shows the eight problem instances and the associated model parameter for which we generate a random data set according to the given probability distribution as input for the model. We have not changed the values of the other input parameters, because most of these values are fixed for different problem instances.

Because improvement projects take place at the DRAFA, we want to gain insight into the cost savings that can be achieved when the DRAFA is able to increase the number of available production hours by a maximum of 10%. In addition, we generated two problem instances to gain insight into the impact of having low or high initial inventory levels and two other problem instances to understand the impact of having low or high expected demand rates on the model decisions. For each of these four problem instances, we use the uniform distribution to generate values within a certain interval. In the problem instances where the initial inventory levels and the expected demand rates are low, we set the lower bound to the first quartile minus 1.5 times the interquartile range and the upper bound to the mean. In the problem instances where both parameter values are high, we set the lower bound to the mean and the upper bound to the third quartile plus 1.5 times the interquartile range. In this way, we exclude outliers from the intervals. The last three problem instances are generated to see what happens when we have a different product portfolio due to an increase in the number of products produced by a group of machines. For each of these three problem instances, we use the Bernoulli distribution to indicate that a product can be assigned to a particular machine with probability p. In the current situation, an average of 25 different products are assigned to one machine. To model an increase in the number of products produced on a particular group of machines, we decided to set the probability for these machines to $\frac{1}{4}$ and for the other machines to $\frac{1}{12}$. With a total number of ± 200 different products, ± 50 products are then assigned to the machines with an increasing product portfolio and ± 15 products to the other machines.

Due to the limited time available for this research, we had to find a balance between the time we had left and the magnitude of the results to be generated. We therefore decided to analyse the results of the different problem instances for one combination of the experimental settings. Because of the uncertainty in the determination of the unit holding costs, we decided to use the settings of experiment 6 provided in Table 5.1. In this experiment, we use the new inventory parameters, a holding cost rate of 25% of the cost price and a target fill rate of 95%. In this section, we analyse the results for the eight generated problem instances obtained after a maximum computational time of 10 minutes.

Table 5.3 - Different problem instances.

Description of problem instance	Modified model parameter	Parameter value
1. Situation with an increase in the resource capacity	Available resource capacity for machine m in week t in minutes (R_{mt})	R_{mt} = R_{mt} * (1 + Uniform[0.01, 0.10])
2. Situation with low initial inventory levels	Initial inventory of product i in m/kg ($IntI_i$)	$IntI_i$ = Uniform[0, 8694]
3. Situation with high initial inventory levels	Initial inventory of product i in m/kg ($IntI_i$)	$IntI_i$ = Uniform[8694, 46703]
4. Situation with low expected demand rates	Expected demand for product i in week t in m/kg (d_{it})	d_{it} = Uniform[0, 1779]
5. Situation with high expected demand rates	Expected demand for product i in week t in m/kg (d_{it})	d_{it} = Uniform[1779, 8338]

6. Situation with a different product portfolio due to an increase in the number of products produced on the wire drawing machines	If product i can be assigned to machine m for production (v_{im})	If m = 1, 2,…, 8 then
		v_{im} = Bernoulli[NrOfProducts,$\frac{1}{4}$]
		Else
		v_{im} = Bernoulli[NrOfProducts,$\frac{1}{12}$]

7. Situation with a different product portfolio due to an increase in the number of products produced on the bunching machines	If product i can be assigned to machine m for production (v_{im})	If m = 9, 10,…, 12 then v_{im} = Bernoulli[NrOfProducts,$\frac{1}{4}$] Else v_{im} = Bernoulli[NrOfProducts,$\frac{1}{12}$]
8. Situation with a different product portfolio due to an increase in the number of products produced on the stranding machine	If product i can be assigned to machine m for production (v_{im})	If m = 13, 14 then v_{im} = Bernoulli[NrOfProducts,$\frac{1}{4}$] Else v_{im} = Bernoulli[NrOfProducts,$\frac{1}{12}$]

Problem instance 1 – Increase in the resource capacity

In Figure 5.3, we compare the results obtained for the first problem instance in which we increase the resource capacity with the results obtained after solving the model with the current resource capacity based on the input data collected on August 15, 2022.

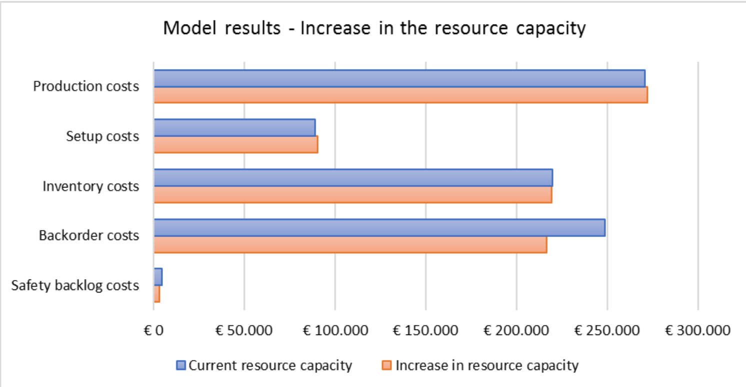

Figure 5.3 - Model results when increasing the resource capacity.

If we increase the number of available production hours between 1% and 10%, we achieve a cost reduction in the objective function value of 3.74% from € 833,603 to € 802,466. Because the expected demand rates and the planned purchase quantities to be received are the same in both cases, the model decides to plan more production as the resource capacity increases, which leads to a reduction in the number of backorders. Due to an increase in the resource capacity, we see an increase in the production and setup costs, but a more than ten times greater decrease in the backorder costs.

Problem instances 2 and 3 – Low and high initial inventory levels

If we compare the results in Figure 5.4 obtained for the two problem instances where the initial inventory levels are low and high, we find that there are differences in the values of the KPIs and the objective function.

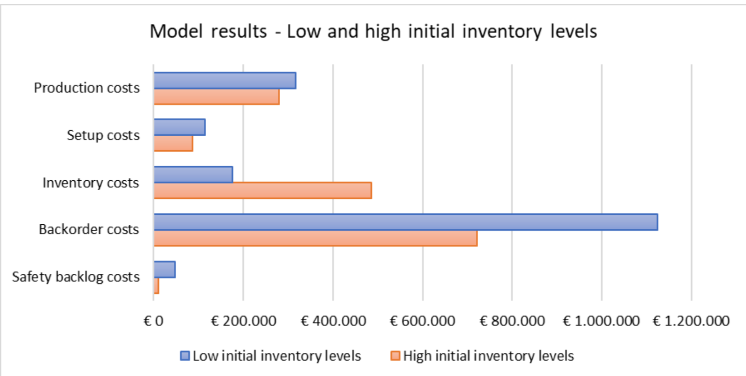

Figure 5.4 - Model results when having low and high initial inventory levels.

Both the production and setup costs are higher when having lower initial inventory levels. Because the expected demand rates and the planned purchase quantities to be received are the same in both problem instances, less demand can be met directly from stock when initial inventory levels are low. In addition, we expect the inventory levels of the MTS products to approach the safety stock levels faster, which explains the difference in the safety backlog costs in Figure 5.4. As a result, the model decides to plan more production in case initial inventory levels are low, which leads to an increase in both the production and setup costs.

In the current production situation of the DRAFA, we are not able to meet the total demand with the limited resource capacity. When the initial inventory levels are lower, we run out of stock sooner and have to accept backorders sooner. As a result, we see in Figure 5.4 that the backorder costs are higher when having lower initial inventory levels. The difference can also be explained in terms of the delivery reliability, as we obtain a delivery reliability of 92.0% in case of low initial inventory levels and 95.1% in case of high initial inventory levels.

The big difference between the inventory holding costs indicates the large impact of the initial inventory levels. Having low initial inventory levels for products with a high expected demand together with the limited resource capacity do not make it possible to build up inventories after demand has been met. On the contrary, having high initial inventory levels for products with a low expected demand result in high inventory levels that are carried over to the next weeks. An increase in the time these products spend in inventory leads to high inventory holding costs that are charged for several weeks in a row.

Problem instances 4 and 5 – Low and high expected demand rates

In addition to modelling differences in the initial inventory levels, we are interested in the results obtained for the two problem instances where the expected demand rates are low and high, as shown in Figure 5.5.

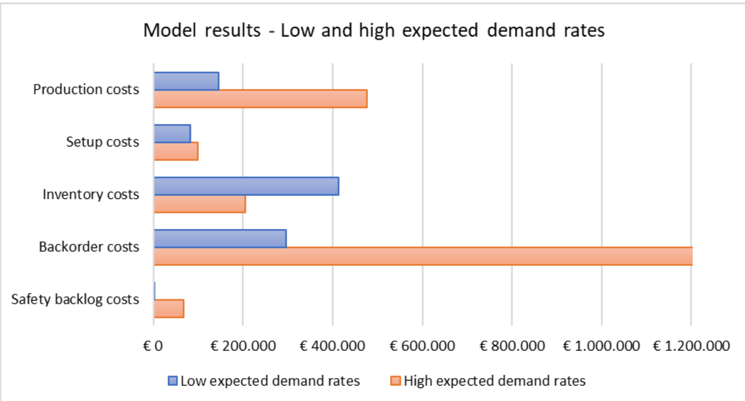

Figure 5.5 - Model results when having low and high expected demand rates.

Logically, an increase in the expected demand rates leads to an increase in both the production and setup costs. Because the initial inventory levels and planned purchase quantities are fixed in both problem instances, production is the only option to meet the increasing demand. The increase in the demand directly affects the planned production for the parents that are supplied to another department. It also indirectly affects the planned production for the components required to produce the parents. We see a doubling of the average resource utilization from ± 44% to ± 91% when we compare the situation with low and high expected demand rates.

The initial inventory levels taken as input for the model are based on a situation where the expected demand rates are roughly in the middle of both problem instances. When the expected demand rates are low, we see for some products that the initially built up inventory exceeds the sum of the expected demand over the planning horizon, leading to high inventory holding costs. On the contrary, when the expected demand rates are high, we see for some products that the expected demand in the first week of the planning horizon is already greater than the initially built up inventory. As a result, inventory levels are rapidly decreasing and there is limited resource capacity to increase the inventory levels after the high demand has been met. This also explains the increase in the safety backlog costs in case of high expected demand rates in Figure 5.5.

The big difference between the backorder costs indicates the large impact of the expected demand rates. Although the expected demand rates are low, we are still dealing with backorders. Based on the model results, we see that in case of low expected demand rates backorders mainly occur at the beginning of the planning horizon. This is because for each product we consider the initial backorders to be produced on top of the expected demand. From week 3, almost all initial backorders have been planned for production, which leads to a decrease in both the number of backorders and the utilization of the machines. When the expected demand rates are high, we see a major increase in the backorder costs up to ± € 10 million, because most machines are occupied much of the time. To improve the readability of Figure 5.5, we have set the maximum bound to € 1.2 million. The difference in the backorder costs is also visible in the delivery reliability, as we obtain a delivery reliability of 96.3% with low expected demand rates and 54.3% with high expected demand rates.

Problem instances 6, 7 and 8 – Different product portfolios

Besides understanding the performance of the model when changing the input parameters, we are interested in the results when modelling different product portfolios. As explained in this section, to model a particular change in the product portfolio, we assign more products to a particular group of machines and fewer products to the other machines. If a product is randomly assigned to a machine, we also generate a random data set for the production and setup times/costs of that product-machine combination. We decided to generate random values from the uniform distribution within a certain interval that is based on the minimum and maximum value of the corresponding model parameter. We analyse the model results in terms of the resource utilization per group of machines for each product portfolio, as shown in Figure 5.6.

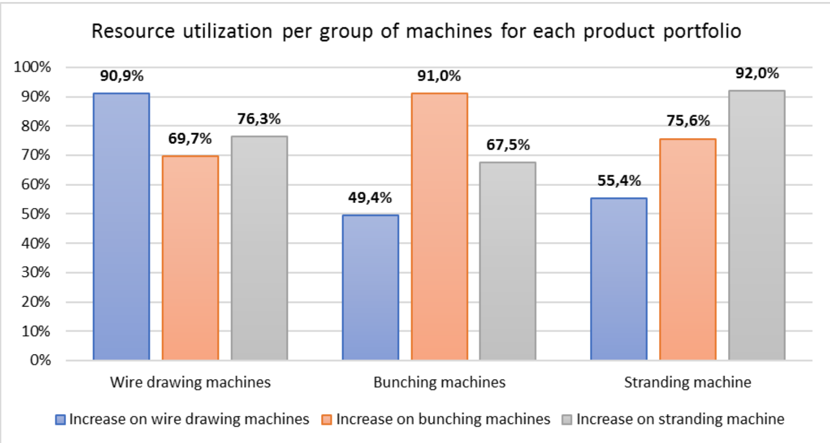

Figure 5.6 - Model results in terms of the resource utilization per group of machines for different product portfolios.

If we compare the results in Figure 5.6, we find that an increase in the number of products produced on the wire drawing machines leads to a relatively high average utilization of 90.9% compared to the other two problem instances. In this case, more products are assigned to the wire drawing machines, while fewer products are assigned to the bunching and stranding machines. Because the initial inventory levels, the expected demand rates and the planned purchase quantities to be received are the same in the three problem instances, we are facing an increase in the expected demand for parents and components assigned to the wire drawing machines. As a result, the machines that have a low utilization rate in practice, such as Fijntrek 2 and 3, are now also needed to meet the total expected demand.

Similarly, we obtain a relatively high average utilization of 91.0% and 92.0% compared to the other two problem instances when increasing the number of products produced on the bunching machines and the stranding machine. Based on the model results for the eight generated problem instances, we see that the model performs well for different problem instances under the same model settings.

5.5 Extended optimization time

Based on our analysis in Section 5.4.1, we found that our model was not able to find a solution where the lower bound equals the upper bound, i.e. a 0% gap, for any of the experiments within 10 minutes. For our minimization model, the lower bound gives a bound on the best possible objective, while the upper bound is the objective of the best known feasible solution. As the percentage deviation of the upper bound from the lower bound increases, we become more uncertain about the quality of our objective function value. As a result, we are interested in what happens to the gap if we increase the computational time limit of the model for the different experiments. We increase the computational time limit to 30 minutes, one hour, two hours and three hours, respectively. Figure 5.7 visually shows for each experiment how the gap develops over the computational time. For all experiments, the largest reduction occurs in the first interval from 10 to 30 minutes. The larger the computational time, the lower the absolute reduction of the percentage deviation of the upper bound from the lower bound per minute increase in the computational time. The graph helps the capacity planner to make a trade-off between the computational time and the resulting gap.

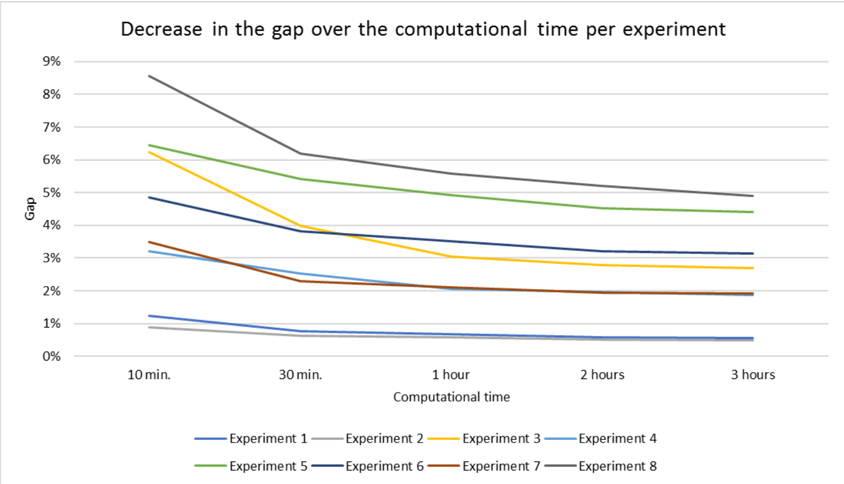

Figure 5.7 - Decrease in the gap over the computational time per experiment.

5.6 Future-oriented growth scenarios

Based on our analyses in Sections 5.4 and 5.5, we argue that the model is able to solve the medium-term production planning problem with different experimental settings and for different problem instances within a reasonable time and with an acceptable gap. However, since TKF is a growing company with a growing product portfolio and an increasing number of machines, we are interested in what happens to the gap if we increase the number of products and machines. This analysis is relevant to provide insight into whether the model works as desired for future-oriented growth scenarios. Table 5.4 shows several growth scenarios that we want to test to analyse what happens when there is an increase in the product portfolio, the number of machines or both. In the last scenario, we double both the number of products and machines. Although this is an extreme scenario that is not expected to occur in practice, it serves as an upper bound for the future situation. As stated in Section 5.4, the problem on June 17, 2022 consists of 187 products and 14 machines. The numbers in Table 5.4 have been rounded down.

Table 5.4 - Growth scenarios.

Growth scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Number of products	Factor 1.2: 1.2 * 187 ≈ 224	Factor 1.5: 1.5 * 187 ≈ 280	Factor 1: 1 * 187 = 187	Factor 1: 1 * 187 = 187	Factor 1.2: 1.2 * 187 ≈ 224	Factor 1.5: 1.5 * 187 ≈ 280	Factor 2: 2 * 187 = 374
Number of machines	Factor 1: 1 * 14 = 14	Factor 1: 1 * 14 = 14	Factor 1.2: 1.2 * 14 ≈ 16	Factor 1.5: 1.5 * 14 ≈ 21	Factor 1.2: 1.2 * 14 ≈ 16	Factor 1.5: 1.5 * 14 ≈ 21	Factor 2: 2 * 14 = 28

To model additional products and/or machines, we decided to randomly duplicate products and/or machines that exist in the data set of June 17, 2022. We also duplicate the input parameters associated with the duplicated product or machine. The number of duplicated products and machines depends on the growth scenario. For example, for growth scenario 6, we randomly duplicate 93 of the 187 products and 7 of the 14 machines that exist in the data set to obtain a total of (93+187=) 280 products and (7+14=) 21 machines. Due to randomness, some products and/or machines may appear more than twice.

Table 5.5 shows the gaps obtained in Section 5.4.1 per experiment for the current situation and the gaps obtained for the seven growth scenarios when using a maximum computational time of 10 minutes. We expect the gaps to increase as the problem complexity increases, i.e. the number of products and/or machines increases. Although the absolute values of the objective function increase with an increase in the problem size, the gaps obtained for the growth scenarios fluctuate around the gaps obtained for the current situation. In other words, the percentage deviation of the upper bound from the lower bound does not necessarily increase as the number of products and/or machines increases. This means that the quality of the objective function value obtained by the model is mainly influenced by other model characteristics than the size of the problem. Our experiments show that even for the growth scenario in which we double the number of products and machines, we still find solutions with an acceptable gap within a reasonable computational time. We conclude that the model is able to perform well for future-oriented growth scenarios and thus no heuristics are needed.

Table 5.5 - Comparison of the gaps for the future-oriented growth scenarios with the current situation.

Experiments	Current situation	Growth scenarios						
		1	2	3	4	5	6	7
1	1.25%	1.62%	0.64%	0.81%	0.74%	1.21%	0.98%	1.29%
2	0.88%	1.33%	1.03%	0.98%	0.87%	1.29%	0.82%	1.02%
3	6.23%	3.39%	1.53%	5.09%	3.98%	2.58%	1.45%	2.32%
4	3.21%	2.62%	1.66%	2.79%	2.72%	2.21%	0.95%	2.18%
5	6.45%	5.61%	0.88%	6.87%	2.93%	6.89%	5.06%	2.80%
6	4.85%	2.43%	1.99%	5.63%	4.16%	3.36%	7.24%	3.12%
7	3.48%	2.84%	1.42%	3.04%	1.93%	2.27%	1.45%	2.41%
8	8.55%	2.86%	1.46%	7.41%	5.81%	3.15%	2.40%	3.12%

5.7 Conclusion

In this chapter, we implemented the MILP model to solve the medium-term production planning problem at the DRAFA. We see that our model makes different model decisions under different experimental settings, leading to differences in the values of the KPIs. First, using the newly defined inventory parameters instead of the old inventory parameters leads to lower inventory holding costs and a higher delivery reliability. Our model uses the new safety stock levels that are up to date and not based on static values. Second, the unit holding costs have a significant impact on the model's decisions. This indicates the importance of a correct determination of this cost factor for TKF. When using higher unit holding costs (25% instead of ± 5.6% of the cost price), we see that the sum of the production, setup and inventory holding costs almost doubles as the model aims to minimize backorders by increasing production. Finally, when increasing the target fill rate from 90% to 99%, we obtain an increase in the average utilization per machine and the delivery reliability as the model increases production and thus inventories to reduce backorders.

The model performs well for problem instances where we increase the resource capacity, we have low or high initial inventory levels and low or high expected demand rates based on the differences in the KPIs and the objective function. In addition, the model can cope with different product portfolios due to an increase in the number of products produced by a group of machines, as the average utilization for this group increases.

As the computational time increases, we notice that both the objective function values and gaps decrease. The largest reduction occurs in the interval from 10 to 30 minutes, after which the absolute reduction of the percentage deviation of the upper bound from the lower bound per minute increase in the computational time becomes smaller. In an extreme scenario that serves as an upper bound for the future situation at the DRAFA, we double both the number of products and machines. For the extreme scenario, we find solutions with a gap varying between 1.02% and 3.12% over all experiments within 10 minutes. To conclude, because our model works as desired for future-oriented growth scenarios, we decided to focus in Chapter 6 on the performance of the prototype planning tool for the short-term, rather than developing heuristics for the medium-term.

6 Results and analysis – Part II

This chapter continues to answer the fourth research question stated in Section 1.7 and focuses on the short-term prototype planning tool. In Section 6.1, we elaborate on the setup of the model by an explanation of the data sets that we use as input. In Section 6.2 we discuss the results of our short-term planning tool. Section 6.3 compares the results of our tool with the current situation, i.e. the short-term production schedule of MTS and MTO products per machine made by the capacity planner based on static minimum and maximum inventory levels for the MTS products. In Section 6.4, we provide insight into the link between the results of the medium-term and short-term planning model. We discuss the main limitations of the model results in Section 6.5, the implementation plan in Section 6.6 and end this chapter with a conclusion in Section 6.7.

6.1 Model setup

The input data relevant to the medium-term planning model also applies to a large extent to the short-term planning model. We therefore only discuss the data sets that have not been discussed earlier in Section 5.2.

- Expected daily demand

In contrast to the medium-term model, we base the expected demand per day on the production schedules of the departments Multi Conductor, Energy and Installation. These production schedules provide insight into the corresponding quantities per product that will be requested from the DRAFA in the coming days. The day on which each semi-finished product will be requested from the DRAFA is based on when the next departments plan to start production of an order according to their production schedules.

- Initial setup states and remaining production quantities

The planner should take into account which product is currently in production on each machine, as this affects the resource capacities and the expected increase in the inventory levels. Navision keeps track of which products are currently in production on which machines and which part of the production orders is ready. We use this information to determine the initial setup state of a product on a machine at the beginning of the planning horizon. In addition, we use the information in Navision to determine the remaining production quantities. We force the model to complete the production orders currently in production by scheduling the remaining production quantities at the beginning of the planning horizon. When production orders take longer than one day, we spread the remaining production quantities over several days.

- Setup fractions

For the short-term, we determine the sequence of all products produced on a particular machine and on a particular day. Instead of always considering the full setup time and costs, it is possible to consider only a fraction of the full setup time and costs by switching over from one product to another with similar product characteristics. To model this, we determine for all product combinations a value between 0 and 1 that indicates what fraction of the setup time and costs should be taken into account when switching over from one product to another. For products with similar product characteristics (i.e. the wire diameter or the number of wires), a smaller part of the full setup time is required and thus the setup fraction between the two products is lower. For an explanation of how we determined the setup fractions based on certain decision rules that have been established in collaboration with the capacity planner, we refer to Appendix I.

6.2 Model performance analysis short-term

In this section, we discuss the results of our short-term prototype planning tool. We solve the short-term production planning problem by implementing the model provided in Appendix G in Python. We use this model to determine which quantities of which products to produce on which day, in which sequence and on which machine by incorporating positive supply lead times, setup carry-overs and sequence-dependent setup times. We use a supply lead time of one day for each product, which means that the demand for a product on a given day can be satisfied through production on the day before. Based on our calculations of the unit holding costs in Appendix C, we have found that the costs range from € X to € X per m/kg per day. Due to the uncertainty in the determination of this cost parameter, we decided to use a holding cost rate of 25% of the cost price according to Durlinger (2014). Because of the increasing number of decision variables compared to the model developed for the medium-term and therefore the increase in the model complexity, we decided to increase the maximum computational time to 1.5 hours. According to the capacity planner, 1.5 hours is an acceptable running time at the operational level, because the planner can perform other work at the same time.

6.2.1 Initial operational production schedule

We ran the model for 1.5 hours with the input data collected on July 25, 2022. After 1.5 hours, we obtain an acceptable gap of 5.49%. Although the maximum computational time limit is nine times higher compared to the model used in Section 5.4.1 for the medium-term, the gap is not necessarily smaller due to the increase in the model complexity. One problem that arises in the Gantt chart is related to the fixed resource capacity for each machine on a day, along with the requirement to produce completely filled packaging units for MTS products. To solve this problem, we allow the model to carry over the remaining resource capacities to the next production day by extending the MILP model in Appendix J with the following model characteristics.

Additional decision variable

RC_{mt} — Remaining resource capacity in minutes on machine m that can be carried over from the previous day to day t

Additional constraints

$$\sum_{j=1}^{N} PT_{jm}\, X_{jmt} + \sum_{i=1}^{N}\sum_{j=1}^{N} SF_{ij} ST_{jm} Y_{ijmt} \leq R_{mt} + RC_{mt} \qquad \forall m \in V, \forall t \in T \qquad (4.40)$$

$$RC_{m1} = 0 \qquad \forall m \in V \qquad (4.41)$$

$$RC_{mt} = R_{m,t-1} + RC_{m,t-1} - \sum_{j=1}^{N} PT_{jm}\, X_{jm,t-1} - \sum_{i=1}^{N}\sum_{j=1}^{N} SF_{ij} ST_{jm} Y_{ijm,t-1} \quad \forall m \in V, t = 2, ..T \qquad (4.42)$$

We modified constraint (4.40) by adding the remaining capacity from the previous day to the available resource capacity on a day. In addition, we added constraints (4.41) and (4.42) to assign a value to the decision variable for each machine-day combination. The remaining capacity is always based on the previous production day. Since there is currently no production on Saturday and Sunday, the remaining resource capacity on a Friday cannot be used on Saturday or Sunday but is instead carried over to the next Monday.

However, this extension of the model leads to an infeasible production schedule, as we exceed the resource capacities. To avoid exceeding the resource capacities, we developed a backwards-oriented post-processing step that is performed after an initial solution is obtained when solving the model. The objective is to resolve the capacity exceedance for each machine and each day in the planning horizon by moving production orders backwards. We start by checking the production schedule of the first machine on the last day of the planning horizon. After we have resolved the capacity exceedance for all machines on the last day of the planning horizon, we move backwards and continue with the previous day. We stop when we have resolved the capacity exceedance for all machines and all days in the planning horizon. The backwards-oriented post-processing step is based on the logic described in the flowchart in Appendix K and generates a feasible production schedule without any capacity exceedance. In addition, Appendix K explains the steps we have taken to obtain a feasible production schedule on which the analysis in Section 6.2.2 is based.

6.2.2 Results obtained after the backwards-oriented post-processing step

Figure 6.1 visualizes the operational production schedule obtained over the planning horizon of 10 days by means of a Gantt chart after performing the backwards-oriented post-processing step, where days 6 and 7 are empty because no production takes place during the weekends. The Gantt chart separates the production schedule per machine used within the DRAFA. Each bar represents a production order of a product whose length indicates the sum of the expected setup and production time needed. The product that is planned for production at a particular point in time is indicated vertically by the product number at the start of the bar. The grey bars in the Gantt chart at the end of the planning horizon indicate which part of the production schedule per machine is uncertain and therefore subject to change, which we explain later in this section.

As discussed earlier in the model description in Section 4.3, we consider an OEE percentage when determining the resource capacity per machine. Although the machines can produce 24 hours a day, our planning tool takes into account a lower number of available production hours due to possible efficiency losses. To draw the Gantt chart, we chose to include the OEE percentage in determining the duration of a production order and thus the length of the bar. As a result, the bars are slightly stretched to fill 24 hours of production in a day to avoid empty spaces in the production schedule for which no production can be planned.

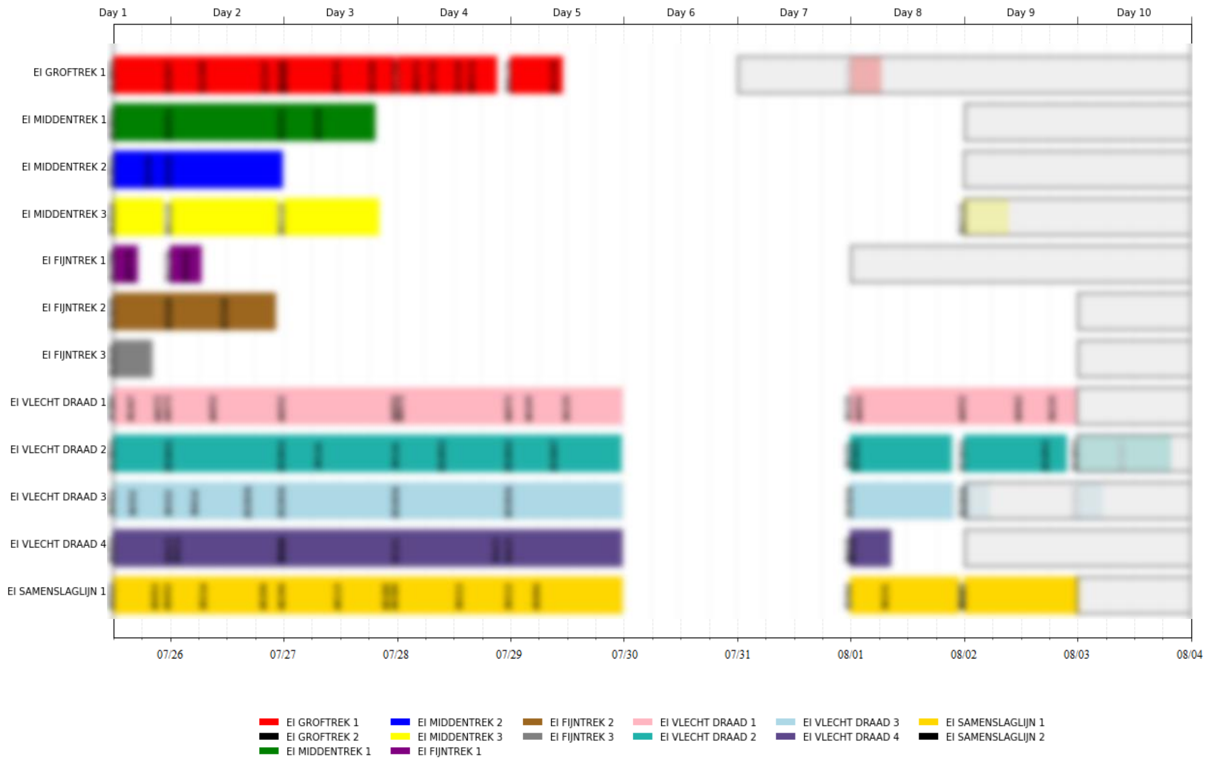

Figure 6.1 - Gantt chart after performing the backwards-oriented post-processing step.

Now we obtain a feasible production schedule in which there are no overlapping bars in the Gantt chart and there is no production planned during the weekends. The model minimizes setup costs by taking into account the setup fractions explained in Section 6.1. As an example, the model decides to switch over from product X to product Y during day 2 on Fijntrek 2. Given that on the Fijntrek machines, the wire diameters range from 0.16 to 0.49 mm and the number of wires ranges from 1 to 8, the characteristics of both products provided in Table 6.1 indicate that the wire diameters and the number of wires of the two products are close to each other. According to the decision rules provided in Appendix I, only a fraction 0.46 of the setup time and costs is involved.

Table 6.1 - Characteristics of two products needed to determine the setup fraction.

Product	Wire diameter	Number of wires
X	0.40 mm	3
Y	0.49 mm	2

We regularly see in the Gantt chart that the same product number appears several times in succession on the same machine. This occurs when the model decides to carry over a setup state to the next day to produce a product in one run over several days. For example, the setup state for product X on Vlechtdraad 1 is carried over from day 2 to 3 and from day 3 to 4 to plan production on three consecutive days.

The Gantt chart helps the capacity planner in making purchasing-related decisions. It is remarkable that little production is planned on the Fijntrek machines. TKF has decided to purchase a lot externally for the products produced on Fijntrek 1, because of the uncertainty in the workforce during the holiday period. However, given the low utilization of Fijntrek 1, as shown in Figure 6.1, the capacity planner should consider whether to purchase smaller quantities and produce more instead.

Finally, it is remarkable that especially on the wire drawing machines (i.e. Groftrek, Middentrek and Fijntrek), little production is planned towards the end of the planning horizon. This can be illustrated by an example that explains the parent-component relationships along with the supply lead times. Figure 6.2 shows in a timeline the sequence of products to be produced on different machines in order to satisfy a certain expected demand for product 4 on day 5. Given the supply lead times of one day for each product, we have to produce this product one day before we expect demand to arise (i.e. day 4). In addition, we have to produce the component product 3 one day before we plan to produce the parent product 4 (i.e. day 3). Similarly, we plan to produce the component products 2 and 1 on days 2 and 1, respectively. This example makes clear that the expected demand for a component becomes known once the parent is planned for production. In other words, the earlier a product is produced in the production process, the less we know about the expected demand further away in the planning horizon. The grey bars in Figure 6.1 indicate which part of the production schedule per machine is subject to change. We determined this for each machine by taking into account the maximum number of remaining production steps (i.e. production days) that must be performed in the DRAFA before the semi-finished product can be forwarded to the next department. Since the wire drawing machines are used at the beginning of the production process, a relatively large part of the production schedule is subject to change and little production is planned on these machines towards the end of the planning horizon.

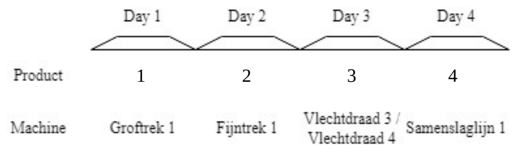

Figure 6.2 - Example explaining the parent-component relationships along with positive supply lead times.

6.3 Comparison of results with current situation

In this section, we compare the results of our short-term model with the production schedule created manually by the capacity planner. To make an appropriate comparison, we made sure that both the model and the capacity planner were using the same input data by running the model for 1.5 hours on the same day the capacity planner was manually scheduling production. We make this comparison to gain insight into the differences that occur when scheduling with the help of a mathematical model and when scheduling manually. We first compare the results in terms of our KPIs and then focus on the analysis of the differences between the two production schedules by comparing the decisions made by the model and the capacity planner. Appendix L contains both operational production schedules on which the analysis in this section is based.

Because the capacity planner usually schedules production no more than 48 hours in advance, we can only use a part of the production schedule that is obtained by the model for the comparison. The first day in the planning horizon represents only half a production day, because we assume that the capacity planner schedules production halfway through the day on average. In addition, instead of scheduling 24 hours of production on a machine per day, we take into account an OEE percentage and thus a lower number of available production hours. As a result, we decided to compare the first three days of both production schedules.

Table 6.2 shows the results of the production schedule created manually by the capacity planner and the production schedule that is obtained by the model in terms of our KPIs. A percentage decrease in the costs compared to the current situation is indicated in green, while a percentage increase is indicated in red. The production and setup costs are based on the sequence of the products and the corresponding production quantities planned on days 1 to 3. Because we use a supply lead time of one day for each product, the production planned on day 3 is added to inventory on day 4 and can be used to meet demand from day 4. We have therefore decided to base the inventory holding costs, backorder costs and safety stock backlog costs on days 1 to 4, so that the impact of the planned production on day 3 on these KPIs is also included in the analysis.

Table 6.2 - Model results compared to the results of the production schedule created manually by the capacity planner.

Performance indicator	Current performance	Model performance	Percentage change
Production costs	€ 19,498	€ 16,808	-13.80%
Setup costs	€ 4,351	€ 4,692	+7.84%
Inventory holding costs	€ 13,519	€ 13,338	-1.34%
Backorder costs	€ 51,078	€ 47,462	-7.08%
Safety stock backlog costs	€ 1,537	€ 1,505	-2.08%
Objective function value	**€ 89,983**	**€ 83,805**	**-6.87%**

The results in Table 6.2 show that the total costs obtained by the model are lower than the total costs of the production schedule created manually by the planner. The objective function has been improved from € 89,983 to € 83,805, which is a cost reduction of almost 7%. In addition, we see an increase in the setup costs, while we have achieved a cost reduction for the other four KPIs. In the remainder of this section, we focus on the differences between the two production schedules that cause the differences in the values of the KPIs.

The first KPI is the production costs, which are reduced by 13.8%. This decrease is caused by two reasons. First, the model decided not to schedule production when the inventory positions and the expected purchase orders are sufficient to meet the expected demand. Instead, the planner schedules production for MTS products based on static minimum and maximum inventory levels. This occurs on Vlechtdraad 2, where the model decides not to continue production after the production order currently in production has been completed, while the planner decided to switch over to another product because the inventory position has dropped below the minimum inventory level. Second, the model decided to set up the machines more often and to schedule products with higher setup times, leading to an increase in the setup costs. The time an operator is setting up a machine to another product is at the expense of the time available for production.

The second KPI is the setup costs, which are increased by 7.84%. This increase is mainly caused by the decisions made for Samenslaglijn 1. The setup times per product are also the highest on this machine compared to all other machines. Both the model and the planner decided to schedule four different products on this machine. However, the products scheduled by the model result in a total setup time of 15.7 hours and total setup costs of € 1.659, while the products scheduled by the planner result in a total setup time of 9 hours and total setup costs of € 949. Apparently, the model accepts the increase in the setup costs to achieve a greater reduction in the backorder costs. We also see an increase in the setup costs on Fijntrek 2. Both the model and the planner start with the same product, as the remaining production quantities of the product currently in production must be completed first. After this, the model decided to reduce the setup costs by switching over to another product for which the setup fraction is 0.59, while the planner reduces the setup costs even more by switching over to another product for which the setup fraction is 0.5. Also, the model accepts switching over to another product at higher setup costs to achieve a greater reduction in the backorder costs.

The backorder costs are the fourth KPI and are reduced by 7.08%. The backorder costs are the largest cost factor and therefore have the most impact on the total costs. We are always dealing with backorders in the production situation of the DRAFA due to the limited resource capacity. The objective is therefore to minimize the backorder costs by prioritizing products for which the backorder costs are high, which is based on the cost price and the quantity to be backordered as derived from the expected demand. Given the expected demand per product and per day, the model is able to generate a production schedule for which the total backorder costs are reduced by € 3.616 compared to the manual production schedule.

To conclude, the inventory holding costs and safety stock backlog costs have decreased slightly. We see no remarkable differences in the results that have a major impact on any of these KPIs.

6.4 Comparison of results between both planning levels

In this section, we provide insight into the link between the results of the medium-term and short-term planning model. To compare the results, we ran the two models on the same day and therefore with the same input data both for 1.5 hours. The objective is to determine whether the tactical production plan obtained after solving the medium-term model is also feasible at an operational level. In other words, we want to check whether we can distribute the quantities of the products planned in a week over the days of the week when taking into account the sequence-dependent setup times between the products at an operational level.

Because the planning horizon of our operational production schedule is 10 days and because little production is planned towards the end of the planning horizon for machines used at the beginning of the production process, as explained in Section 6.2.2, we decided to compare the results of the short-term model with one full production week of the tactical production plan. Since we ran the two models on a Monday, we compare days 1 to 5 (i.e. Monday to Friday) of the operational production schedule with week 1 of the tactical production plan. Figure 6.3 shows the total production time (i.e. blue bars), setup time (i.e. red bars) and remaining capacity (i.e. green bars) for each machine in the first week of the planning horizon according to both planning levels. The top of the stacked bars indicates the available resource capacity of the machine. The rounded value above the bars indicates the total time a machine is up and running according to the production plan, being the sum of the production and setup time. This means that the green bars indicate the difference between the available resource capacity and the sum of the production and setup time.

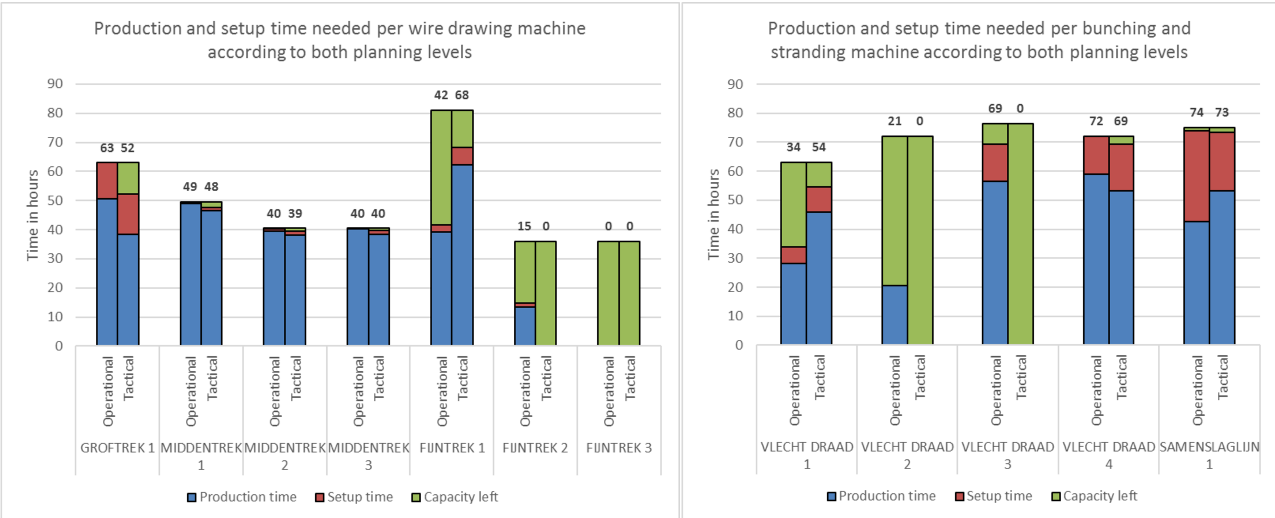

Figure 6.3 - Production and setup time needed per machine according to both planning levels.

If we compare the operational production schedule with the tactical production plan per machine, we find that there are both similarities and differences between the products and production quantities planned. Appendix M contains the results obtained for both planning levels on which the analysis in the remainder of this section is based. The differences between both planning levels can be explained by several reasons, which are explained below.

First, at the operational level, the model tries to minimize setup costs for the Middentrek and Fijntrek machines by determining the sequence of the products based on the characteristics of the products. For example, although the number of different products planned on Middentrek 1 and 2 is higher at the operational level than at the tactical level, we see in Figure 6.3 that the total setup time is lower. This is because, at the operational level, sequence-dependent setup times and costs are taken into account. As a result, the model tries to minimize setup costs by determining the sequence of the products.

Second, at the operational level, the model is forced to plan the remaining production quantities of the production orders currently in production. For example, at the tactical level, the model decides to plan only one type of product on all three Middentrek machines. At the operational level, however, the model must first complete the products that are currently in production, after which the machine can be switched over to the same type of product as planned at the tactical level. According to Figure 6.3, Fijntrek 2 is left empty at the tactical level only, while at the operational level the machine is occupied about half of the time, because the model was forced to plan the remaining production of the production order that was currently in production.

Third, we differentiate in determining the expected demand at both planning levels. As a result, the week in which a certain quantity of a product is expected to be requested from the DRAFA at the operational level may differ at the tactical level. As an example, the capacity planner of another department decided to plan a production order that requires a specific semi-finished product to be produced on Fijntrek 2 earlier than needed to meet the due date. We notice this at the operational level, because the expected demand is based on the production schedules of the other departments. At the tactical level, however, we do not expect the demand until the due date approaches. As a result, the model decided to plan the product for production in the first week at the operational level as shown in Figure 6.3.

Fourth, at the tactical level, more information is available on the expected demand and purchase orders as we look several weeks ahead. For example, because there was production capacity left on Vlechtdraad 1, the model decided to already produce a product in the first week, which is expected to be requested later. This product was not scheduled at the operational level, because the expected demand was not yet known. This leads to higher production and setup times on Vlechtdraad 1 at the tactical level in Figure 6.3. In addition, at the tactical level, the model did not plan a product on Samenslaglijn 1 in the first week that was planned at the operational level, because a purchase order for that product is expected to arrive a week later.

Fifth, for machines that produce components, we see differences between both planning levels due to differences in the production schedule of the successive machines. The reason for this is that there is no demand for components until the parent is planned for production. In other words, the production schedule of machines producing parents determines the production schedule of machines producing the corresponding components. This applies to Groftrek 1, Fijntrek 1 and Vlechtdraad 3 and 4. For example, the utilization of Vlechtdraad 3 and 4 is higher at the operational level, because the products and production quantities planned on Samenslaglijn 1 generate a greater demand flow from Vlechtdraad 3 and 4 compared to the tactical level.

Finally, there is one additional reason that can cause the difference between the products and production quantities that are planned according to both planning levels. At the operational level, we allow the model to carry over the remaining resource capacities to the next production day. This is not allowed at the tactical level, while in practice the operator can start a production order at the end of the week and continue production after the weekends. This gives the model limited possibilities at the tactical level to fill up the remaining capacity at the end of a week during busy periods for the machines where MTS products are produced with a minimum production quantity. However, since it only affects the possibilities on the last production day of the week, we expect the impact to be small relative to the reasons mentioned above.

6.5 Limitations

The development of our short-term model entails certain limitations of the model results. First, the setup fractions are based on characteristics of the Fijntrek and Middentrek machines and the products. However, by talking to the operators, we found additional characteristics that can be considered when determining the production sequence of products, which are discussed in the recommendations in Section 7.2.

Second, we force the model to plan the remaining production quantities of the production orders currently in production. For the majority of the products, the planner can see in Navision which part of the production order is currently ready. However, for some products, the part of the production order that is ready is not updated during the production run. Our planning tool therefore always plans the complete production order, even if the order is expected to be partially ready and so only a part of the production time is still needed.

Third, we have found that the determination of the quantity of a component required to produce a parent in Navision is not always accurate. Our planning tool was unable to find a feasible solution if we forced the model to plan the remaining production quantities of a parent, while the inventory level of a component was insufficient to meet the planned production of the parent. To solve this problem, we decided to set the initial inventory level of the components at least equal to the quantity needed to produce the remaining production quantity of the parent. In addition, we decided to keep track of the adjustments in the initial inventory levels of the components, so that the capacity planner can assess whether these changes are justified.

Fourth, our planning tool is not able to reschedule products at an operational level if unexpected events occur. As a result, the expertise and experience of the planner remain important. Our planning tool can thus be used as a support tool rather than replacing the current production planning process. We elaborate on this limitation in the suggestions for further research in Section 7.4.

6.6 Implementation

This section answers the fifth research question stated in Section 1.7. The fifth research question is formulated as follows: *How can the proposed medium-term and short-term planning tools be integrated and implemented in practice?* The purpose of the medium-term planning tool is to determine whether production orders can be realized with the available capacity and to help the capacity planner in responding to future capacity problems. In addition, the purpose of the short-term planning tool is to help the capacity planner in the day-to-day decision-making process. To implement the proposed planning tools, different steps should be taken by different people from different departments and thus change management is required. The end-user, the capacity planner of the DRAFA, must understand the benefits of implementing both planning tools in the production planning process. The problem analysis in Section 1.3 can be used for this.

This research focuses on the production planning process of the DRAFA. However, to determine the performance of the proposed planning tools in practice and the possibilities to apply the planning tools more broadly in the organization, it is necessary to perform a test period as the first step of the implementation. In this test period, the planning tools should be used by the capacity planner for a period that is at least equal to the medium-term planning horizon (i.e. ± 10 weeks) to verify whether the results are in line with the expectations. During the test period, the impact of the (s, nQ)-policy to reduce the risk of an MTS product being out of stock due to uncertainty in the demand should also be assessed. The goal of this test period is to further improve the tactical production plan and the operational production schedule.

Obviously, running the medium-term planning tool every day is not realistic. Therefore, we recommend using the planning tool periodically. We recommend doing this once a week, as the capacity planner can run the planning tool while performing other activities at the same time. In addition, the computational time is not too long, as we find solutions with a gap varying between 0.58% and 5.58% over all experiments within one hour, as shown in Section 5.5. However, the frequency with which the medium-term planning tool should be used is open for discussion. Furthermore, the short-term planning tool should be used on a daily basis, because the capacity planner uses the results to schedule production at least 24 hours ahead. In addition, new information becomes available every day that influences the model's decisions. However, situations occur where the tactical production plan is not feasible at the operational level and therefore has to be adjusted in a week. We therefore recommend implementing a feedback loop that integrates the decisions made at the tactical and operational level. Incorrect work, machine breakdowns, rework due to quality problems and rush orders are sources of production disturbances that occur at the operational level and lead to necessary changes in the tactical production plan (Li, Li, Li, & Hu, 2000). We visualize this feedback loop between both planning levels in Figure 6.4.

Figure 6.4 - Feedback loop between the tactical and operational level.

During the test period, it is important to create a clear communication line with other departments to assess the results. First, communication with the purchasing department is important to make sure that sufficient raw materials are available to realize production according to the plan. Second, the logistics department must be informed about the occupied storage space in the factory. The maximum inventory levels of the MTS products should be revised if it appears that the occupied storage space is too high. Third, communication with the planners of the departments Multi Conductor, Energy and Installation is important to discuss whether the model makes the right choices when prioritizing products in case of limited resource capacity. If needed, unit backorder costs can be adjusted. To complete the test period, we advise the capacity planner to discuss the results with the supply chain manager.

The next step is to implement the prototype planning tools in the ERP system of TKF, as it improves the user-friendliness to have it integrated into the same system that is used to manage the other business processes. The system developer of TKF is responsible for the implementation and can be informed by the capacity planner if clarification is needed. After implementation in practice, the capacity planner should monitor and observe over time whether the implementation was successful. A feedback loop from the capacity planner to the system developer is important to resolve issues as soon as noticed.

The last step is to determine whether the proposed planning tools can be applied more broadly in the organisation for the other production departments of TKF (i.e. Multi Conductor, Energy and Installation).

6.7 Conclusion

In this chapter, we implemented the MILP model to solve the short-term production planning problem at the DRAFA. We obtained a feasible operational production schedule by allowing the model to carry over the remaining resource capacities to the next production day and by developing a backwards-oriented post-processing step to avoid exceeding the resource capacities. Our model minimizes setup costs by taking into account the setup fractions that indicate the fraction of the setup time and costs involved when switching over from one product to another. In addition, the model helps the capacity planner in making purchasing-related decisions, as the Gantt chart visualizes how occupied the machines are according to the production schedule.

Based on the comparison of the model results with the operational production schedule created manually by the planner, our model achieves a cost reduction of almost 7% from € 89,983 to € 83,805. First, the production costs are reduced by 13.8%, because the model decided not to schedule additional production when the inventory positions and the expected purchase orders to be received are sufficient to meet the expected demand, while the planner schedules production for MTS products based on static min/max levels. Second, the setup costs are increased by 7.84%, as the model accepts the increase in the setup costs by setting up the machines more often and by scheduling products with higher setup times to achieve a greater reduction in the backorder costs. Third, the backorder costs that have the most impact on the total costs are reduced by 7.08%, because the model prioritizes products for which the unit backorder costs are high. Fourth, there are no remarkable differences in the inventory holding costs and safety backlog costs, which have decreased slightly.

When we compare the operational production schedule with the tactical production plan per machine, we find that there are both similarities and differences between the products and the corresponding quantities planned. First, at the operational level, the model tries to minimize setup costs for the Middentrek and Fijntrek machines based on the sequence of the products. Second, at the operational level, the model is forced to plan the remaining production quantities of the production orders currently in production. Third, for all machines, the week in which a certain quantity of a product is expected to be requested from the DRAFA at the operational level may differ at the tactical level due to the difference in the determination of the expected demand at both planning levels. Fourth, at the tactical level, more information is available on the expected demand and purchase orders as we look several weeks ahead. Fifth, for machines that produce components, differences between both planning levels are caused by differences in the production schedule of the successive machines due to the parent-component relationships.

7 Conclusions and recommendations

This chapter concludes the research in Section 7.1 by answering the main research question stated in Section 1.7. For this, we use the research sub-questions answered in the previous chapters. Section 7.2 contains the recommendations given to the company, based on the results of the research. Section 7.3 discusses the impact of the requirements that we set and the assumptions that we make on the results. Finally, in Section 7.4 we provide suggestions for further research in line with the results of the research.

7.1 Conclusions

In this research, we aim to answer the main research question that is formulated as follows:

"How can the DRAFA automate their medium-term and short-term production planning process to improve the delivery reliability of semi-finished products to the next departments in the production process?"

We conducted this research, because the delivery reliability of semi-finished products from the DRAFA was too low. Based on the analysis of the current situation, we found three main problems to solve in this research. First, the capacity planner of the DRAFA is not able to react adequately to uncertainties and fluctuations in daily product requests from other departments, because the current inventory methodology is based on static minimum and maximum inventory levels. Second, the capacity planner lacks insight into whether medium-term production orders can be realized with the available capacity, because the medium-term production plan currently does not take into account the available capacity. Third, the capacity planner lacks insight into the quality of the short-term production schedule, as it is executed manually based on knowledge, expertise and intuition. To solve those problems, we decided to use a stepwise approach throughout the research. The first step is to improve the current inventory management of the MTS products by coping with uncertainties and fluctuations in the expected demand. The second step is to provide insight into the medium-term production plan of the semi-finished products produced within the DRAFA several weeks ahead. The third step is to generate the short-term production schedule of the semi-finished products produced within the DRAFA several days ahead. This section summarizes the most important results and findings gained during our research, separated for the medium-term and short-term prototype planning tool.

1. **Medium-term prototype planning tool**

According to Section 5.4.1, we conclude that our medium-term prototype planning tool reduces inventory holding costs and increases the delivery reliability when using the newly defined inventory parameters (i.e. new safety stock levels) instead of the old inventory parameters (i.e. static min/max levels) based on the stock movements of the MTS products. In addition, when using higher unit holding costs (25% instead of ± 5.6% of the cost price), we see that the sum of the production, setup and inventory holding costs almost doubles as the model aims to minimize backorders by increasing production. This emphasizes the importance of a correct determination of the unit holding costs for TKF as input for the model. Furthermore, when increasing the target fill rate from 90% to 99%, we obtain an increase in the average utilization per machine and the delivery reliability as the model increases production and thus inventories to reduce backorders.

Our medium-term prototype planning tool performs well for different problem instances, as shown in Section 5.4.2. First, with a maximum increase in the resource capacity of 10%, we see an increase in the production and setup costs, but a more than ten times greater decrease in the backorder costs. Second, the model decides to plan more production in case initial inventory levels are low, which leads to an increase in the production and setup costs. In addition, the backorder costs are higher when having lower initial inventory levels, due to the limited resource capacity. We achieve a delivery reliability of 92.0% and 95.1% when having low and high initial inventory levels, respectively. Third, when comparing the situation where the expected demand rates are low and high, we see a doubling of the average resource utilization from ± 44% to ± 91%. In addition, the backorder costs are much higher when the expected demand rates are higher, which explains the delivery reliability of 96.3% and 54.3% when having low and high expected demand rates, respectively. Fourth, an increase in the number of products produced on the wire drawing, bunching and stranding machines leads to an increase in the average utilization for this group of machines to 90.9%, 91.0% and 92.0%, respectively.

We showed in Section 5.6 that our medium-term prototype planning tool works as desired for future-oriented growth scenarios. In an extreme scenario that serves as an upper bound for the future situation at the DRAFA, we double both the number of products and machines. For the extreme scenario, we find solutions with a gap varying between 1.02% and 3.12% over all experiments within 10 minutes.

2. **Short-term prototype planning tool**

Our short-term prototype planning tool minimizes setup times and costs and helps the capacity planner in making purchasing-related decisions, as shown in Section 6.2.2. The setup times and costs are minimized for the Middentrek and Fijntrek machines, because the model considers the setup fractions that indicate what fraction of the setup time and costs should be taken into account when switching over from one product to another. In addition, the Gantt chart visualizes how occupied the machines are according to the production schedule. For machines with a low utilization rate and high expected purchase quantities to be received, the capacity planner should consider whether to purchase smaller quantities and produce more instead.

Our short-term prototype planning tool achieves a cost reduction of almost 7% from € 89,983 to € 83,805 compared to the operational production schedule created manually by the capacity planner, as mentioned in Section 6.3. A cost reduction of 13.8% is obtained in terms of the production costs. While the planner schedules production for MTS products based on static min/max levels, our model decides not to schedule production when the inventory positions and the expected purchase orders to be received are sufficient to meet the expected demand. In addition, a cost increase of 7.84% is obtained in terms of the setup costs. Our model makes a trade-off between the increase in the setup costs and the resulting decrease in the backorder costs. As a result, our model accepts the increase in the setup costs by scheduling more different products and products with higher setup times to achieve a greater reduction in the backorder costs. Furthermore, a cost reduction of 7.08% is obtained in terms of the backorder costs. This reduction has the greatest impact on the total costs and is achieved by the model by prioritizing products with high unit backorder costs. Finally, there are no remarkable differences in the inventory holding costs and safety backlog costs, which have decreased slightly.

We showed in Section 6.4 that there are both similarities and differences between the products and the corresponding quantities planned when comparing the operational production schedule with the tactical production plan. First, at the operational level, the model aims to minimize setup costs for the Middentrek and Fijntrek machines by taking into account sequence-dependent setup times and costs. Second, at the operational level, we force the model to plan the remaining production quantities of the production orders currently in production. Third, we differentiate in determining the expected demand at both planning levels. As a result, the week in which a certain quantity of a product is expected to be requested from the DRAFA at the operational level may differ at the tactical level. Fourth, at the tactical level, more information is available on the expected demand and purchase orders as we look several weeks ahead. Fifth, for machines that produce components, we see differences between both planning levels caused by differences in the production schedule of the successive machines due to the parent-component relationships.

7.2 Recommendations

This section contains the recommendations that are given to TKF, based on the results of the research.

1. **Integrate and implement medium-term and short-term prototype planning tools**

First, we recommend TKF to integrate and implement the medium-term and short-term prototype planning tools according to the implementation plan in Section 6.6. It is important to emphasize that both planning tools can be used as a support tool rather than replacing the current production planning process. The model is needed because of its computational power, making it possible to generate near-optimal production schedules within a reasonable computational time. In addition, the planner remains important to make decisions that are needed to deal with unexpected events, based on the expertise and experience of the planner. The mathematical models developed in this research can be used after Python is installed. In addition, we recommend TKF to purchase the Gurobi Optimizer licence as a package of Python that we also used in this research, because of the ease to capture business problems in a mathematical optimization model.

2. **Implement inventory control policy for MTS products and update on a weekly basis**

Second, we recommend TKF to implement the (s, nQ)-policy for the MTS products that we developed in this research by means of a dynamic dashboard in Excel. The dashboard provided in Figure 4.3 can be used by the capacity planner of the DRAFA to calculate the safety stock levels of the MTS products. We recommend to update the safety stock levels on a weekly basis, as the computational time of the dashboard is only a few minutes. Because the safety stock levels of the MTS products are needed as input for the medium-term and short-term planning model, it is important to regularly update the safety stock levels.

3. **Improve data registration in Navision**

Third, we recommend TKF to improve the data registration in Navision. Our planning tools can only generate feasible and useable production schedules if the input data exported from Navision is correct. During our research, we had to make assumptions, because data needed as input for our models is not available or because data registered in Navision is incorrect. For example, TKF currently does not have a method to determine the exact costs of inventory storage and handling, which are needed to calculate the unit holding costs. In addition, in Section 6.5, we already mentioned two other problems that occur concerning the data registration that affect the performance of our models. First, for products produced on Vlechtdraad 3 and 4, the part of the production order that is ready is not updated during the production run. Second, the determination of the quantity of a component required to produce a parent in Navision is not always accurate.

4. **Consider other machine and product characteristics when determining the production sequence**

Fourth, we recommend TKF to determine other machine and product characteristics that can be considered by the model when determining the sequence of products on the machines to further improve the short-term model results. Currently, our model minimizes setup times and costs for the Middentrek and Fijntrek machines by determining the sequence of the products based on the characteristics of the machines and products. However, by talking to the operators and team leaders, we found additional characteristics that can be considered when determining the sequence of products on the machines. On Vlechtdraad 3 and 4, reductions in the setup times and costs can be achieved by switching over to a product with the same number of wires but twisted in the opposite direction. Additionally, setup times and costs can be reduced on the wire drawing machines by switching over to a product that requires the same chain in the machine.

5. **Prepare production orders for the operators 2 or 3 days in advance**

Fifth, we recommend the capacity planner of the DRAFA to prepare the production orders for the operators already 2 or 3 days in advance. Our short-term planning tool takes into account less than 24 production hours per machine per day due to possible efficiency losses. As a result, we can finish production earlier than planned according to our operational production schedule. If the actual machine capacity is higher than our short-term planning tool assumes, we advise TKF to already start producing the orders planned for the subsequent production days on the same machine instead of leaving the machine empty.

6. **Create a dashboard to visualize the performance indicators**

Sixth, we recommend TKF to create a dashboard that visualizes the performance indicators. For both the medium-term and short-term, we analysed the results in terms of five cost factors, the delivery reliability and the resource utilization. In this research, we manually created the visualizations of the performance indicators. Instead, it would be better to create one unique dashboard with the results of the performance indicators to avoid differences in the interpretations of the different planners. Based on the wishes of the planner, other performance indicators can be added to the dashboard, such as the length of stay of products in stock and the time that production orders are late. Another example is adding a pop-up notification to indicate whether a certain purchasing decision should be reconsidered based on the occupancy rate.

7.3 Discussion

Our first point of discussion is related to the determination of the safety stock levels for the MTS products. In collaboration with the capacity planner, we classified a product as an MTS product with a positive safety stock if on average the product is requested on a weekly basis. We assumed that demand during the lead time is normally distributed for all MTS products. The normal distribution is valid if the CoV of the lead time demand is not more than 0.5 (Silver, Pyke, & Thomas, 2017). Based on the calculations of the CoVs in Appendix E, we see that this assumption is not valid as the CoVs are greater than 0.5. When we use the normal distribution for products with a relatively high variance in demand and thus a high CoV, we have a significant probability of negative demand. This is not desired and affects the safety stock levels. Due to the probability of negative demand, we expect lower demand and therefore obtain lower safety stock levels. In this case, the gamma and lognormal distribution provide a better fit, because both probability distributions run on the interval $[0, \infty)$. In other words, those distributions always expect demand to be positive. We expect the safety stock levels to be higher when using the gamma or lognormal distribution for two reasons. First, the gamma and lognormal distribution do not consider negative demand, while the normal distribution does. Second, the gamma and lognormal distribution have a higher probability to return higher demand levels. As a result, we obtain higher estimates for the lead time demand and thus higher safety stock levels. Based on the results of our research, we have improved the inventory management of MTS products by using a normal approximation for the safety stock levels compared to the situation where static min/max levels are used. However, it is important to keep in mind that we expect the safety stock levels to be higher when using the gamma or lognormal distribution.

Our second point of discussion is that we used Excel to export the data from Navision, to analyse the data and to do the calculations needed to get the correct input data. Due to the large data sets and the use of VBA codes, it takes minutes before the input data is ready to be loaded into Python. There will be alternatives that are preferred over Excel in terms of efficiency and calculation speed. However, because the Exsion Reporting tool in Excel is used by TKF to export the data from Navision, we decided to do the data analysis and calculations in Excel as well. In addition, we have tried to avoid formulas that make the Excel workbook slow.

7.4 Suggestions for further research

We have developed a short-term planning tool that is able to generate a production schedule that fits the situation of the DRAFA. However, our planning tool is not able to reschedule products at an operational level if unexpected events occur. In this case, the expertise and experience of the planner remain important. Li, Li, Li and Hu (2000) mention incorrect work, machine breakdowns, rework due to quality problems and rush orders as sources of production disturbances. Currently, our planning tool is not able to respond to such production disturbances. We therefore advise TKF to conduct further research into the job shop rescheduling problem, which deals with uncertainty caused by the external environment and internal production conditions.

In addition, we found opportunities to further improve the operational production schedule and the tactical production plan. First, our short-term planning tool only considers reductions in the setup time and costs for the Middentrek and Fijntrek machines, as discussed in Section 7.2. To improve the short-term model results, we advise TKF to conduct further research into other machine and product characteristics that can be considered by the model when determining the sequence of products on the machines. Second, we differentiate in determining the expected demand at both planning levels. To obtain consistency between the model results at both planning levels, we advise TKF to base the expected demand for the first two weeks as input for the medium-term planning tool on the production schedules of the departments Multi Conductor, Energy and Installation, as we do for the short-term. Third, our medium-term planning tool uses historical demand data to determine the expected demand from week 6 to the end of the planning horizon. To improve the medium-term model results, we advise TKF to research advanced forecasting techniques to improve the accuracy in determining the expected demand as input for the medium-term planning tool.

Finally, we have assumed that demand during the lead time is normally distributed for all MTS products, as discussed in Section 7.3. To further improve the inventory management of the MTS products, we advise TKF to conduct further research into the use of the gamma or lognormal distribution to determine the safety stock levels. The gamma and lognormal distribution provide a better fit when looking at the CoVs.

References

Axsäter, S. (2006). *Inventory control* (2nd ed.). Springer.

Beerens, A., & Kusters, R. (2015). *Optimizing inventory capital while maintaining a competitive service level.* Breda: Groenewout.

Boucherie, R., Braaksma, A., & Tijms, H. (2021). *Operations Research - Introduction to Models and Methods.* World Scientific Publishers.

Buschkühl, L., Sahling, F., Helber, S., & Tempelmeier, H. (2010). Dynamic capacitated lot-sizing problems: a classification and review of solution approaches. *OR Spectrum*, 231-261.

Chen, W. -H., & Thizy, J. -M. (1990). Analysis of relaxations for the multi-item capacitated lot-sizing problem. *Annals of Operations Research*, 29-72.

Chopra, S. (2019). *Supply chain management: strategy, planning and operation* (7th ed.). Pearson Education Limited.

Dhoka, D. K., & Choudary, Y. L. (2013). "XYZ" Inventory Classification & Challenges. *IOSR Journal of Economics and Finance*, 23-26.

Durlinger, P. (2014). *Inventory and holding costs.* Posterholt: Durlinger Consultancy.

Ekanayake, N., Joshi, N., & Thekdi, S. (2016). Comparison of single-echelon vs. multi-echelon inventory systems using multi-objective stochastic modelling. *International Journal of Logistics Systems and Management*, 255-280.

Haase, K. (1996). Capacitated lot-sizing with sequence dependent setup costs. *OR Spektrum*, 51-59.

Hariharan, R., & Zipkin, P. (1995). Customer-Order Information, Leadtimes, and Inventories. *Management Science*, 1599-1607.

Heerkens, H., & van Winden, A. (2017). *Solving Managerial Problems Systematically.* Groningen: Noordhoff Uitgevers.

Janssen, F. (1998). *Inventory management systems: Control and information issues.* CentER, Center for Economic Research.

Janssen, F., Heuts, R., & de Kok, T. (1998). On the (R,s,Q) Inventory Model when Demand is Modelled as a Compound Process. *European Journal of Operational Research*, 423-436.

Karimi, B., Fatemi Ghomi, S., & Wilson, J. (2003). The capacitated lot sizing problem: a review of models and algorithms. *Omega*, 365-378.

Katok, E., Lewis, H. S., & Harrison, T. P. (1998). Lot Sizing in General Assembly Systems with Setup Costs, Setup Times, and Multiple Constrained Resources. *Management Science*, 859-877.

Kuik, R., & Salomon, M. (1990). Multi-level lot-sizing problem: Evaluation of a simulated-annealing heuristic. *European Journal of Operational Research*, 25-37.

Larsen, C., & Kiesmüller, G. (2007). Developing a closed-form cost expression for an (R,s,nQ) policy where the demand process is compound generalized Erlang. *Operations Research Letters*, 567-572.

Law, A. M. (2015). *Simulation Modeling and Analysis.* New York: McGraw-Hill Education.

Li, H., Li, Z., Li, L. X., & Hu, B. (2000). A production rescheduling expert simulation system. *European Journal of Operational Research*, 283-293.

Pandya, B., & Thakkar, H. (2016). A Review on Inventory Management Control Techniques : ABC-XYZ Analysis. *REST Journal on Emerging trends in Modelling and Manufacturing*, 82-86.

Patel, R. C. (1986). A note on inventory reorder point determination. *Journal of Accounting Education*, 131-140.

Pinedo, M. (2009). *Planning and scheduling in manufacturing and services* (2nd ed.). Springer.

Quadt, D., & Kuhn, H. (2008). Capacitated lot-sizing with extensions: a review. *4OR*, 61-83.

Rajagopalan, S. (2002). Make to Order or Make to Stock: Model and Application. *Management Science*, 241-256.

Ramya, R., Rajendran, C., Ziegler, H. M., & Ganesh, K. (2019). *Capacitated Lot Sizing Problems in Process Industries.* Springer.

Rao, S. S., & Bahari-Kashani, H. (1990). Economic order quantity and storage size - Some considerations. *Engineering Costs and Production Economics*, 201-204.

Scholz-Reiter, B., Heger, J., Meinecke, C., & Bergmann, J. (2012). Integration of demand forecasts in ABC-XYZ analysis: Practical investigation at an industrial company. *International Journal of Productivity and Performance Management*, 445-451.

Sezen, B. (2006). Changes in performance under various lengths of review periods in a periodic review inventory control system with lost sales: A simulation study. *International Journal of Physical Distribution & Logistics Management*, 360-373.

Silver, E. A., Pyke, D. F., & Thomas, D. J. (2017). *Inventory and Production Management in Supply Chains* (4th ed.). Taylor & Francis Group.

Teunter, R. H., Babai, M. Z., & Syntetos, A. A. (2010). ABC Classification: Service Levels and Inventory Costs. *Production and Operations Management*, 343-352.

Teunter, R. H., Syntetos, A. A., & Babai, M. Z. (2017). Stock keeping unit fill rate specification. *European Journal of Operational Research*, 917-925.

van der Heijden, M. (2020a). *09a. The (R, S) inventory control system.* Retrieved March 17, 2022, from University of Twente: https://canvas.utwente.nl/courses/6952/files/1965535?module_item_id=189292

van der Heijden, M. (2020b). *07c. Other service measures.* Retrieved March 18, 2022, from University of Twente: https://canvas.utwente.nl/courses/6952/files/1965525?module_item_id=189287

van der Heijden, M. (2020c). *06a. The Normal Loss function and its application.* Retrieved March 18, 2022, from University of Twente: https://canvas.utwente.nl/courses/6952/files/1965517?module_item_id=189279

van der Heijden, M. (2020d). *09c. The (R, s, S) and (R, s, Q) inventory control system.* Retrieved March 18, 2022, from University of Twente: https://canvas.utwente.nl/courses/6952/files/1965537?module_item_id=189296

van Kampen, T., van Donk, D., & van der Zee, D. (2010). Safety stock or safety lead time: coping with unreliability in demand and supply. *International Journal of Production Research*, 7463-7481.

Wijngaard, J., & Karaesmen, F. (2007). Advance demand information and a restricted production capacity: On the optimality of order base-stock policies. *OR Spectrum*, 643-660.

Zangwill, W. I. (1969). A Backlogging Model and a Multi-Echelon Model of a Dynamic Economic Lot Size Production System - A Network Approach. *Management Science*, 506-527.

A Properties per machine used within the DRAFA

This appendix provides a more detailed explanation of the properties per machine used for the part of the production process of cables at the DRAFA.

Table A.1 - Machines within the DRAFA and the corresponding properties.

Machine	Properties
Groftrek 1	• Used to reduce the diameter of copper wire with an initial diameter of 8 mm. • The copper wire that has undergone the drawing operation can be put in small or large baskets or spooled on cilipacks or reels with a height of 630 mm.
Groftrek 2	• Used to reduce the diameter of aluminium wire with an initial diameter of 9.5 mm. • The aluminium wire that has undergone the drawing operation can be spooled on reels with a height of 630 mm.
Middentrek 1	• Used to reduce the diameter of copper wire with a diameter of ± 3 mm which has undergone the wire drawing operation on the "Groftrek 1" machine. • The copper wire that has undergone the drawing operation can be put in small baskets or spooled on reels with a height of 630 mm.
Middentrek 2	• Used to reduce the diameter of copper wire with a diameter of ± 3 mm which has undergone the wire drawing operation on the "Groftrek 1" machine. • The copper wire that has undergone the drawing operation can be spooled on reels with a height of 630 mm.
Middentrek 3	• Used to reduce the diameter of copper wire with a diameter of ± 3 mm which has undergone the wire drawing operation on the "Groftrek 1" machine. • The copper wire that has undergone the drawing operation can be spooled on reels with a height of 630 mm.
Fijntrek 1	• Used to reduce the diameter of copper wire with a diameter of ± 1.8 mm which has undergone the wire drawing operation on the "Groftrek 1" machine. • The machine is able to process 1-8 wires per operation. • The copper wire that has undergone the drawing operation can be spooled on reels with a height of 400 or 630 mm.
Fijntrek 2	• Used to reduce the diameter of copper wire with a diameter of ± 1.8 mm which has undergone the wire drawing operation on the "Groftrek 1" machine. • The machine is able to process 1-4 wires per operation. • The copper wire that has undergone the drawing operation can be spooled on reels with a height of 400 mm.
Fijntrek 3	• Used to reduce the diameter of copper wire with a diameter of ± 1.8 mm which has undergone the wire drawing operation on the "Groftrek 1" machine. • The machine is able to process 1-4 wires per operation. • The copper wire that has undergone the drawing operation can be spooled on reels with a height of 400 mm.
Vlechtdraad 1	• Used to produce medium-sized conductors consisting of multiple wires. • The input for this machine is a maximum of 12 baskets or 7 reels with a height of 630 mm. • The output for this machine are reels with a height of 1250 mm.
Vlechtdraad 2	• Used to produce small-sized conductors consisting of multiple wires. • The input for this machine is a maximum of 7 reels with a height of 630 mm. • The output for this machine are reels with a height of 630 mm.
Vlechtdraad 3	• Used to produce bunches consisting of multiple wires. • The input for this machine is a maximum of 16 reels with a height of 630 mm. • The output for this machine are reels with a height of 630 mm.
Vlechtdraad 4	• Used to produce bunches consisting of multiple wires. • The input for this machine is a maximum of 16 reels with a height of 630 mm. • The output for this machine are reels with a height of 630 mm.

Samenslaglijn 1	• Used to produce large-sized conductors consisting of multiple layers of copper wires. • The input for this machine is copper wires or bunches spooled on reels coming from the machines “Groftrek 1”, “Vlechtdraad 3” or “Vlechtdraad 4”. • The output for this machine are reels with a height of 1250-2240 mm.
Samenslaglijn 2	• Used to produce large-sized conductors consisting of multiple layers of aluminium wires. • The input for this machine is aluminium wires spooled on reels coming from the machine “Groftrek 2”. • The output for this machine are reels with a height of 1250-3400 mm.

B Explanation of standard literature

This appendix contains an explanation of standard literature that is used in this research and what is supposed to be known to the reader.

ABC classification

As stated by Teunter, Babai and Syntetos (2010), a common classification scheme used in practice is the ABC classification to streamline the management of inventories consisting of large numbers of SKUs. The ABC classification groups products in a decreasing order of the annual dollar usage. The following equation is used to calculate the annual dollar usage of product i, where D_i is the annual demand and v_i is the value of product i.

$$Annual\ dollar\ usage\ of\ product\ i = D_i v_i$$

According to Silver, Pyke and Thomas (2017), class A products comprise roughly 20% of the total number of products and represent ± 80% of the annual dollar usage. Therefore, class A products are the most important products in terms of the annual dollar usage and should be closely monitored. Class B products comprise roughly 30% of the total number of products and represent ± 15% of the annual dollar usage. As a result, class B products are of secondary importance in relation to class A products and should receive a moderate but significant amount of attention. Finally, class C products comprise roughly 50% of the total number of products and represent ± 5% of the annual dollar usage. Therefore, class C products are the remaining products that make up only a small part of the total dollar usage. The effort in inventory control for these items should be kept to a minimum. For class C products, most companies try to keep a relatively large number of units in stock to minimize the amount of inconvenience caused by a stockout. Two-bin systems are often used for controlling class C products. Figure B.1 shows the distribution of the products over the A, B and C categories.

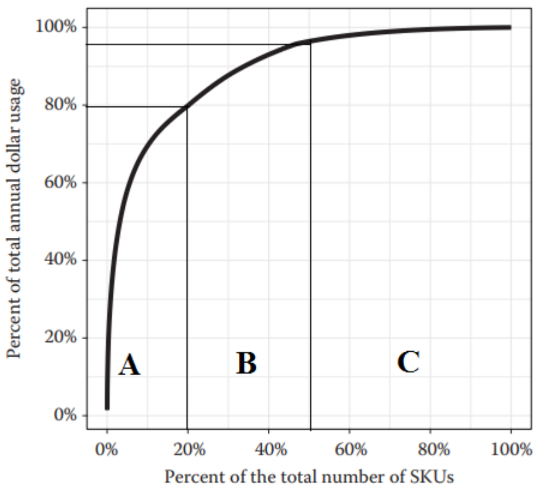

Figure B.1 - Distribution of products based on the ABC classification (Silver, Pyke, & Thomas, 2017).

XYZ classification

Another common classification scheme used in practice is the XYZ classification, which is based on the level of demand uncertainty. As stated by Scholz-Reiter, Heger, Meinecke and Bergmann (2012), the XYZ classification distinguishes between products according to their fluctuations in demand. Class X products have a low demand uncertainty and a constant consumption. Class Y products have a medium demand uncertainty and stronger fluctuations in consumption. Class Z products have a high demand uncertainty and a completely irregular consumption. The CoV is used as a statistical measure to determine the level of demand uncertainty of a product. The following equation is used to calculate the CoV of product i, where σ_i is the standard deviation of the demand pattern for product i and $\bar{x}_i$ is the average demand for product i (Dhoka & Choudary, 2013).

$$CoV_i = \frac{\sigma_i}{\bar{x}_i}$$

Scholz-Reiter, Heger, Meinecke and Bergmann (2012) provide a framework for the XYZ classification to determine to which class a product belongs based on the CoV, as shown in Table B.1.

Table B.1 - Distribution of products based on the XYZ classification (Scholz-Reiter, Heger, Meinecke, & Bergmann, 2012).

Class	**CoV range**
X	[0, 0.5)
Y	[0.5, 1]
Z	(1, ∞)

The ability to predict the demand for class X products is high due to the stable demand pattern and the low demand uncertainty. The ability to predict the demand for class Y products is medium due to fluctuating demand. Fluctuations in the demand pattern occur and therefore the demand pattern is not stable. However, the fluctuations in the demand pattern are often caused by known factors such as seasonality or trends. The ability to predict the demand for class Z products is low due to the strong fluctuations and the high demand uncertainty (Pandya & Thakkar, 2016).

Combined ABC & XYZ classification

Instead of using the ABC or XYZ classification separately, it is possible to combine both classification schemes. The products can be categorized according to two pillars, which are the annual dollar usage and the level of demand uncertainty. The combined ABC-XYZ classification can be used to determine which service level target to use for which class. Table B.2 shows the nine classes obtained when combining the ABC and XYZ classification. The most effort in inventory control should be spent on the class AX products. These products are the most important products in terms of the annual dollar usage and the demand pattern can be accurately predicted due to the low demand uncertainty. The least effort in inventory control should be spent on the class CZ products. These products make up only a small part of the total dollar usage and the demand pattern is difficult to predict due to the high demand uncertainty (Pandya & Thakkar, 2016).

Table B.2 - Combined ABC-XYZ classification.

ABC class / **XYZ class**	**A**	**B**	**C**
X	High annual dollar usage Close monitoring Low demand uncertainty High ability to predict	Moderate annual dollar usage Significant amount of attention Low demand uncertainty High ability to predict	Low annual dollar usage Minimal effort Low demand uncertainty High ability to predict
Y	High annual dollar usage Close monitoring Medium demand uncertainty Medium ability to predict	Moderate annual dollar usage Significant amount of attention Medium demand uncertainty Medium ability to predict	Low annual dollar usage Minimal effort Medium demand uncertainty Medium ability to predict
Z	High annual dollar usage Close monitoring High demand uncertainty Low ability to predict	Moderate annual dollar usage Significant amount of attention High demand uncertainty Low ability to predict	Low annual dollar usage Minimal effort High demand uncertainty Low ability to predict

Continuous versus periodic review

Before we describe the most common types of single-echelon inventory control policies, we discuss the problem of how often the inventory status should be reviewed. A distinction can be made between a continuous and a periodic review. In a continuous review, the inventory position is continuously tracked and therefore always known. In a periodic review, the inventory position is reviewed at regular points in time (Chopra, 2019). The review period (R) is the time between two consecutive moments at which the inventory status is reviewed. Because a continuous review is usually not required, in practice each transaction often triggers an immediate update of the inventory status. As a result, there may be uncertainty about the value of the inventory status between the review moments (Silver, Pyke, & Thomas, 2017).

In production environments, some products are produced on the same piece of equipment. In those situations, a periodic review is often attractive because all products in a coordinated group can be given the same review period. A disadvantage of using a continuous review is that it is more expensive, both in terms of reviewing costs and reviewing errors. This is especially the case for fast-moving products where the number of transactions per time unit is high. However, an advantage of continuous review is that less safety stock is required compared to using a periodic review to provide the same level of customer service. This is because the period over which the safety stock is required to reduce the risk that the item will be out of stock is longer when using a periodic review (Silver, Pyke, & Thomas, 2017). As concluded by Axsäter (2006), it is common to use a continuous review for products with low demand and a periodic review for products with higher demand.

Inventory control policies

According to Silver, Pyke and Thomas (2017), the inventory control policy specifies when to place a replenishment order and what quantity to order. To clarify, an order refers to a production order for the DRAFA. It is important to note that this decision is based on the inventory position instead of the net inventory level. The inventory position takes into account the outstanding production orders, which are the production orders that have already been planned but not yet produced. The following equation is used to determine the inventory position.

$$Inventory\ position = On\ hand\ stock + Outstanding\ production\ orders - Backorders$$

Table B.3 shows the most common types of single-echelon inventory control policies. The inventory control policies can be categorized according to two pillars, which are the review period and the lot size. A distinction can be made between a continuous and a periodic review. In addition, the inventory control policies can be divided into fixed or variable lot size. In the case of a fixed lot size, the order quantity is always the same or a multiple of the order quantity. In the case of a variable lot size, the order quantity varies to reach a certain inventory position.

Table B.3 - Inventory control policies.

	Continuous review	Periodic review
Fixed lot size	(s,Q) or (s,nQ)	(R,s,Q) or (R,s,nQ)
Variable lot size	(s,S)	(R,S) or (R,s,S)

The (s,Q) or (s,nQ)-policy is a policy with a continuous review and a fixed lot size. According to the (s,Q)-policy, a fixed quantity Q is ordered whenever the inventory position drops to or below the reorder point s. Silver, Pyke and Thomas (2017) describe the (s,Q)-policy as a two-bin system, because in some practical situations two-bins are used for the storage of a product. As long as units are available in the first bin, demand is satisfied from it. The storage quantity in the second bin is equal to the reorder point. Once the first bin is empty and products are taken from the second bin, a replenishment order is placed. The relevant advantages of the (s,Q)-policy are that this policy is easy to understand and that errors made by the capacity planner are less likely to occur. A disadvantage of the (s,Q)-policy is that it may not be able to respond adequately to large individual product requests, as the fixed quantity Q does not always raise the inventory position above the reorder point s. In this case, it is also possible to order a multiple of the fixed quantity Q, known as the (s,nQ)-policy.

The (s,S)-policy is a policy with a continuous review and a variable lot size. As was the case for the (s,Q)-policy, a replenishment order is made whenever the inventory position drops to or below the reorder point s. However, different to the (s,Q)-policy, a variable quantity is ordered to raise the inventory position to the order-up-to-level S. If all individual product requests are unit sized, the (s,Q)-policy and the (s,S)-policy are identical. In this case, a replenishment order is made whenever the inventory position is equal to the reorder point s, so $S = s + Q$. The (s, S)-policy is a min-max system because the inventory position is always between a minimum value s and a maximum value S, except when the inventory position temporarily drops below the minimum value. Compared to the (s, Q)-policy, Silver, Pyke and Thomas (2017) argued that the best (s, S)-policy can result in the total costs not exceeding the total costs obtained when using the best (s, Q)-policy. However, since the computational effort to find the best values of s and S is significantly greater when using the (s, S)-policy, the (s, Q)-policy may be preferred depending on the potential savings of a product.

The (R, s, Q) or (R, s, nQ)-policy is a policy with a periodic review and a fixed lot size. According to the (R, s, Q)-policy, every R units of time a fixed quantity Q is ordered whenever the inventory position drops to or below the reorder point s. As a result, the inventory position is raised to a value between s and $s + Q$ (Janssen, Heuts, & de Kok, 1998). Similar as with the (s, Q)-policy, a disadvantage of the (R, s, Q)-policy is that it may not be able to respond adequately to large individual product requests, as the fixed quantity Q does not always raise the inventory position above the reorder point s. In this case, it is also possible to order a multiple of the fixed quantity Q, known as the (R, s, nQ)-policy (Larsen & Kiesmüller, 2007).

The (R, S) or (R, s, S)-policy is a policy with a periodic review and a variable lot size. According to the (R, S)-policy, every R units of time a variable quantity is ordered to raise the inventory position to the order-up-to-level S. An advantage of the (R, S)-policy is that it provides possibilities to coordinate the replenishments of related products. Therefore, the (R, S)-policy is frequently used when products require resource sharing and are produced on the same piece of equipment. In addition, it is possible to adjust the order-up-to-level S at each review moment R, which is preferred when the demand pattern fluctuates over time. A disadvantage of the (R, S)-policy is that the order quantities differ and that the holding costs are higher compared to inventory control policies with a continuous review. The (R, s, S)-policy is a combination of the (s, S)-policy and the (R, S)-policy. According to the (R, s, S)-policy, every R units of time the inventory position is checked. If the inventory position drops to or below the reorder point s, a variable quantity is ordered to raise the inventory position to the order-up-to-level S. If the inventory position is above the reorder point s, nothing is done until the next review moment. Silver, Pyke and Thomas (2017) argued that the best (R, s, S)-policy can result in the lowest total costs compared to all other inventory control policies. However, the computational effort to find the best values of R, s and S is greater when using the (R, s, S)-policy, which may give preference to other inventory control policies.

Cost and service objectives

Under probabilistic demand, there is a change of not being able to satisfy some of the demand directly out of stock. Demand may occasionally be high and as a result a stockout may occur or an emergency action may be required to avoid the stockout. On the other hand, demand may be lower than expected. In this case, the replenishment order arrives earlier than needed, which can lead to unnecessary inventory costs. As discussed by Silver, Pyke and Thomas (2017), there are different perspectives on how to balance the probability of stockouts and the inventory costs. The following four methods can be used to arrive at appropriate decision rules. The choice depends on the chosen perspective and the customers' perception of what is important.

1. <u>Safety stock based on a simple-minded approach.</u> The objective of this method is to assign a common safety factor as the safety stock of each product.
2. <u>Safety stock based on minimizing costs.</u> The objective of this method is to select a way to measure the costs, after which the total costs are minimized.
3. <u>Safety stock based on customer service.</u> The objective of this method is to introduce a service level as a constraint in establishing the safety stock of a product.
4. <u>Safety stock based on aggregate considerations.</u> The objective of this method to determine the safety stocks of individual products to provide the best aggregated service for a range of products, given a certain budget.

When focusing on the second method, Janssen (1998) discusses three relevant types of shortage costs, as discussed below.

1. Shortage costs per stockout occasion (B1). This costing method assumes that the costs of a stockout are charged with a fixed value B1, which is independent of the magnitude or duration of the stockout.
2. Shortage costs per unit short (B2). This costing method assumes that the costs per unit short are charged with a fixed value B2, which is independent of the duration of the stockout.
3. Shortage costs per unit short per unit time (B3). This costing method assumes that the costs per unit short per unit of time are charged with a fixed value B3.

When focusing on the third method, Beerens and Kusters (2015) mention that the service level is used as input for calculating the optimal safety stock of a product. There are several ways to define customer service targets. Each customer service target leads to a different level of the safety stock. The four most common customer service targets are discussed below.

1. Cycle Service Level (P1). According to the CSL, the safety stock is based on the desired percentage of replenishment cycles in which no stockout occurs. A replenishment cycle is defined as the period between two replenishments.
2. Fill rate (P2). According to the fill rate, the safety stock is based on the desired percentage of products that can be supplied immediately from stock.
3. Ready rate (P3). According to the ready rate, the safety stock is based on the desired percentage of time during which the available stock on hand is positive.
4. Time Between Stockout Occasions. According to the TBS, the safety stock is based on the desired average time between two stockout occasions. The TBS is a variant of the ready rate (P3).

Review period (R)

As discussed, the review period (R) is the time between two consecutive moments at which the inventory status is reviewed. The study by Sezen (2006) examined the impacts of changing the length of the review period on the performance of a periodic review system. Most studies in the literature assume that the value of the review period is predetermined. However, there are also some recent studies that focus on the length of the review period as a determining factor in periodic review systems.

Sezen (2006) concluded that there are no particular rules for selecting the appropriate length of the review period for a periodic review system. However, for products with high variable demand, relatively shorter review periods are preferred. Otherwise, the average inventory levels and the probability of shortages will increase with increasing lengths of the review period. On the other hand, for products with low fluctuating and low average demand, relatively longer review periods are preferred.

According to van der Heijden (2020a), the review period is approximately equal to the Economic Order Quantity (EOQ) divided by the annual demand rate as follows, where EOQ is the replenishment order quantity and D is the annual demand rate.

$$R = \frac{EOQ}{D}$$

Order quantity (Q)

According to Rao and Bahari-Kashani (1990), the EOQ model is developed to find an order quantity that minimizes the sum of the holding and ordering costs. Under linear holding costs, the EOQ model balances the holding and ordering costs. The traditional EOQ model assumes linear holding costs in the number of products held in stock and fixed ordering costs each time an order is placed. In the situation of no back logging, no quantity discounts, constant lead time and constant demand, the total relevant cost function is as follows, where Q is the replenishment order quantity, v is the unit variable cost, r is the holding cost rate, A is the fixed ordering cost and D is the annual demand rate (Silver, Pyke, & Thomas, 2017).

$$TRC(Q) = \frac{Qvr}{2} + \frac{AD}{Q}$$

The EOQ function can be derived from the total relevant cost function and is as follows.

$$EOQ = \sqrt{\frac{2AD}{vr}}$$

As stated by Silver, Pyke and Thomas (2017), the EOQ model assumes that the whole replenishment quantity arrives at the same time. However, in production environments, the production quantity becomes available during the production time. The Economic Production Quantity (EPQ) model assumes that the production quantity becomes available at a rate of m per unit time. In other words, the EPQ model takes into account that products become available and are added to inventory during the production run. Based on the EPQ model, the average inventory level becomes $\frac{Q\left(1-\frac{D}{m}\right)}{2}$. Hence, the total relevant cost function is as follows.

$$TRC(Q) = \frac{Q\left(1-\frac{D}{m}\right)vr}{2} + \frac{AD}{Q}$$

The EPQ function can be derived from the total relevant cost function and is as follows.

$$EPQ = \sqrt{\frac{2AD}{vr\left(1-\frac{D}{m}\right)}}$$

Reorder point (s)

According to Patel (1986), the time to place an order is when the inventory position drops to a point where sufficient inventory exists to meet the expected demand during the lead time. Under deterministic demand, it is assumed that the demand and the lead time are known. Hence, the reorder point is equal to the expected demand during the lead time. If the lead time (L) is equal to zero, the reorder point (s) should also be equal to zero. In other words, an order is placed when the inventory position is equal to zero and the order is received immediately. If the lead time (L) is greater than zero, an order should be placed L time units earlier and the reorder point (s) should be equal to the expected demand during the lead time ($\hat{x}_L$) (Axsäter, 2006).

Under probabilistic demand, the expected demand during the lead time is uncertain and must be replaced by the mean of the probability distribution of the lead time demand. The provision of a safety stock is needed to cover higher than average demand that may arise during the lead time (Patel, 1986). The safety stock is inventory carried to reduce the risk that the item will be out of stock and is computed by multiplying a safety factor and the standard deviation of the lead time demand (Silver, Pyke, & Thomas, 2017). In a continuous review, the reorder point is equal to the expected demand during the lead time ($\hat{x}_L$) plus the safety stock ($k\sigma_L$). The standard deviation of the lead time demand (σ_L) is the square root of the lead time (L) multiplied by the variance of the demand per period (σ_D^2), given that the lead time is constant. The formulas for calculating the reorder point and the standard deviation of the lead time demand are as follows.

$$s = \hat{x}_L + k * \sigma_L$$

$$\sigma_L = \sqrt{L * \sigma_D^2}$$

In a periodic review, the reorder point is equal to the expected demand during the lead time and the review period ($\hat{x}_{L+R}$) plus the safety stock ($k\sigma_{L+R}$). The standard deviation of the demand during the lead time and the review period (σ_{L+R}) is the square root of the sum of the lead time and the review period ($L + R$) multiplied by the variance of the demand per period (σ_D^2), given that the lead time is constant. The formulas for calculating the reorder point and the standard deviation of the demand during the lead time and the review period are as follows.

$$s = \hat{x}_{L+R} + k\sigma_{L+R}$$

$$\sigma_{L+R} = \sqrt{(L+R) * \sigma_D^2}$$

The safety factor k is determined based on the desired customer service target. The formulas for calculating the four most common customer service targets and the corresponding formula for calculating the safety factor k are given below. The CSL (P1) is based on the desired percentage of replenishment cycles in which no stockout occurs. The higher the CSL, the higher the safety factor and therefore also the reorder point (van der Heijden, 2020b). In the formulas below, $\Phi(k)$ is the standard normal distribution function.

$$CSL = \Phi\left(\frac{s - \hat{x}_{L+R}}{\sigma_{L+R}}\right) = \Phi(k)$$

$$k = \left(\frac{s - \hat{x}_{L+R}}{\sigma_{L+R}}\right) = \Phi^{-1}(CSL)$$

The fill rate (P2) is based on the desired percentage of products that can be supplied immediately from stock. In the formulas below, $ESPRC$ is the expected shortage per replenishment cycle and G(k) is the standard normal loss function (van der Heijden, 2020c).

$$Fill\,rate = 1 - \frac{ESPRC}{Q} = 1 - \frac{\sigma_{L+R}G(k)}{Q}$$

$$G(k) = \frac{Q(1 - Fill\,rate)}{\sigma_{L+R}}$$

The ready rate (P3) is based on the desired percentage of time during which the available stock on hand is positive. In the formulas below, $\varphi(k)$ is the standard normal density function (van der Heijden, 2020b).

$$Ready\,rate = 1 - \frac{\sigma_{L+R}}{Q}\left(G(k) - G\left(k + \frac{Q}{\sigma_{L+R}}\right)\right)$$

$$G(k) = \varphi(k) - k(1 - \Phi(k))$$

The TBS is based on the desired average time between two stockout occasions (van der Heijden, 2020b).

$$TBS = \frac{Q}{D} * \frac{1}{1 - \Phi(k)}$$

$$k = \Phi^{-1}(1 - \frac{Q}{D * TBS})$$

According to van der Heijden (2020d), when using the (R, s, S)-policy and the fill rate as customer service target, the safety factor k should be chosen such that it satisfies the following expression.

$$(1 - Fill\,rate)Q \approx \frac{\sigma_{L+R}^2 J(k)}{2\hat{x}_R}$$

Where the expected order size (Q) is computed as follows.

$$Q = S - s + \frac{\sigma_R^2 + \hat{x}_R^2}{2\hat{x}_R}$$

Order-up-to-level (S)

The order-up-to-level is the level up to which the inventory is replenished. For the (s, S) and (R, s, S)-policy, if the inventory position drops to or below the reorder point s, a variable quantity is ordered to raise the inventory position to the order-up-to-level S. The order quantity (Q) is therefore equal to the order-up-to-level (S) minus the reorder point (s). For the (s, S) and (R, s, S)-policy, the order-up-to-level is computed as follows.

$$S = s + (S - s) = s + EOQ$$

On the other hand, for the (R, S)-policy, no reorder point is used and every R units of time a variable quantity is ordered to raise the inventory position to the order-up-to-level S. Since a periodic review applies, the order-up-to-level must be sufficient to meet all demand until the arrival of the next replenishment order. Under probabilistic demand, the order-up-to-level is equal to the expected demand during the lead time and the review period ($\hat{x}_{L+R}$) plus the safety stock ($k\sigma_{L+R}$). For the (R, S)-policy, the order-up-to-level is computed as follows (Silver, Pyke, & Thomas, 2017).

$$S = \hat{x}_{L+R} + k\sigma_{L+R}$$

C Determination of the cost parameters

This appendix has been removed from the public version for confidentiality reasons.

D MILP model for the medium-term

This appendix contains the MILP model that integrates inventory control and lot sizing decisions to solve the medium-term production planning problem at the DRAFA.

Set	**Description**
i	Product with i = 1,…, N
j	Product with j = 1,…, N
m	Machine with m = 1,…, V
t	Week with t = 1,…, T

Parameters	**Description**
N	Number of products
V	Number of machines
T	Number of weeks in the planning horizon
$IntI_i$	Initial inventory of product i in m/kg
$IntB_i$	Initial number of backorders of product i in m/kg
R_{mt}	Available resource capacity for machine m in week t in minutes
Pur_{it}	Planned purchase quantity for product i to receive in week t in m/kg
d_{it}	Expected demand for product i in week t in m/kg
C_{im}	Unit production costs of product i on machine m in euros per m/kg
S_{im}	Setup costs for product i on machine m in euros per setup
h_i	Unit holding costs of product i in euros per m/kg per week
$B1_i$	Shortage costs for backlogging one unit of product i in euros per m/kg per week
PT_{im}	Unit production time for product i on machine m in minutes per m/kg
ST_{im}	Setup time for product i on machine m in minutes per setup
M	Sufficiently large number
a_{ij}	Number of units of component i required to produce one unit of parent j
v_{im}	$\begin{cases} 1, \text{if product } i \text{ can be assigned to machine } m \text{ for production} \\ 0, \text{otherwise} \end{cases}$
Min_i	Minimum production quantity of product i in m/kg
SS_i	Safety stock level of product i in m/kg
$B2_i$	Penalty costs for having one unit of product i below the safety stock level in euros per m/kg
Max_i	Maximum storage quantity of product i in m/kg

Decision variables	**Description**
X_{imt}	Number of units of product i produced on machine m in week t
I_{it}^+	Inventory of product i at the end of week t
I_{it}^-	Number of backorders of product i at the end of week t
Y_{imt}	$\begin{cases} 1, \text{if product } i \text{ is produced on machine } m \text{ in week } t \\ 0, \text{otherwise} \end{cases}$
n_{imt}	Multiple of the minimum production quantity of product i produced on machine m in week t
SS_{it}^-	Number of units of product i below the safety stock level at the end of week t

Objective function

$$\text{Min} \sum_{i=1}^{N}\sum_{m=1}^{V}\sum_{t=1}^{T} C_{im}X_{imt} + \sum_{i=1}^{N}\sum_{m=1}^{V}\sum_{t=1}^{T} S_{im}Y_{imt} + \sum_{i=1}^{N}\sum_{t=1}^{T} h_i I_{it}^+ + \sum_{i=1}^{N}\sum_{t=1}^{T} B1_i I_{it}^- + \sum_{i=1}^{N}\sum_{t=1}^{T} B2_i SS_{it}^-$$

Subject to

$$\sum_{i=1}^{N} PT_{im}\, X_{imt} + \sum_{i=1}^{N} ST_{im} Y_{imt} \leq R_{mt} \qquad \forall m \in V, \forall t \in T \qquad (4.1)$$

$$Pur_{i1} + \sum_{m=1}^{V} X_{im1} - \sum_{j=1}^{N}\sum_{m=1}^{V} a_{ij} X_{jm1} + IntI_i - I_{i1}^{+} + I_{i1}^{-} - IntB_i = d_{i1} \quad \forall i \in N \qquad (4.2)$$

$$Pur_{it} + \sum_{m=1}^{V} X_{imt} - \sum_{j=1}^{N}\sum_{m=1}^{V} a_{ij} X_{jmt} + I_{i,t-1}^{+} - I_{it}^{+} + I_{it}^{-} - I_{i,t-1}^{-} = d_{it} \quad \forall i \in N, t = 2, ..T \qquad (4.3)$$

$$X_{imt} \leq M\, Y_{imt} \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (4.4)$$

$$X_{imt} = 0 \qquad \forall i \in N, \forall m \in V, \forall t \in T, v_{im} = 0 \qquad (4.5)$$

$$X_{imt} = n_{imt}\, Min_i \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (4.6)$$

$$I_{it}^{+} + SS_{it}^{-} \geq SS_i \qquad \forall i \in N, \forall t \in T \qquad (4.7)$$

$$I_{it}^{+} \leq Max_i \qquad \forall i \in N, \forall t \in T \qquad (4.8)$$

$$I_{it}^{-} = 0 \qquad \forall i \in N \ if \textstyle\sum_{j=1}^{N} a_{ij} > 0, \forall t \in T \qquad (4.9)$$

$$X_{imt} \geq 0 \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (4.10)$$

$$I_{it}^{+} \geq 0 \qquad \forall i \in N, \forall t \in T \qquad (4.11)$$

$$I_{it}^{-} \geq 0 \qquad \forall i \in N, \forall t \in T \qquad (4.12)$$

$$Y_{imt} \in \{0,1\} \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (4.13)$$

$$n_{imt}\ as\ integer \qquad \forall i \in N, \forall m \in V, \forall t \in T \qquad (4.14)$$

$$SS_{it}^{-} \geq 0 \qquad \forall i \in N, \forall t \in T \qquad (4.15)$$

E Combined ABC-XYZ classification

This appendix has been removed from the public version for confidentiality reasons.

F Inventory control tool DRAFA for calculating safety stock levels

We have developed an Excel tool to calculate the corresponding safety stock levels of the MTS products needed to reduce the effects of demand uncertainty. Figure F.1 provides an overview of the dashboard that can be used to calculate the safety stock levels of the MTS products. The article number of the product is required as input for the tool. After the article number is given as input, the tool is able to retrieve the article description and the minimum production quantity from Navision. In addition, the tool determines the class according to the combined ABC-XYZ classification and the corresponding target fill rate. The supply lead time, demand lead time and safety lead time should also be given as input to the tool. Then the lead time can be modelled as the supply lead time minus the demand lead time plus the safety lead time, due to ADI on customer demand.

The tool is able to retrieve historical demand data from Navision given the demand period, that is used to calculate the average historical demand per day and the standard deviation of the historical demand. With this information, the tool calculates the standard deviation of the demand during the lead time and the standard normal loss function, respectively. By using the Goal Seek function in Excel, the safety factor can be derived from the standard normal loss function. Finally, the tool calculates the safety stock by multiplying the safety factor and the standard deviation of the lead time demand.

Inventory control tool DRAFA - Calculating safety stocks

	Date T periods ago		10-11-2021
	Article		
	Description		
	ABC-XYZ class		AZ
	Target fill rate		93%
	% of days with no demand		2,4%
	Threshold		80%
MPQ	Minimum production quantity		400 [KG]
LSu	Supply lead time		2 [days]
LD	Demand lead time		1 [days]
LSa	Safety lead time		0,5 [days]
L	Lead time (production)	L = [LSu-LD+LSa]+	1,5 [days]
OH	Current on-hand inventory		64.835 [KG]
T	Demand period		182 [days]
D	Historical demand over the period		1.034.317 [KG]
µ	Average historical demand per day	µ = D / T	8.341 [KG]
σD	Standard deviation of historical demand		3.180 [KG]
µL	Mean lead time demand	µL = µ x L	12.512 [KG]
σL	Standard deviation of lead time demand	σL = σD x √L	3.894 [KG]
G(k)	Standard normal loss function	G(k) = MPQ x (1 - Target fill rate) / σL	0,0072
G(k)2	Standard normal loss function 2		0,0073
k	Safety factor		2,0567
SS	Safety stock	SS = k x σL	8.010 [KG]

Cells to be filled in per article
Default parameters
Calculated values

Calculate safety factor | Calculate safety stocks

Historical demand data

#	Date	Day	Quantity	Quantity 2
1	10-11-2021	woensdag	11.618	11.618
2	11-11-2021	donderdag	2.166	2.166
3	12-11-2021	vrijdag	1.736	6.121
4	13-11-2021	zaterdag	878	
5	14-11-2021	zondag	3.507	
6	15-11-2021	maandag	31.084	31.084
7	16-11-2021	dinsdag	1.313	1.313
8	17-11-2021	woensdag	2.580	2.580
9	18-11-2021	donderdag	25.544	25.544
10	19-11-2021	vrijdag	867	3.901
11	20-11-2021	zaterdag	1.728	
12	21-11-2021	zondag	1.305	
13	22-11-2021	maandag	13.691	13.691
14	23-11-2021	dinsdag	3.877	3.877
15	24-11-2021	woensdag	5.514	5.514
16	25-11-2021	donderdag	886	886
17	26-11-2021	vrijdag	4.482	8.001
18	27-11-2021	zaterdag	1.799	
19	28-11-2021	zondag	1.720	
20	29-11-2021	maandag	6.721	6.721
21	30-11-2021	dinsdag	1.790	1.790
22	1-12-2021	woensdag	4.805	4.805
23	2-12-2021	donderdag	5.687	5.687
24	3-12-2021	vrijdag	2.599	6.124
25	4-12-2021	zaterdag	1.755	
26	5-12-2021	zondag	1.770	
27	6-12-2021	maandag	4.391	4.391
28	7-12-2021	dinsdag	1.321	1.321
29	8-12-2021	woensdag	7.074	7.074
30	9-12-2021	donderdag	766	766

Figure F.1 - Inventory control tool DRAFA for calculating the safety stock levels.

G MILP model for the short-term

This appendix contains the MILP model by incorporating positive supply lead times, setup carry-overs and sequence-dependent setup times to solve the short-term production planning problem at the DRAFA.

Set	Description
i	Product with i = 1,…, N
j	Product with j = 1,…, N
k	Product with k = 1,…, N
m	Machine with m = 1,…, V
t	Day with t = 1,…, T

Parameters	Description
N	Number of products
V	Number of machines
T	Number of days in the planning horizon
$IntI_j$	Initial inventory of product j in m/kg
$IntB_j$	Initial number of backorders of product j in m/kg
R_{mt}	Available resource capacity for machine m on day t in minutes
Pur_{jt}	Planned purchase quantity for product j to receive on day t in m/kg
d_{jt}	Expected demand for product j on day t in m/kg
C_{jm}	Unit production costs of product j on machine m in euros per m/kg
S_{jm}	Setup costs for product j on machine m in euros per setup
h_j	Unit holding costs of product j in euros per m/kg per day
$B1_j$	Shortage costs for backlogging one unit of product j in euros per m/kg per day
PT_{jm}	Unit production time for product j on machine m in minutes per m/kg
ST_{jm}	Setup time for product j on machine m in minutes per setup
M	Sufficiently large number
a_{jk}	Number of units of component j required to produce one unit of parent k
v_{jm}	$\begin{cases} 1, \text{if product } j \text{ can be assigned to machine } m \text{ for production} \\ 0, \text{otherwise} \end{cases}$
Min_j	Minimum production quantity of product j in m/kg
$Pack_j$	Fixed number of packaging units to produce of product j in m/kg
SS_j	Safety stock level of product j in m/kg
$B2_j$	Penalty costs for having one unit of product j below the safety stock level in euros per m/kg
Max_j	Maximum storage quantity of product j in m/kg
L_j	Supply lead time of product j in days
SF_{ij}	Fraction of the setup time of product j needed and setup costs of product j involved when switching over from product i to product j between 0 and 1
α_{jm}^0	Initial setup state of product j on machine m at the beginning of the planning horizon
$IntP_{jmt}$	Initial production quantity of product j on machine m on day t according to the orders currently in production.

Decision variables	Description
X_{jmt}	Number of units of product j produced on machine m on day t
I_{jt}^+	Inventory of product j at the end of day t

I_{jt}^{-}	Number of backorders of product j at the end of day t
Y_{ijmt}	$\begin{cases} 1, \text{if a setup is performed from product } i \text{ to product } j \text{ on machine } m \text{ on day } t \\ 0, \text{otherwise} \end{cases}$
n_{jmt}	Multiple of the minimum production quantity of product j produced on machine m on day t
o_{jm}	Multiple of the standard production quantity of product j produced on machine m over the entire planning horizon
SS_{jt}^{-}	Number of units of product j below the safety stock level at the end of day t
β_{jmt}	$\begin{cases} 1, \text{if the setup state for product } j \text{ on machine } m \text{ is carried over from day } t \text{ to } t+1 \\ 0, \text{otherwise} \end{cases}$
γ_{jmt}	Position of product j on machine m on day t

Objective function

$$\text{Min} \sum_{j=1}^{N}\sum_{m=1}^{V}\sum_{t=1}^{T} C_{jm}X_{jmt} + \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{m=1}^{V}\sum_{t=1}^{T} SF_{ij}S_{jm}Y_{ijmt} + \sum_{j=1}^{N}\sum_{t=1}^{T} h_j I_{jt}^{+} + \sum_{j=1}^{N}\sum_{t=1}^{T} B1_j I_{jt}^{-} + \sum_{j=1}^{N}\sum_{t=1}^{T} B2_j SS_{jt}^{-}$$

Subject to

$$\sum_{j=1}^{N} PT_{jm}\, X_{jmt} + \sum_{i=1}^{N}\sum_{j=1}^{N} SF_{ij}ST_{jm}Y_{ijmt} \le R_{mt} \qquad \forall m \in V, \forall t \in T \qquad (4.16)$$

$$Pur_{j1} - \sum_{k=1}^{N}\sum_{m=1}^{V} a_{jk}X_{km1} + IntI_j - I_{j1}^{+} + I_{j1}^{-} - IntB_j = d_{j1} \qquad \forall j \in N \qquad (4.17)$$

$$Pur_{jt} + \sum_{m=1}^{V} X_{jmt-L_j} - \sum_{k=1}^{N}\sum_{m=1}^{V} a_{jk}X_{kmt} + I_{j,t-1}^{+} - I_{jt}^{+} + I_{jt}^{-} - I_{j,t-1}^{-} = d_{jt} \quad \forall j \in N, t = 2,..T \qquad (4.18)$$

$$X_{jm1} \le M\,(\textstyle\sum_{i=1}^{N} Y_{ijm1} + \alpha_{jm}^{0}) \qquad \forall j \in N, \forall m \in V \qquad (4.19)$$

$$X_{jmt} \le M\,(\textstyle\sum_{i=1}^{N} Y_{ijmt} + \beta_{jm,t-1}) \qquad \forall j \in N, \forall m \in V, t = 2,..T \qquad (4.20)$$

$$X_{jmt} = 0 \qquad \forall j \in N, \forall m \in V, \forall t \in T, v_{jm} = 0 \qquad (4.21)$$

$$X_{jmt} = n_{jmt}\, Min_j \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.22)$$

$$X_{jmt} \ge IntP_{jmt} \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.23)$$

$$\textstyle\sum_{t=1}^{T} X_{jmt} = o_{jm}Pack_jMin_j \qquad \forall j \in N, \forall m \in V \qquad (4.24)$$

$$I_{jt}^{+} + SS_{jt}^{-} \ge SS_j \qquad \forall j \in N, \forall t \in T \qquad (4.25)$$

$$I_{jt}^{+} \le Max_j \qquad \forall j \in N, \forall t \in T \qquad (4.26)$$

$$I_{jt}^{-} = 0 \qquad \forall j \in N \; if \textstyle\sum_{k=1}^{N} a_{jk} > 0, \forall t \in T \qquad (4.27)$$

$$\textstyle\sum_{j=1}^{N} \beta_{jmt} = 1 \qquad \forall m \in V, \forall t \in T \qquad (4.28)$$

$$\alpha_{jm}^{0} + \textstyle\sum_{i=1}^{N} Y_{ijm1} = \sum_{k=1}^{N} Y_{jkm1} + \beta_{jm1} \qquad \forall j \in N, \forall m \in V \qquad (4.29)$$

$$\textstyle\sum_{i=1}^{N} Y_{ijmt} + \beta_{jm,t-1} = \sum_{k=1}^{N} Y_{jkmt} + \beta_{jmt} \qquad \forall j \in N, \forall m \in V, t = 2,..T \qquad (4.30)$$

$$\gamma_{jmt} \ge \gamma_{imt} + 1 - N\,(1 - Y_{ijmt}) \qquad \forall i,j \in N, \forall m \in V, \forall t \in T \qquad (4.31)$$

$$X_{jmt} \geq 0 \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.32)$$

$$I_{jt}^{+} \geq 0 \qquad \forall j \in N, \forall t \in T \qquad (4.33)$$

$$I_{jt}^{-} \geq 0 \qquad \forall j \in N, \forall t \in T \qquad (4.34)$$

$$Y_{ijmt} \in \{0,1\} \qquad \forall i, j \in N, \forall m \in V, \forall t \in T \qquad (4.35)$$

$$n_{jmt} \; as \; integer \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.36)$$

$$SS_{jt}^{-} \geq 0 \qquad \forall j \in N, \forall t \in T \qquad (4.37)$$

$$\beta_{jmt} \in \{0,1\} \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.38)$$

$$\gamma_{jmt} \geq 0 \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.39)$$

H Solving a toy problem

In this appendix, we discuss the results obtained after solving a toy problem. We solve a toy problem to test the mathematical model and to analyse the decisions made by the model. The toy problem serves as a simplified problem with clear parameters and constraints used to understand the more advanced real problem at the DRAFA. The real problem at the DRAFA contains a set of approximately $N = 200$ products, $V = 14$ machines and $T = 8$ weeks. The set of products fluctuates over time, because we only include those products in the model with a positive expected demand over the planning horizon. In the toy problem, we have a set of $N = 40$ products, $V = 5$ machines and $T = 3$ weeks. In order to solve the toy problem, we use the AIMMS software. We decided to generate random input data in AIMMS based on an appropriate range for each parameter of the model that corresponds to the production context of the DRAFA. The random input data is drawn from the uniform distribution with a certain lower and upper bound. Table H.1 depicts the parameter characteristics used to generate a random data set as input for the model. For the sake of simplicity, we exclude the inventory control decisions and ignore the presence of parent-component relationships among the products in the production process. In addition, we do not consider planned purchase orders and assume that each product can be assigned to any of the five machines for production. Finally, we use a target fill rate of 95% to determine the shortage costs per product.

Table H.1 - Toy problem: Parameter characteristics.

Model parameter	**Description**	**Parameter value**	**Unit of measure**
$IntI_i$	Initial inventory of product i	[1000, 2000]	Meters/Kg
$IntB_i$	Initial number of backorders of product i	[0, 1000]	Meters/Kg
R_{mt}	Available resource capacity for machine m in period t	[3000, 6000]	Minutes per week
d_{it}	Expected demand for product i in period t	[1000, 3000]	Meters/Kg
C_{im}	Unit production costs of product i on machine m	[0.05, 0.45]	Euros per m/kg
S_{im}	Setup costs for product i on machine m	[100, 400]	Euros per setup
h_i	Unit holding costs of product i	[0.01, 0.05]	Euros per m/kg per week
PT_{im}	Unit production time for product i on machine m	[0.05, 0.40]	Minutes per m/kg
ST_{im}	Setup time for product i on machine m	[75, 300]	Minutes per setup
$B1_i$	Shortage costs for backlogging one unit of product i	$B_i = \frac{h_i\ 0.95}{1 - 0.95}$	Euros per m/kg per week

The model is able to solve the toy problem to optimality within a reasonable time. Table H.2 summarizes the results obtained after solving the model for three randomly generated data sets. We conclude that the model is able to find the optimal production schedule within seconds. The differences in the objective values are caused by the randomness involved in the data set used as input for the model.

Table H.2 - Results for the toy problem over 3 runs.

	Results for the toy problem		
Performance indicators	**Run 1**	**Run 2**	**Run 3**
# Constraints	1336	1336	1336
# Variables	1441	1441	1441
Solving time	6.45 sec.	5.55 sec.	5.53 sec.
Best lower bound	€ 41,010.65	€ 35,076.70	€ 45,265.91
Gap	0%	0%	0%
Best feasible solution	€ 41,010.65	€ 35,076.70	€ 45,265.91

To illustrate the functionality of the model, we discuss the decisions made by the model for the third run. Table H.3 shows the optimal production schedule for machine 1 over the planning horizon, expressed in the number of units of a particular product to produce in a particular time period.

Table H.3 - Production schedule for machine 1 in run 3 in m/kg.

	Time period	**1**	**2**	**3**
Machine	**Product**			
1	14	4564.35	-	-
	16	2456.04	-	1814.05
	20	3701.62	-	2519.69
	23	5588.31	-	-
	25	1314.31	3856.05	-
	26	2597.22	-	-
	30	3287.67	-	2734.21
	31	-	5947.81	-
	33	3114.67	-	-
	36	-	3992.84	-

Table H.4 shows the amount of inventory and the number of backorders for 10 of the 40 products over the planning horizon. We observe that the model makes a trade-off when determining the amount and timing of production over the planning horizon under capacity constraints. On the one hand, the model tries to produce early by aggregating production for multiple time periods in the planning horizon to reduce machine setup times. On the other hand, the model tries to produce just-in-time to reduce inventory holding costs.

Table H.4 - Amount of inventory and number of backorders for 10 products in run 3 in m/kg.

	Amount of inventory			**Number of backorders**		
Time period	**1**	**2**	**3**	**1**	**2**	**3**
Product						
1	3343.25	2220.45	-	-	-	-
2	421.29	1704.33	-	-	-	-
3	2948.08	1070.87	-	-	-	-
4	5204.93	2296.52	-	-	-	-
5	2161.07	970.29	-	-	-	30.82
6	1828.84	-	-	-	-	-
7	3309.13	2299.55	-	-	-	-
8	4228.07	1466.62	-	-	-	-
9	-	2488.95	-	-	-	-
10	-	1416.18	-	179.46	-	-

I Explanation of the setup fractions

This appendix explains how we determine the setup fractions that indicate what fraction of the setup time and costs should be taken into account when switching over from one product to another. If we switch over to the same product on a Vlechtdraad or Samenslaglijn machine, we still have to change reels during production. Therefore, we count half of the setup time and costs in this situation. In addition, we reduce the setup time and costs on a Middentrek machine when switching over to a product with a comparable wire diameter. On the Middentrek machines the wire diameters range from 0.30 to 1.28 mm. Finally, we reduce the setup time and costs on a Fijntrek machine when switching over to a product with a comparable wire diameter and/or number of wires. On the Fijntrek machines the wire diameters range from 0.16 to 0.49 mm and the number of wires range from 1 to 8. To clarify, a switch to another product on a particular machine is only possible if both products can be assigned to that machine for production.

For the third and fourth situation in Table I.1, we have decided to round off all fractions smaller than 0.3 to 0.3, because a certain fraction of the setup time and costs should always be taken into account in the production schedule when switching over to another product. This lower bound is based on conversations with operators who indicate that about this part of the setup time is always needed when switching over to another product.

Table I.1 - Setup fractions when switching over from product i to product j (w.d. = wire diameter, no.w. = number of wires).

Situation	Decision rule
We switch over from product i to product j on Groftrek 1 or Middentrek 1, 2, 3 or Fijntrek 1, 2, 3 where product i = product j	$SF_{ij} = 0$
We switch over from product i to product j on Vlechtdraad 1, 2, 3, 4 or Samenslaglijn 1 where product i = product j	$SF_{ij} = 0.5$
We switch over from product i to product j on Middentrek 1, 2, 3 where product $i \neq$ product j	$SF_{ij} = 1 - \left(\frac{Min(w.d.product\ i, w.d.product\ j)}{Max(w.d.product\ i, w.d.product\ j)}\right)$
We switch over from product i to product j on Fijntrek 1, 2, 3 where product $i \neq$ product j	$SF_{ij} = 1 - \left(\frac{Min(w.d.product\ i, w.d.product\ j)}{Max(w.d.product\ i, w.d.product\ j)} * \frac{Min(no.w.product\ i, no.w.product\ j)}{Max(no.w.product\ i, no.w.product\ j)}\right)$

J Extended MILP model for the short-term

This appendix contains the MILP model from Appendix G extended with an additional decision variable RC_{mt} that indicates the remaining resource capacity in minutes that can be carried over from the previous day. We modified constraint (4.40) by adding the remaining capacity from the previous day to the available resource capacity on a day. In addition, we added constraints (4.41) and (4.42) to assign a value to the decision variable for each machine-day combination.

Set	**Description**
i	Product with i = 1,…, N
j	Product with j = 1,…, N
k	Product with k = 1,…, N
m	Machine with m = 1,…, V
t	Day with t = 1,…, T

Parameters	**Description**
N	Number of products
V	Number of machines
T	Number of days in the planning horizon
$IntI_j$	Initial inventory of product j in m/kg
$IntB_j$	Initial number of backorders of product j in m/kg
R_{mt}	Available resource capacity for machine m on day t in minutes
Pur_{jt}	Planned purchase quantity for product j to receive on day t in m/kg
d_{jt}	Expected demand for product j on day t in m/kg
C_{jm}	Unit production costs of product j on machine m in euros per m/kg
S_{jm}	Setup costs for product j on machine m in euros per setup
h_j	Unit holding costs of product j in euros per m/kg per day
$B1_j$	Shortage costs for backlogging one unit of product j in euros per m/kg per day
PT_{jm}	Unit production time for product j on machine m in minutes per m/kg
ST_{jm}	Setup time for product j on machine m in minutes per setup
M	Sufficiently large number
a_{jk}	Number of units of component j required to produce one unit of parent k
v_{jm}	$\begin{cases} 1, \text{if product } j \text{ can be assigned to machine } m \text{ for production} \\ 0, \text{otherwise} \end{cases}$
Min_j	Minimum production quantity of product j in m/kg
$Pack_j$	Fixed number of packaging units to produce of product j in m/kg
SS_j	Safety stock level of product j in m/kg
$B2_j$	Penalty costs for having one unit of product j below the safety stock level in euros per m/kg
Max_j	Maximum storage quantity of product j in m/kg
L_j	Supply lead time of product j in days
SF_{ij}	Fraction of the setup time of product j needed and setup costs of product j involved when switching over from product i to product j between 0 and 1
α_{jm}^0	Initial setup state of product j on machine m at the beginning of the planning horizon
$IntP_{jmt}$	Initial production quantity of product j on machine m on day t according to the orders currently in production.

Decision variables	**Description**
X_{jmt}	Number of units of product j produced on machine m on day t

I_{jt}^{+}	Inventory of product j at the end of day t
I_{jt}^{-}	Number of backorders of product j at the end of day t
Y_{ijmt}	$\begin{cases} 1, \text{if a setup is performed from product } i \text{ to product } j \text{ on machine } m \text{ on day } t \\ 0, \text{otherwise} \end{cases}$
n_{jmt}	Multiple of the minimum production quantity of product j produced on machine m on day t
o_{jm}	Multiple of the standard production quantity of product j produced on machine m over the entire planning horizon
SS_{jt}^{-}	Number of units of product j below the safety stock level at the end of day t
β_{jmt}	$\begin{cases} 1, \text{if the setup state for product } j \text{ on machine } m \text{ is carried over from day } t \text{ to } t+1 \\ 0, \text{otherwise} \end{cases}$
γ_{jmt}	Position of product j on machine m on day t
RC_{mt}	Remaining resource capacity in minutes on machine m that can be carried over from the previous day to day t

Objective function

$$\text{Min} \sum_{j=1}^{N}\sum_{m=1}^{V}\sum_{t=1}^{T} C_{jm}X_{jmt} + \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{m=1}^{V}\sum_{t=1}^{T} SF_{ij}S_{jm}Y_{ijmt} + \sum_{j=1}^{N}\sum_{t=1}^{T} h_j I_{jt}^{+} + \sum_{j=1}^{N}\sum_{t=1}^{T} B1_j I_{jt}^{-} + \sum_{j=1}^{N}\sum_{t=1}^{T} B2_j SS_{jt}^{-}$$

Subject to

$$\sum_{j=1}^{N} PT_{jm}\, X_{jmt} + \sum_{i=1}^{N}\sum_{j=1}^{N} SF_{ij}ST_{jm}Y_{ijmt} \leq R_{mt} + RC_{mt} \qquad \forall m \in V, \forall t \in T \qquad (4.40)$$

$$RC_{m1} = 0 \qquad \forall m \in V \qquad (4.41)$$

$$RC_{mt} = R_{m,t-1} + RC_{m,t-1} - \sum_{j=1}^{N} PT_{jm}\, X_{jm,t-1} - \sum_{i=1}^{N}\sum_{j=1}^{N} SF_{ij}ST_{jm}Y_{ijm,t-1} \quad \forall m \in V, t = 2,..T \qquad (4.42)$$

$$Pur_{j1} - \sum_{k=1}^{N}\sum_{m=1}^{V} a_{jk}X_{km1} + IntI_j - I_{j1}^{+} + I_{j1}^{-} - IntB_j = d_{j1} \qquad \forall j \in N \qquad (4.43)$$

$$Pur_{jt} + \sum_{m=1}^{V} X_{jmt-L_j} - \sum_{k=1}^{N}\sum_{m=1}^{V} a_{jk}X_{kmt} + I_{j,t-1}^{+} - I_{jt}^{+} + I_{jt}^{-} - I_{j,t-1}^{-} = d_{jt} \quad \forall j \in N, t = 2,..T \qquad (4.44)$$

$$X_{jm1} \leq M\left(\textstyle\sum_{i=1}^{N} Y_{ijm1} + \alpha_{jm}^{0}\right) \qquad \forall j \in N, \forall m \in V \qquad (4.45)$$

$$X_{jmt} \leq M\left(\textstyle\sum_{i=1}^{N} Y_{ijmt} + \beta_{jm,t-1}\right) \qquad \forall j \in N, \forall m \in V, t = 2,..T \qquad (4.46)$$

$$X_{jmt} = 0 \qquad \forall j \in N, \forall m \in V, \forall t \in T, v_{jm} = 0 \qquad (4.47)$$

$$X_{jmt} = n_{jmt}\, Min_j \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.48)$$

$$X_{jmt} \geq IntP_{jmt} \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.49)$$

$$\textstyle\sum_{t=1}^{T} X_{jmt} = o_{jm}Pack_j Min_j \qquad \forall j \in N, \forall m \in V \qquad (4.50)$$

$$I_{jt}^{+} + SS_{jt}^{-} \geq SS_j \qquad \forall j \in N, \forall t \in T \qquad (4.51)$$

$$I_{jt}^{+} \leq Max_j \qquad \forall j \in N, \forall t \in T \qquad (4.52)$$

$$I_{jt}^{-} = 0 \qquad \forall j \in N \text{ if } \textstyle\sum_{k=1}^{N} a_{jk} > 0, \forall t \in T \qquad (4.53)$$

$$\sum_{j=1}^{N} \beta_{jmt} = 1 \qquad \forall m \in V, \forall t \in T \qquad (4.54)$$

$$\alpha_{jm}^{0} + \sum_{i=1}^{N} Y_{ijm1} = \sum_{k=1}^{N} Y_{jkm1} + \beta_{jm1} \qquad \forall j \in N, \forall m \in V \qquad (4.55)$$

$$\sum_{i=1}^{N} Y_{ijmt} + \beta_{jm,t-1} = \sum_{k=1}^{N} Y_{jkmt} + \beta_{jmt} \qquad \forall j \in N, \forall m \in V, t = 2, ..T \qquad (4.56)$$

$$\gamma_{jmt} \geq \gamma_{imt} + 1 - N\,(1 - Y_{ijmt}) \qquad \forall i, j \in N, \forall m \in V, \forall t \in T \qquad (4.57)$$

$$X_{jmt} \geq 0 \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.58)$$

$$I_{jt}^{+} \geq 0 \qquad \forall j \in N, \forall t \in T \qquad (4.59)$$

$$I_{jt}^{-} \geq 0 \qquad \forall j \in N, \forall t \in T \qquad (4.60)$$

$$Y_{ijmt} \in \{0,1\} \qquad \forall i, j \in N, \forall m \in V, \forall t \in T \qquad (4.61)$$

$$n_{jmt} \; as\; integer \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.62)$$

$$SS_{jt}^{-} \geq 0 \qquad \forall j \in N, \forall t \in T \qquad (4.63)$$

$$\beta_{jmt} \in \{0,1\} \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.64)$$

$$\gamma_{jmt} \geq 0 \qquad \forall j \in N, \forall m \in V, \forall t \in T \qquad (4.65)$$

K Steps towards a feasible operational production schedule

This appendix explains the steps we have taken to obtain a feasible operational production schedule by allowing the model to carry over the remaining resource capacities to the next production day and by developing a backwards-oriented post-processing step to avoid exceeding the resource capacities.

Operational production schedule with unwanted model decisions

We ran the model for 1.5 hours based on the input data collected on July 25, 2022. Figure K.1 visualizes the operational production schedule obtained over the planning horizon of 10 days by means of a Gantt chart, where days 6 and 7 are empty because no production takes place during the weekends.

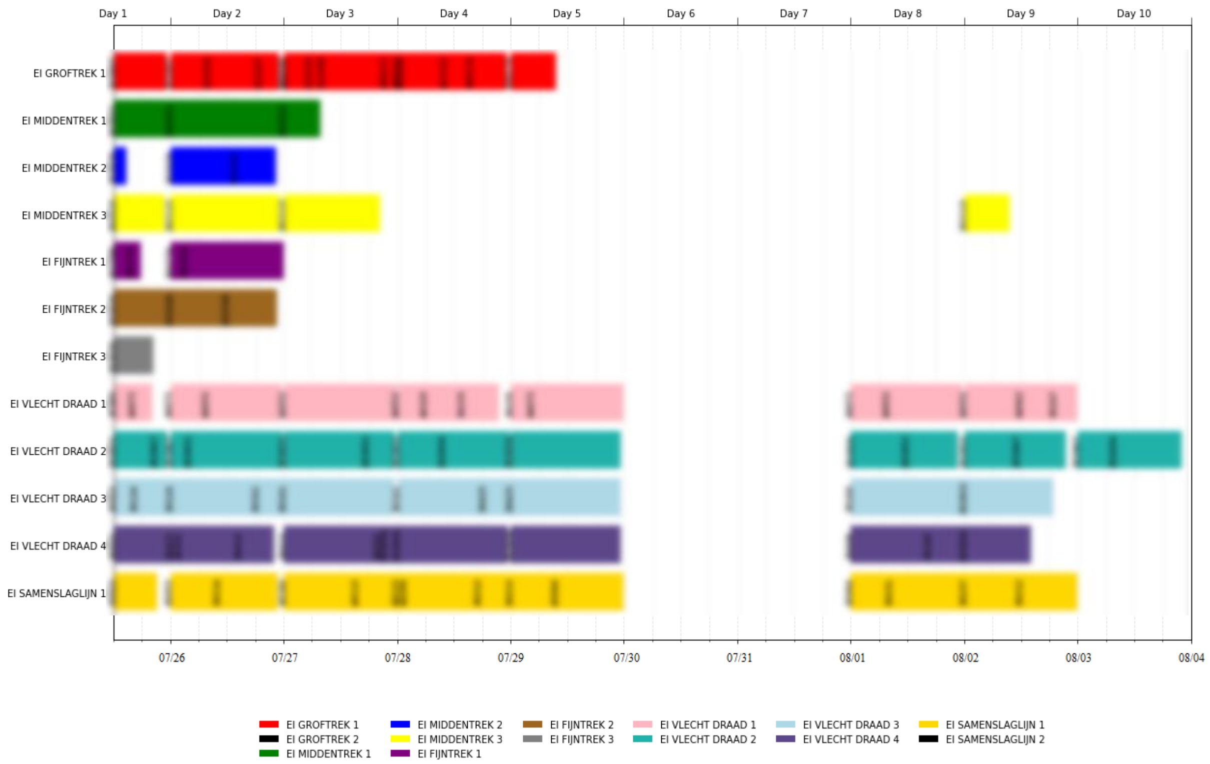

Figure K.1 - Gantt chart visualizing the operational production schedule.

One problem that arises in the Gantt chart provided in Section 6.2.1 is related to the fixed resource capacity for each machine on a day, along with the requirement to produce completely filled packaging units for MTS products. In Figure K.2, we focus on a part of the production schedule that belongs to Vlechtdraad 2 to explain the unwanted scheduling decisions made by the model. One parameter that is input to the model is the remaining production quantity of the production order that is currently in production on Vlechtdraad 2. In this problem instance, a total of 1750 kg still has to be produced of MTS product X on Vlechtdraad 2. In practice, this quantity is produced in one production run without producing other products in between. However, when taking into account the resource capacity per day and the restriction that we can only produce completely filled packaging units of 350 kg, the model plans 350 kg on day 1 and 700 kg on days 2 and 3. In addition, the model decides to use the remaining capacity on days 1 and 2 to switch over to product Y and to produce a certain amount of this product in between as indicated by the red circle in Figure K.2.

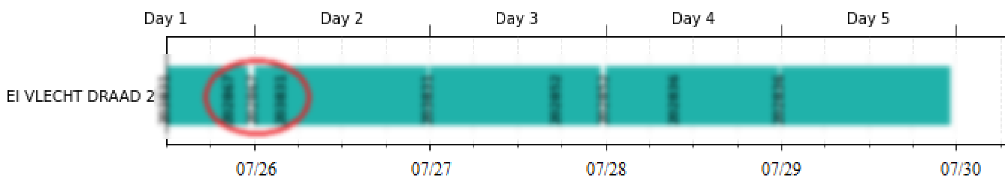

Figure K.2 - Unwanted model decision that occurs in the Gantt chart.

Carrying over remaining resource capacities

In order to solve the problem described in the previous section, we extended the MILP model in Appendix J with an additional decision variable RC_{mt} that indicates the remaining resource capacity in minutes on machine m that can be carried over from the previous day to day t. We modified constraint (4.1) by adding the remaining capacity from the previous day to the available resource capacity on a day. In addition, we added constraints (4.2) and (4.3) to assign a value to the decision variable for each machine-day combination. The remaining capacity is always based on the previous production day. Since there is currently no production on Saturday and Sunday, the remaining resource capacity on a Friday cannot be used on Saturday or Sunday but is instead carried over to the next Monday. Figure K.3 visualizes the operational production schedule obtained when allowing the model to carry over the remaining resource capacities to the next production day in the planning horizon.

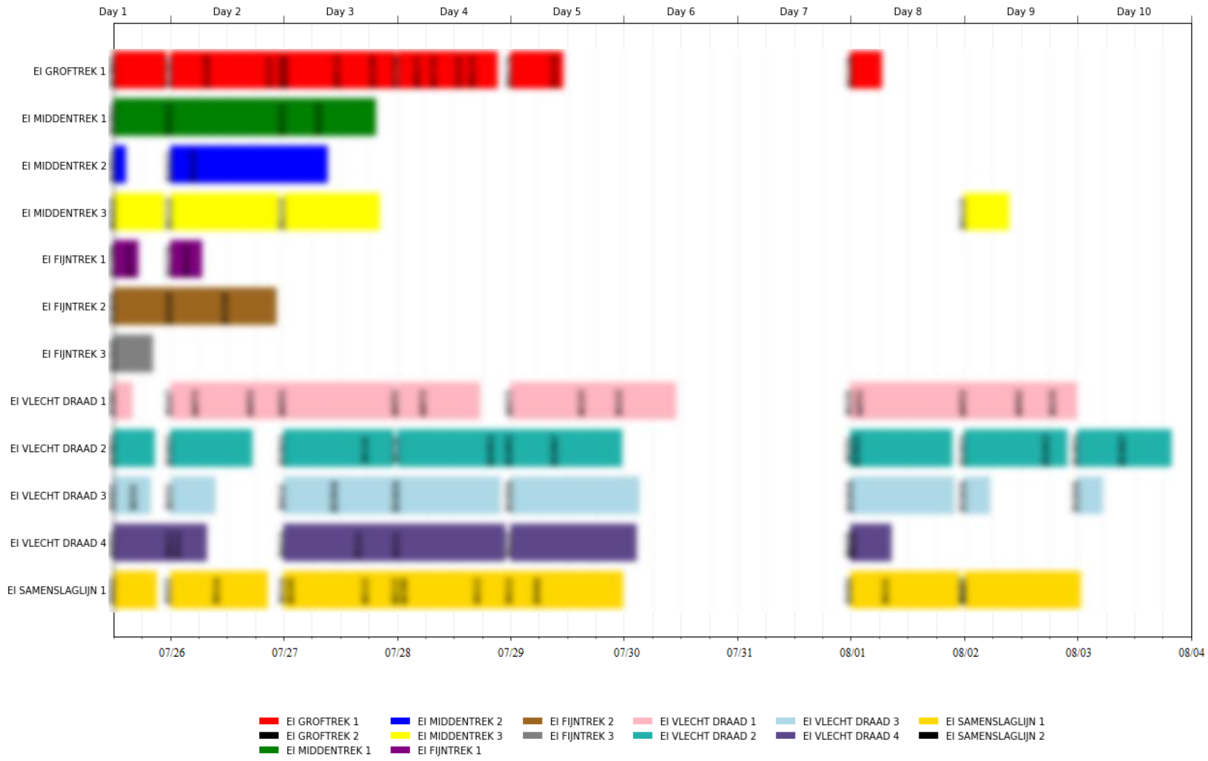

Figure K.3 - Gantt chart visualizing the operational production schedule when carrying over remaining resource capacities.

If we look at the part of the production schedule that belongs to Vlechtdraad 2, we see that the model no longer decides to switch over to another product during the production run of product X. Instead, the model decides to carry over the remaining resource capacity to the next production day and to switch over to another product after the production run is completed on day 3. This prevents a machine change over from product X to product Y and back again. However, this extension of the model leads to an infeasible production schedule. First, if the planning tool decides to move production to the beginning of the next day, part of the available resource capacity remains unused. In practice, the operator starts production on a day and continues production the next day without leaving the machine empty. Second, the available resource capacity is exceeded on some days, leading to overlapping bars in the Gantt chart. Logically, it is not possible to plan two different products at the same time and the same machine for production. This is not visible in Figure K.3, but becomes clear from the values of the decision variables. Third, production is planned during the weekends when no production can take place. To conclude, we need to find a solution that prevents exceedance of the resource capacities.

Backwards-oriented post-processing step

To avoid exceeding the resource capacities, we developed a backwards-oriented post-processing step that is performed after a solution is obtained when solving the model provided in Appendix J. The backwards-oriented post-processing step is based on the logic described in the flowchart in Figure K.4. The objective is to resolve the capacity exceedance for each machine and each day in the planning horizon by moving production orders backwards. We start by checking the production schedule of the first machine on the last day of the planning horizon. We check whether the sum of the expected production plus setup times exceeds the available resource capacity. If this is the case, we check if the expected production plus setup time of the first product that is planned is greater than the amount of time that exceeds the resource capacity. If so, we resolve the capacity exceedance by moving a part of the first production order that is equal to the amount of time that exceeds the resource capacity to the end of the previous day. On the other hand, it may be necessary to move the entire production order to the end of the previous day. If the resource capacity is still exceeded, we continue with the second production order that is planned and proceed until the capacity is no longer exceeded. After we have resolved the capacity exceedance for all machines on the last day of the planning horizon, we move backwards and continue with the previous day. We stop when we have resolved the capacity exceedance for all machines and all days in the planning horizon. The blue ovals in the flowchart indicate the start and end, the yellow diamonds indicate the decisions and the white squares indicate the activities.

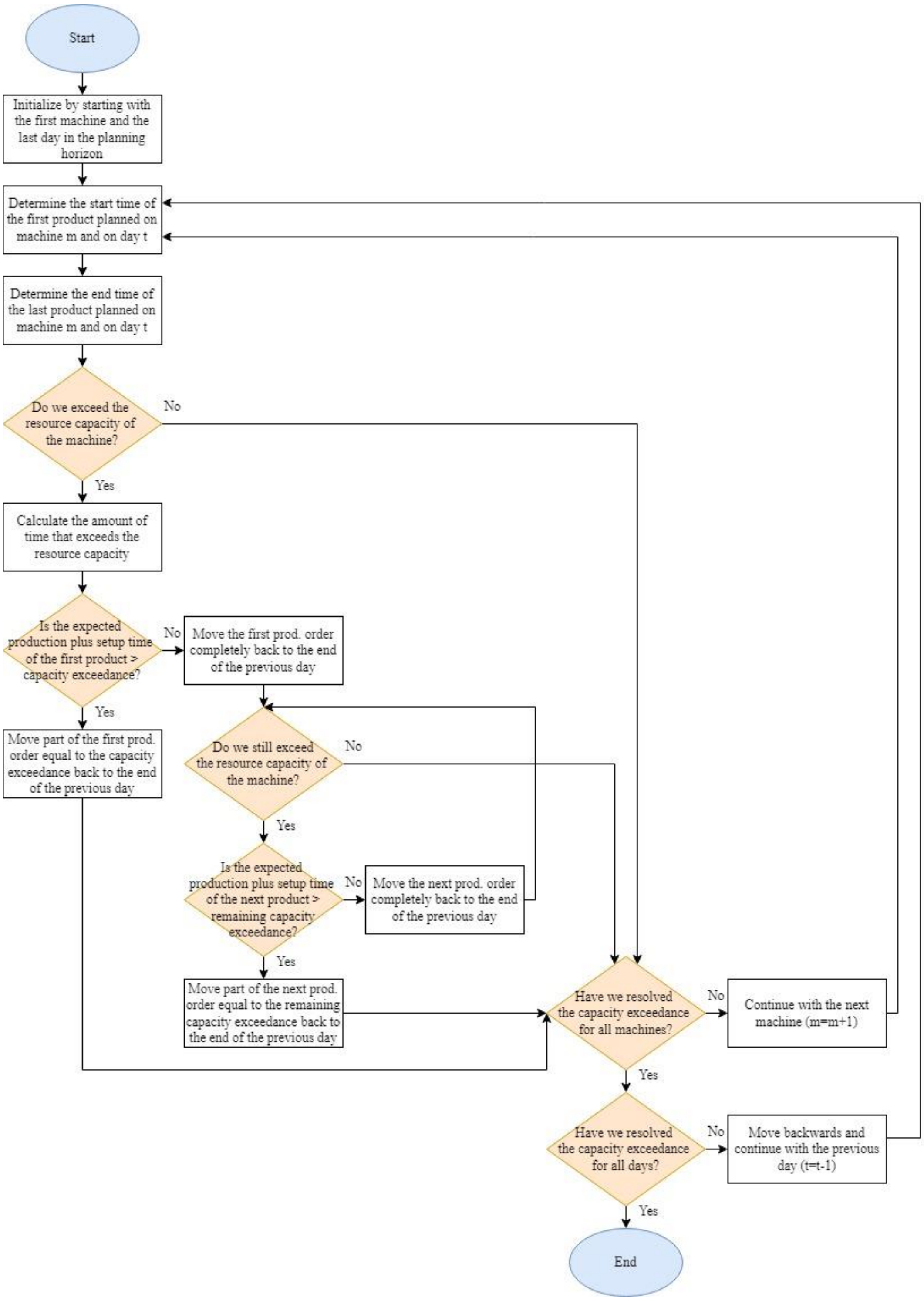

Figure K.4 - Flow chart describing the backwards-oriented post-processing step.

Figure K.5 visualizes the operational production schedule obtained over the planning horizon of 10 days by means of a Gantt chart after performing the backwards-oriented post-processing step. This additional step that is performed after a solution is obtained prevents exceedance of the resource capacities.

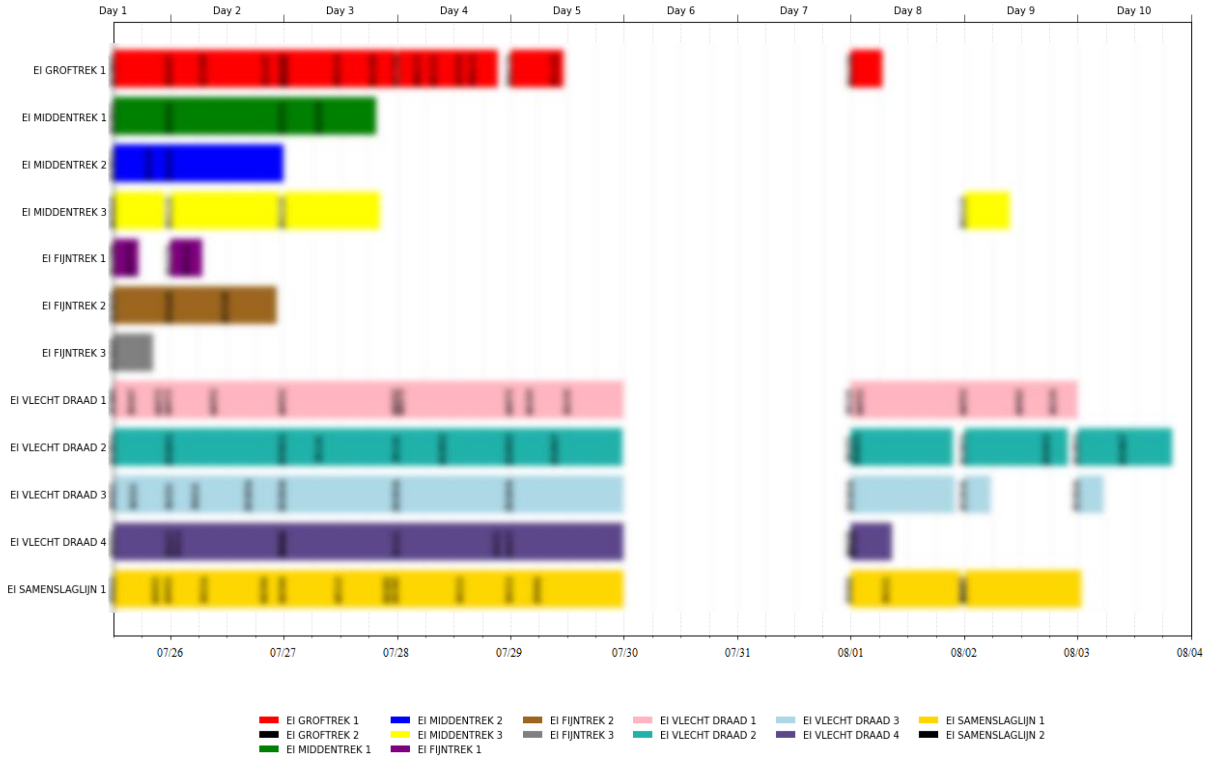

Figure K.5 - Gantt chart after performing the backwards-oriented post-processing step.

Now we obtain a feasible production schedule in which there are no overlapping bars in the Gantt chart and there is no production planned during the weekends. In addition, the unwanted scheduling decision made by the model has been resolved. The production quantity that still has to be produced of MTS product X on Vlechtdraad 2 is now planned for production in one production run without producing other products in between, as shown in Figure K.5.

L Model results for comparison with current situation

This appendix has been removed from the public version for confidentiality reasons.

M Model results for comparison between both planning levels

This appendix has been removed from the public version for confidentiality reasons.