BACHELOR THESIS

Improving production planning for a food processing company

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University of Twente
06-10-2020

UNIVERSITY OF TWENTE.

Improving production planning for a food processing company

Bachelor Thesis Industrial Engineering and Management

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Company X

Supply Chain Manager Company X

Publication Date: 6 October 2020
Number of pages excluding appendices: 66
Number of pages including appendices: 79
Number of pages appendices: 13

This report was written as part of the bachelor thesis of the Industrial Engineering and Management educational program at the University of Twente.

Preface

Dear reader,

I present you my bachelor thesis "*Improving production planning for a food processing company*". This bachelor thesis is written to complete my bachelor programme Industrial Engineering and Management at the University of Twente. This thesis focus on improving production planning in a large producer of plant-based meat alternatives.

First of all, I would like to thank my colleagues of Company X for their interest and their support during my time at the company. Also, I want to thank my colleagues in the supply chain department. Even in the strange times of the Covid-19 period they made me part of the team and showed their support. Also, the team always made time available for helping me in finding the necessary information. Especially, I would thank my supervisor. During the discussions we had, he helped me to stay open-minded, giving me helpful insights, and looking for opportunities for improving my thesis.

Moreover, I would like to thank Marco Schutten for his guidance. During the contact moments, he provided me with new and helpful insights for improving my thesis. I also want to mention that it was pleasant that he provided feedback in a relatively short time.

Finally, I would like to thank my family for their support and interest. They made working at home more pleasant.

Enjoy reading my bachelor thesis!

Jörn Harbers

Holten, October 2020

Management summary

Problem description

Company X is a large producer of plant-based meat alternatives. The production of the plant-based meat alternatives is divided into two-stages, also called a two-stage production system. In the first stage of a two-stage production system, semi-finished products are produced on one of the four production lines, namely production line 11, 21, 31, and the production line at Company Z. The second stage consists of packaging the semi-finished product. This stage creates a finished product. Between the two stages, there is an intermediate warehouse for storing the semi-finished products. Currently, the supply chain has difficulties with production planning of semi-finished products.

After an analysis of the current performance of production planning for semi-finished products we find the following core problem: "*Production planning takes too much time*". At the moment, production planning of semi-finished takes 38 hours. The goal is to reduce the time for production planning of semi-finished products with 50% to 19 hours per week.

Make-to-order and make-to-stock

We perform a demand and variability analysis to distinguish make-to-order and make-to-stock semi-finished products. The idea behind this analysis is that we do not include make-to-order products in our solution for production planning. From a total of 58 semi-finished products, we exclude 19 semi-finished products. We exclude these products in the solution design because of the characteristics for make-to-order, for example, low demand and high variability in demand. The remaining 39 semi-finished products are assigned to a preferred production line. The preference is based on efficiency or technical reasons. We go not in further detail for make-to-order products. The make-to-order products are produced with the remaining processing capacity after producing make-to-stock products.

Fundamental cycle period

We describe a procedure for creating a cyclic production plan with a maximum inventory duration. This procedure is based on the methods described by Soman et al. (2004) and Doll and Whybark (1973). A cyclic production plan in a two-stage production system has the advantage that it will periodically supply semi-finished products to the packaging stage. This reduces the capacity in the intermediate warehouse. Also, the quantities, production frequencies, processing times, and cycle length are already given.

This procedure calculates the fundamental cycle period, also called the length of a single cycle, for every production line. We assign a maximum inventory duration to semi-finished products and this procedure makes sure that this duration is not violated. We also have the production frequencies of the semi-finished products. The production frequencies tell us how many times we need to produce a semi-finished product. With the least common multiple of the production frequencies and the fundamental cycle period we can calculate the total cycle length. For the four production lines we have the following results:

	Production line 11	**Production line 21**	**Production line 31**	**Production line Company Z**
#Products	16	13	7	3
Fundamental cycle period (length single cycle) in weeks	0.6460	0.4997	0.6786	0.5482

Fundamental cycle period (length single cycle) in days (5 production days per week)	3.23	2.5	3.39	2.71
Least common multiple of the production frequencies	8	8	4	4
Total cycle length in weeks	5.17	4.00	2.71	2.19
Holding cost for the total cycle length	€ 1,266.28	€ 1,062.51	€ 643.89	€ 316.82
Setup cost for the total cycle length	€ 1,266.28	€ 1,062.51	€ 643.89	€ 316.82
Total cost for the total cycle length	€ 2,532.55	€ 2,125.02	€ 1,287.78	€ 633.63

Sequence-dependent scheduling
We use a heuristic described by Gupta and Magnusson (2008) for scheduling the semi-finished products on the production lines. We use the fundamental cycle period and the production frequencies of the procedure of the fundamental cycle period as input for the scheduling heuristic. The heuristic consists of three steps, namely: Initialize, Sequence, and Improve (ISI). In the initialize step we assign the semi-finished products to a cycle based on the production frequencies. During the assignment, we look at the available processing hours per cycle. After the initialize step we sequence the semi-finished products. For sequencing, we look at the allergens of the semi-finished products. Each product has a specific allergen code. We need to produce the semi-finished products in a specific order of allergen. When we switch to an allergen code that is not in this order then we have a setup time of 5 to 6 hours for cleaning the production line. After executing the ISI heuristic with the fundamental cycle period and the production frequencies we have the following results:

	Production line 11	**Production line 21**	**Production line 31**	**Production line Company Z**
#Products	16	13	7	3
Total cycle length in days	24	16	12	12
Total number of required cleanings over the total cycle length	16	0	0	4
Total available time	384	256	192	192
Total processing time with cleaning time	461.79	197.22	91.61	67.28
Total remaining processing time	-23.08	58.78	100.39	124.72

For production line 11 we need overtime because of the negative total remaining processing time. However, overtime violates the cycle planning. Therefore, we apply the improvement step of the heuristic. We look for improvements so that we have sufficient processing time available. We reduce the production frequencies of the semi-finished products. This reduces the number of setups. When we change the production frequencies we also need to apply the procedure that calculates the fundamental cycle period and the scheduling heuristic again. We find a solution with a feasible schedule after changing some production frequencies of the semi-finished products. Improved results of the scheduling heuristic are provided below. The number of required cleanings is reduced and therefore also the total processing time.

	Production line 11	Production line 21	Production line 31	Production line Company Z
#Products	16	13	7	3
Fundamental cycle period (length single cycle) in weeks	0.5882	0.4997	0.6786	0.5482
Total cycle length in days	24	16	12	12
Total number of required cleanings over the total cycle length	14	0	0	4
Total available time in hours	384	256	192	192
Total processing time with cleaning time in hours	377.90	197.22	91.61	67.28
Total remaining processing time in hours	6.10	58.78	100.39	124.72

Validation of the results
The result of the fundamental cycle period is not practical because it will give cycles that start and end in the middle of the day. We have changed some production frequencies for eliminating overtime in the schedule. Changing the production frequencies also influences the results of the procedure of the fundamental cycle period. Based on a 5 day production week the fundamental cycle period in days is 2.94, 2.5, 3.39, and 2.74 for production lines 11, 21, 31, and Company Z respectively. To make the results more practical we recalculate the procedure of the fundamental cycle period with periods of a full day production day. A summary of the key results:

	Production line 11	Production line 21	Production line 31	Production line Company Z
Fundamental cycle period (length single cycle) in weeks	0.6000	0.6000	0.8000	0.6000
Fundamental cycle period (length single cycle) in days	3	3	4	3
Least common multiple of the production frequencies	8	8	4	4
Total cycle length in weeks	4.80	4.80	3.20	2.40
Total cost for the total cycle length	€ 2,527.66	€ 2,135.15	€ 1,305.27	€ 636.22

From the procedure, we can also calculate the processing times and the longest duration a semi-finished product is in inventory. The processing times are the number of hours we need to produce a semi-finished product in a given cycle. When we compare these results with the current situation than we can conclude that the average processing time reduces drastically with ± 55% for production lines 11, 21, and 31. For Company Z the average processing time reduces by 24%. The average longest duration in inventory will slightly increase for production lines 11 and 21. For production line 31 and Company Z the longest duration in inventory reduces with 33%, and 36% respectively.

We evaluated the solution design with the stakeholders of Company X. The cyclic planning has several advantages that reduce the time for production planning. Also, it takes the maximum inventory duration into account. Next to this, the solution design also provides a feasible schedule. The production planner only needs to control and improve the cycle planning and the schedule. This reduces the time that is needed for production planning. The stakeholder of Company X foresees significantly reduction for the time that is needed for production planning. Unfortunately, due to the available time for this research we cannot calculate the real decrease in time.

Conclusion and recommendations

A cyclic production plan is a solution for reducing the time that is needed for production planning. We recommend doing a demand and variability analysis every quarter. This gives more insight into the demand variability of the semi-finished products and helps in the classification the semi-finished products in make-to-order or make-to-stock. Furthermore, we also recommended reviewing the production plan and the outcome of the calculation of the fundamental cycle period after every total cycle.

The schedule heuristic that we provide is relatively easy to understand and to implement. It gives a good starting point in the scheduling of the semi-finished products. We recommend to review and improve the schedule. For the production planner this is a continues process.

Table of Contents

List of Abbreviations

Abbreviation	Full description
BPMN	Business Process Model and Notation
CLSP	Capacitated Lot-Sizing Scheduling Problem
CODP	Customer Order Decoupling Point
ERP	Enterprise Resource Planning
FTE	Full-time Equivalents
HPP	Hierarchical Production Planning
IOQ	Incremental Order Quantity
ISI	Initialize, Sequence, Improve
KPI	Key Performance Indicator
LCM	Least Common Multiple
MOQ	Minimum Order Quantity
MTO	Make-To-Order
MTS	Make-To-Stock
SKU	Stock Keeping Unit

1 Introduction

This chapter gives an introduction to the research. Section 1.1 describes the background information of Company X. Next, Section 1.2 explains the research motivation. Furthermore, Section 1.3 gives the problem identification. From the problem identification, Section 1.4 describes the research questions.

1.1 Company X

Company X is a large producer of plant-based meat alternatives. The products of Company X can be found in retailers across Europe under the label of Company X or private labels.

Company X was founded in 1990 by Z Food Group, which consisted of Company Z. Company Z was a large meat processing company. In 2019, Company Z was sold and the name changed to Company X Food Group, which consists nowadays of the companies Company X, Company Y, and Company DTC. Company X chose a new strategy and therefore they sold Company Z. They want to focus completely on the fast-growing demand in plant-based meat alternatives.

In the last three years, Company X had an average annual growth of 25%, resulting in €80 million expected revenue in 2020. Company X has an average weekly production of 1.5 million plant-based products, which is around 300 tons in weight. Within five years they expect to achieve a revenue of €250 million, which is a growth of more than 200%. This fast-growing pace brings challenges to the company and especially to the supply chain of Company X.

1.2 Research Motivation

The supply chain manager of Company X is facing difficulties with the production planning of the semi-finished products. To explain the production planning of semi-finished products we explain the production process at Company X. Figure 1 gives a simple illustration of the overall two-stage production process at Company X. The raw materials are processed into semi-finished and stored in a large warehouse at a temperature of -18 °C, which is an intermediate storage. After that, the semi-finished products go to the packaging department where the products are packed into a finished product. The finished product is stored in the warehouse with a temperature of 3 °C.

The processing department of Company X makes 57 semi-finished products which are packed into around 200 finished products by the packaging department. So the semi-finished products are used as input for multiple finished products.

This research focuses on production planning in the food processing stage. The stage is coloured in yellow in Figure 1.

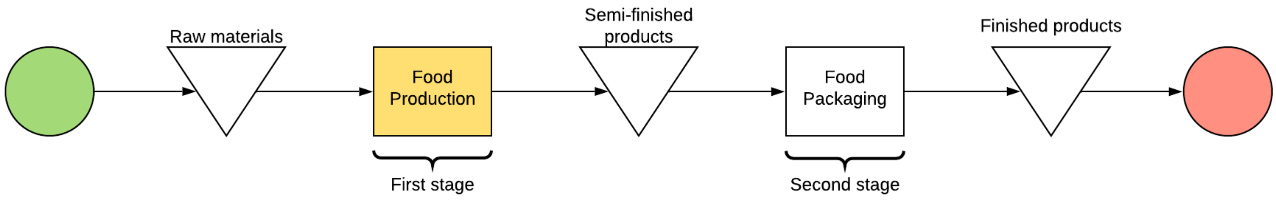

Figure 1: Two-stage production system

Last year, Company X implemented a new scheduling system together with a new production planning system, which includes demand forecasting, and inventory optimization. They expected to create an easier and more efficient production planning process with a more robust production plan. However, after the implementation of the new systems, still, some difficulties occur and the result is not as expected.

The supply chain manager sees the following concrete problems that happen in the supply chain:

1. Production planning takes too much time.
2. The frozen period[1] in production plan is violated.
3. Inventory of the semi-finished products is too high or too low.
4. The inventory of the raw materials is too high or too low.
5. There are extra deliveries from suppliers which result in high cost.

Due to these problems, the supply chain manager is not satisfied with the current performance of production planning. So we can state that Company X does not achieve the current performance of the production plan.

We explain the performance of the production planning of Company X in two different categories namely, performance regarding the product and performance regarding the process. We explain the two categories below.

Product*:*

- **The cost of the production plan execution**: These costs are linked to materials, machines, and staff. Also, costs due to backorders are part of this.
- **Resource utilization:** The supply chain department needs to take into account the utilization. For example machine utilization.
- **Stability of the production plan:** Stability is the degree to which the production plan is robust. In other words, the production plan should be changed as little as possible.

Process:

- **Cost of production planning:** These costs are linked to the number of hours a production planner needs to make and maintain a production plan.
- **Communication quality:** This is the way the production planner communicates changes to its stakeholders.
- **The flexibility of production plan adjustment:** The production plan should be able to change to a certain extend.

These performance criteria can be linked back to the events that are currently happening in the supply chain. For example, for resource utilization, we have machine utilization. Company X wants to have sufficient utilization of the machines. Not achieving the desired performance causes disturbances and uncertainties in the whole supply chain, from supplier to finished product.

Before we go to the problem identification, which we explain in Section 1.3, we give three definitions namely, production planning, production scheduling, and production planning and control. This helps to have a better understanding of the definitions that are widely used in this research. The paragraphs below explain the distinction between the meanings.

Production planning*:* production planning is an administrative process that takes place within a manufacturing company. The goal of production planning is to establish an overall level of output, which is called a production plan. To establish the production plan, production planning needs to take into account the planned sales levels and also the company's general objectives. General objectives are, for example, profit, productivity, lead times, and customer satisfaction. (Encyclopedia.com, 2020)

[1] The frozen period is the period in which changes in the production plan should not occur.

Production scheduling: production scheduling is a process to create a production schedule. The production schedule is derived from the production plan. Production scheduling is an assignment problem that describes what quantity of an item that the company wants to produce in a certain time frame. Also, scheduling is the problem of allocating machines to competing jobs over time, subject to the constraints (Fera, Fruggiero, Lambiase, Giada, & Nenni, 2013). A constraint is, for example, the total available machine time.

Production planning and control: According to Slack et al. (2013) production planning and control is about the activities that attempt to merge the demands of the market and the ability of the operation's resources to deliver. Production planning and control provide the systems, procedures, and decisions to merge the different aspects of supply and demand.

1.3 Problem Identification

This section identifies the problem the help of a problem cluster. Section 1.3.1 describes the problem cluster. From the problem cluster, Section 1.3.2 describes the core problem. Section 1.3.3 measures the core problem and compares it to the current situation. Next, Section 1.3.4. describes the research scope of this research.

1.3.1 Problem Cluster

Together with the Supply Chain Manager and the production planner, we investigate the relationships between the current problems to find a potential core problem. We make a problem cluster to create a clear overview of the problems. Figure 2 shows the problem cluster.

Next, we explain the problem cluster in more detail.

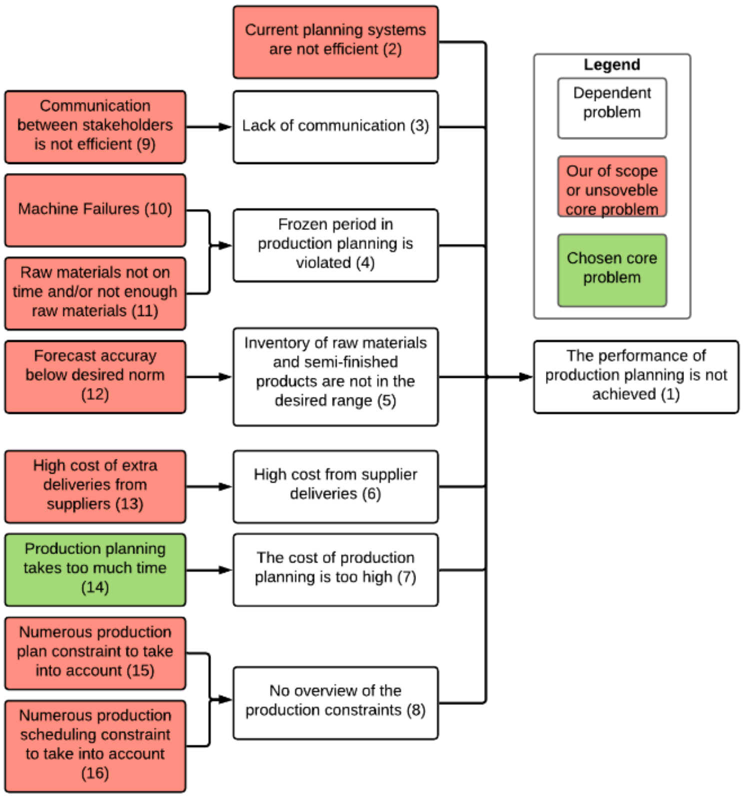

Figure 2: Problem Cluster

1.3.1.1 Current planning systems are not efficient

The current production planning and scheduling systems are not efficient. The production planning system gives a proposal for the quantities that need to be produced based on a forecast and input parameters from the production planner or the demand planner. Some input parameters, for example, the Minimum Order Quantity (MOQ), are not optimal. The MOQ is the minimum quantity that needs to be ordered or in case of production planning the minimum quantity that needs to be produced. For the processing in the first stage is the MOQ a half-day or a full-day production. A full day means 16 hours of production on weekdays.

Next to the planning system, the scheduling system is also not efficient. Making changes in the scheduling system takes a long time due to many calculations that need to be done by hand.

1.3.1.2 Communication between stakeholders is not efficient

With the term communication, we mean the way production plans are communicated to other stakeholders. The stakeholders are, for example, the supply chain manager, processing manager, team leader processing, operators, and supply planning. The production planner must communicate with each stakeholder in case of new product plans or changes in the production plans. At the moment, it is not always clear to what extent new production plans and changes are communicated with different stakeholders. This leads to information asymmetry and causes disruptions.

1.3.1.3 Machine failures

For the frozen period, Company X has the following definition: *The frozen period is the period in which changes in the production plan should not occur*. The reality is that changes occur in the frozen period. One of the changes is due to machine failures. Machine failures occur randomly and when it is not possible to fix the problem in a short time, the production planner needs to change the production plan.

1.3.1.4 Disturbances due to raw materials shortages

Violation of the frozen period is due to shortages of raw materials. This happens when the raw materials are not in time for production from an external warehouse or there are not sufficient raw materials available. Almost all of the raw materials are stored at an external warehouse which is 45 minutes' drive from Company X. When there is too much time loss due to the raw materials there is a chance that the production plan needs to change.

To decrease the downtime Company X has stored internal some "emergency" raw materials for a few products. However, the production planner first needs to change the production plan to produce these products. Also, future production plan needs to revise.

1.3.1.5 Forecast accuracy below the desired norm

Company X is using a program that calculates the forecast for all stock keeping units (SKUs). However, demand has high uncertainty and it appears that the forecast accuracy is below the norm of 70% accuracy.

1.3.1.6 The high cost of extra deliveries from suppliers

The current production planning leads to additional costs. Company X needs additional deliveries from suppliers to sustain their plan because of the multiple consequences of the low performance of the production plan. However, this leads to a higher cost because these orders are not regular orders but extra orders. For extra orders, the suppliers charge additional costs.

1.3.1.7 The production planning takes too much time

The current time that a production planner needs for the process is too long. Some of the tasks in this process are: making a production plan and schedule for the coming weeks, control the production plan and changing the production plan if needed. Due to the overall low performance of the production planning process, the production planner spends a lot of his time on the process of planning. This time is at the expense of other tasks. Other tasks are, for example, improvement projects to be more in control in the production plan and schedule.

1.3.1.8 Production plan constraints

To make a production plan, constraints are taken into account. Production plan constraints are, for example, the available time for processing.

1.3.1.9 Scheduling constraints

The production planner has scheduling constraints. It is not possible to produce some products directly after each other because of the allergen of the semi-finished products. Every product has an allergen classification that is taken into account when scheduling. Also, the number of available machines is a constraint. Each product is made on a special kind of machine and there are not always enough machines available.

1.3.2 The core problem

From this selection, we choose problem number 14 "*The production planning takes too much time"* as the core problem. This problem is for the supply chain department the most important. The expectation of the supply chain department is when the time of the production planning process reduces, the production planner is more in control of the production plan and have time for other tasks such as improvement projects. This can eventually lead to a higher overall performance of production planning because other problems can be tackled, such as problems that are mentioned in the problem cluster.

1.3.3 Measurement of norm and reality

To have a clear overview of the core problem, we measure the norm and reality. Most of the problems are linked to a key performance indicator (KPI). Company X keeps already track of different KPI to evaluate the efficiency in the supply chain. However, these measurements do not measure the core problem itself. To measure the core problem we need to define the cost of time. We do this by measuring the number of full-time equivalents, also known as FTEs. FTE refers to the number of hours worked by a single employee in a week. At Company X a workweek of a full-time employee consists of a working week of 38 hours. So 1 FTE is 38 hours. The production planner executes production planning and scheduling. Currently, to make and schedule a production plan and to maintain the plan takes a certain time. The following norm and reality are established:

Norm: 0,5 FTE (19 hours)

Reality: 1 FTE (38 hours)

This means that the time to make, schedule, and maintain a production plan needs to decrease by 50%. With this reduction in time, the production planner has more time for other tasks, such as improvement projects. Next to this, it is possible for the production planner to be in control of the production plan and can oversee potential problems earlier. This will also increase other performances in the supply chain.

1.3.4 Research scope

This research is restricted to the production planning of semi-finished products, which is the first stage in the overall production system. The first stage consists of 4 production lines namely production line 11, 21, 31, and production line at Company Z. Company X has a two-stage production system and therefore production planning in the first stage depends on the second stage and the other way around. However, we do not cover the second stage, product packaging, because of the different characteristics, the complexity of the two-stage production system, and the time limitations for this research. The second stage, product packaging, is closely related to the first stage. We use the second stage for retrieving data but we will not explain this extensively. Also, the interaction between the first stage and the second stage is important for improving production planning. We will look for opportunities to improve the interaction between the two stages, however, we primarily focus on the first stage.

1.4 Research questions

Section 1.3 explains the core problem. To execute the research, we formulate several research questions. First, we describe an analysis of the current situation at Company X regarding production planning. Second, we conduct a literature review to find literature for improving production planning. Third, we formulate a solution design for improving production planning at Company X. We implement this solution design at the Company X case. Last, we provide a conclusion, give recommendations and explain possibilities for further research.

1.4.1 What is the current situation at Company X regarding production planning?

To find the causes of the core problem we will look at the current situation. First, we look at the current supply chain of Company X and how production planning is integrated into the supply chain. After this, we analyse the process of production planning. Lastly, we analyse the relationship between key performance indicators and the production plan. At the moment, there is no clear insight into what extent KPIs are related to the production plan and how the KPIs influence the decision-making for the production plan. We have the following sub-questions:

1. What is the supply chain design of Company X?
2. How does the first-stage production process of Company X look like?
3. What steps are currently taken by the production planner to make a production plan and schedule?
4. What is the relationship between the current production plan and the KPIs of the supply chain department?

1.4.2 What literature is available to improve production planning?

To formulate solutions, we conduct a literature review. Chapter 3 describes the literature review.

We want to create a robust production plan. With a robust production plan, we mean that the production plan is capable of performing without failure under a wide range of conditions (Merriam-Webster, sd). First, we look at production planning in a two-stage production system. We choose to look at a two-stage system instead of a single-stage system because we want to know the interaction between these stages. Input in the first-stage depends on the information of the second-stage.

Next, we look at the consideration of make-to-order and make-to-stock in the food processing industry. In the food processing industry, we deal with high market standards, such as high delivery performance, and shelf life constraints. Therefore, we want to find the impact of these considerations on production and production planning.

Next to the production plan, we want to find a feasible schedule in a sequence-dependent setup environment. Lastly, we want to measure production planning. Therefore, we look for performance measurements in production planning.

5. How to develop a robust production plan in a two-stage production system?
6. How can we incorporate make-to-order and make-to-stock decisions in production planning?
7. How to create a production schedule with sequence-dependent setups?
8. How can the performance of the production planning be measured?

1.4.3 How can we improve production planning based on the literature?

In Chapter 4 we present a solution to improve production planning at Company X based on the literature that we explain in Chapter 3.

1.4.4 How can we implement the solution design for the Company X case?

In Chapter 5 we implement the solution design of Chapter 4 for the Company X case. We formulate a work way to implement the solution design for Company X. We also look at the data availability for the solution design.

1.4.5 What are the conclusion and recommendations of this research?

Based on the solution that we present in Chapter 4 and Chapter 5 we will formulate the conclusions and the recommendations of this research.

2 Analysis of the current situation

This chapter describes the analysis of the current situation based on the research questions that are formulated in Section 1.4. The chapter starts with describing the current supply chain design of Company X in Section 2.1. After this description, Section 0 describes the production process in the first stage to give more context to production planning. Section 2.3 explains the current systems that the supply chain department uses. Next, Section 2.4 describes the current process of production planning. Section 2.5 explains the current KPIs and performs an analysis based on the data of the current situation. Last, Section 2.6 provides a conclusion.

2.1 Supply chain design of Company X

In this section, we analyse the supply chain design of Company X. We explain the relationships between the activities and the processes. Next, we explain the use of the current systems in the supply chain department. When describing the systems we focus on systems for production planning.

2.1.1 Supply chain footprint

A supply chain footprint refers to the positioning of operation activities in terms of the value chain. The supply chain footprint identifies different operational activities and relationships. Company X Foodgroup consists of multiple companies that produce products for Company X. The importance of this footprint is to find the scope of production planning at Company X.

Before positioning of the operational activities in the supply chain, we explain the corporate structure of Company X Foodgroup. As mentioned in Section 1.1, Company X Foodgroup consists of Company X, Company Y, and Company DTC. Company Z was also part of Company X Foodgroup but was sold in 2019. However, the name of Company Z is still being used because production facilities of Company Z are used for operations of Company X.

Section 1.2 illustrates a simple two-stage production system. However, this illustration does not give a complete overview of Company X. To make this overview complete we need to elaborate on Company Y, Company DTC, and Company Z. Company Y, Company DTC, and Company Z can be seen as an intercompany. They produce products that are sold through the parent Company X. Most of the products that they produce are semi-finished products (first-stage) and are transformed to finished products by Company X (second-stage). Company DTC and Company Y make semi-finished products that cannot be made by the processing department of Company X. These companies operate mostly individually and deliver products to Company X.

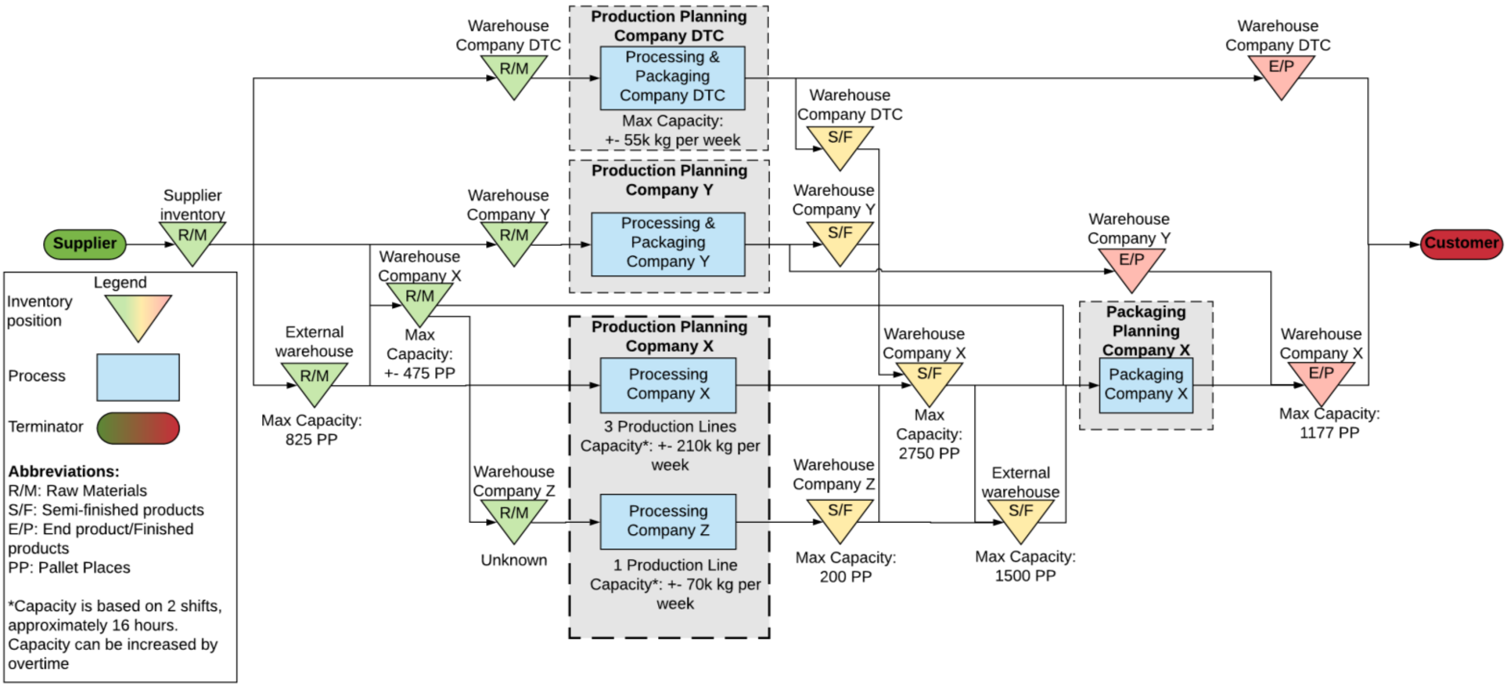

Figure 3: Supply chain footprint of Company X

Now we made the distinction between the different companies it is possible to position the processes in the value chain together with inventory holding points. Figure 3 illustrates the supply chain footprint of Company X. This supply chain footprint identifies the locations of the processes and the warehouses. The supply chain starts with the supplier. The supplier delivers raw materials to one of the warehouses for raw materials. When the raw materials are needed according to the production plan, the raw materials are transported to the different processing departments. The processing departments make a semi-finished product. This semi-finished product is stored at an intermediate warehouse. After this, the semi-finished products continue to the packaging process. The semi-finished products are transformed into finished products. The finished products are stored in a warehouse before they are sent to the customers.

Now the processes and inventories are positioned in the value chain, we determine the scope of production planning at Company X. Company Y and Company DTC have their production planning, but this is done in close cooperation with the supply chain department of Company X. Production planning of Company X deals with the production processes of Company X and Company Z. The production planner determines the production plans of Company X based on the forecast and available and desired capacities on production lines and inventory levels. Figure 3 also gives the maximum capacity.

2.2 The production process semi-finished products at Company X

To increase the understanding of production planning for semi-finished products, we explain the production process at Company X. Section 2.2.1 provides an overview of the production process at Company X. Section 2.2.2 explains the process specifications. Next, Section 2.2.3 illustrates the process layout.

2.2.1 Overview of the production process

At the facility of Company X, there are 3 production lines and there is 1 production line at Company Z. All four production lines are almost identical. The production lines differ in some machines and layout of processes but it always starts with mixing raw materials and a forming machine. The process ends with freezing and bulk packaging. Some products do not require coating or frying but do require cooking.

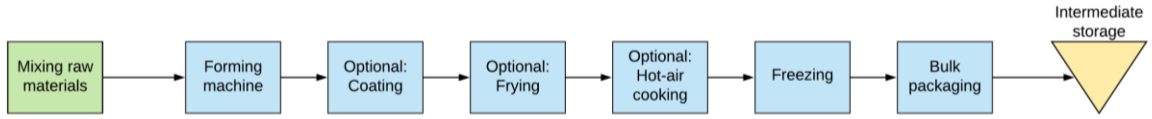

Figure 4: Simple overview of the production process at Company X

Figure 4 illustrates the process steps at Company X. First, the raw materials are mixed. The main component in semi-finished products is soybeans. The output after mixing is called dough. When mixing is complete, the dough is transported to a forming machine. This machine makes a certain form. For example, plant-based hamburgers have a circular form. Next, the product is coated, fried and/or cooked according to the product recipe. The last step in production is freezing, which cools down the product to -18°C.

The final step is to pack the products in crates and pack the crates on a pallet. Finally, the pallets are stored at the intermediate storage before the packaging department uses the products. The transfer of semi-finished products to the packaging department has a lead time of at least 3 days. This is because the products undergo a laboratory test. This laboratory test is for a check on any hazardous bacteria. When a semi-finished product has a positive release it is available for the packaging department.

2.2.2 Process specifications

The semi-finished products are produced in batches sizes that contain a half-day or a full-day production. A full-day production gives around 15,000 kg of semi-finished products depending on the product specifications. These batch sizes are relatively large because of the cleaning time between production. Semi-finished products are produced according to an allergen scheme. We illustrate the allergen scheme in Appendix A: Allergen flow scheme. Switching to a different semi-finished product that is not part of the allergen flow scheme requires cleaning. Cleaning the production line and the processing department takes around 5 to 6 hours and this is taking place every night after two production shifts.

2.2.3 Production process layout

Most of the semi-finished products have a preferred production line and some have a fixed production line. Most of the time the products are scheduled on the preferred line. This preference is because of efficiency reasons. For example, semi-finished products produced on a particular line have less waste in comparison with other production lines due to newer machines. Products with a fixed production line are produced on this line because of technical reasons. Figure 5 illustrates the layout of the processing department. Between the different machines in the production line, there are curved arrows. These arrows represent the belts between the machines. For example, on production line 31 there is a curved flow line between the frying and cooking. Some products cannot make this curve and therefore it is not possible to produce this product on the production line.

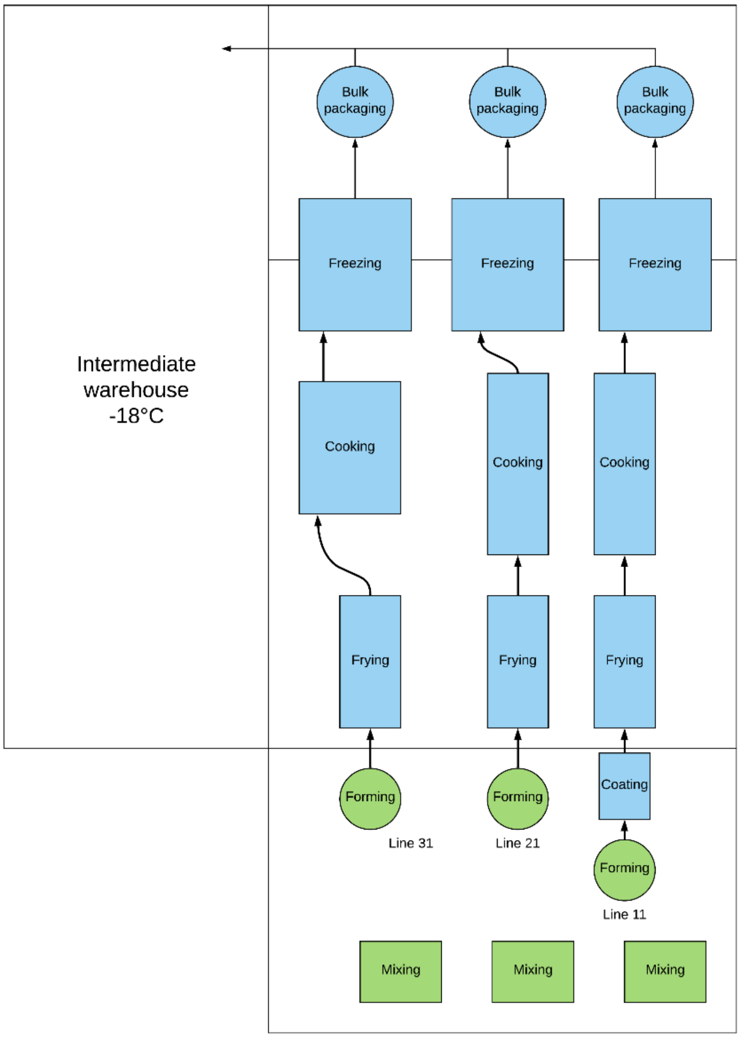

Figure 5: Production process layout

2.3 Systems for production planning

In this section, we explain the systems that are used for production planning. Section 2.3.1 explains the different systems that are used in the supply chain department and production planning. Next, Section 2.3.2 describes cyclic production planning at Company X.

2.3.1 Systems used for supply chain and production planning

The supply chain department of Company X is using three different systems namely, an enterprise resource planning (ERP) system, an inventory management system, and a production planning and scheduling system. The inventory management system and the production and scheduling system are implemented last year and they are currently still implementing additional features and making improvements to the systems. The three systems respectively are explained along with the different connections between these systems. These systems play an important role in production planning. First, Section 2.3.1.1 explains the ERP system. Furthermore, Section 2.3.1.2 explains the inventory management system. Next, Section 2.3.1.3 describes the production planning and scheduling system.

2.3.1.1 ERP system

The first system is an enterprise resource planning (ERP) system, named Fobis. Fobis is used to manage and integrate the important parts of the company, so not only the supply chain department. The ERP program is important for the company because it helps them by integrating all the processes that are needed to run the company with a single system. Fobis is mainly used for processing and tracking customer orders, purchasing orders, production orders and real-time inventory control.

2.3.1.2 Inventory management system

Next to the ERP program, the supply chain department uses an inventory management system named Slim4. Slim4 is a program that is used for forecasting, demand planning, supply planning and inventory optimisation. Slim4 is for a large part a stand-alone system, however, it is also connected with Fobis to get input about the customer orders, inventory levels, outstanding purchasing orders and production orders. Also, Slim4 gets input from a database that contains historical data and the master data about every product, such as lead times, MOQs and lot sizes. Slim4 uses this information to determine forecasts for every SKU based on the forecast of the finished products. This can be seen as a top-down process. Forecast for finished products will lead to a forecast for semi-finished products and eventually leads to a forecast for raw materials.

Based on the forecast Slim4 gives a purchasing and production advice to optimize the inventory and prevent non-deliveries. Non-deliveries means a failure to deliver a finished product to the customer. It is a very extensive program in which a lot of parameters can be used. For example, SKUs can be grouped or can have different production strategies such as make-to-order (MTO) or make-to-stock (MTS). However, Slim4 does not take into account the total capacity of production lines and inventory capacity.

2.3.1.3 Production planning and scheduling system

The third program that is used is Rob-Ex, a production planning and scheduling system. Slim4 is connected with Rob-Ex to advise about production plans. For example, based on the forecast, Slim4 advises on the quantity that needs to be produced of a semi-finished product and gives the due date. This advice is turned into a production order which is placed in the ERP system Fobis. This production order is now visible in Rob-Ex where the final production plan is determined and scheduled. However, it is also possible to plan products not based on the direct advice of Slim4. The plans can also be created from external input and implemented into Rob-Ex. Section 2.3.2 explains a cyclic production plan that is used by production planning.

When the final production plan is established, Slim4 calculates the required quantities of raw materials that are needed to execute the production plan. Based on this purchasing orders are generated and supply planning orders the raw materials by suppliers. Also, the production schedule is translated to production orders in the ERP system. To illustrate, Figure 6 gives a simple overview of the connections between the different systems and which processes take place. The process of the systems could be visualised as an ongoing circle.

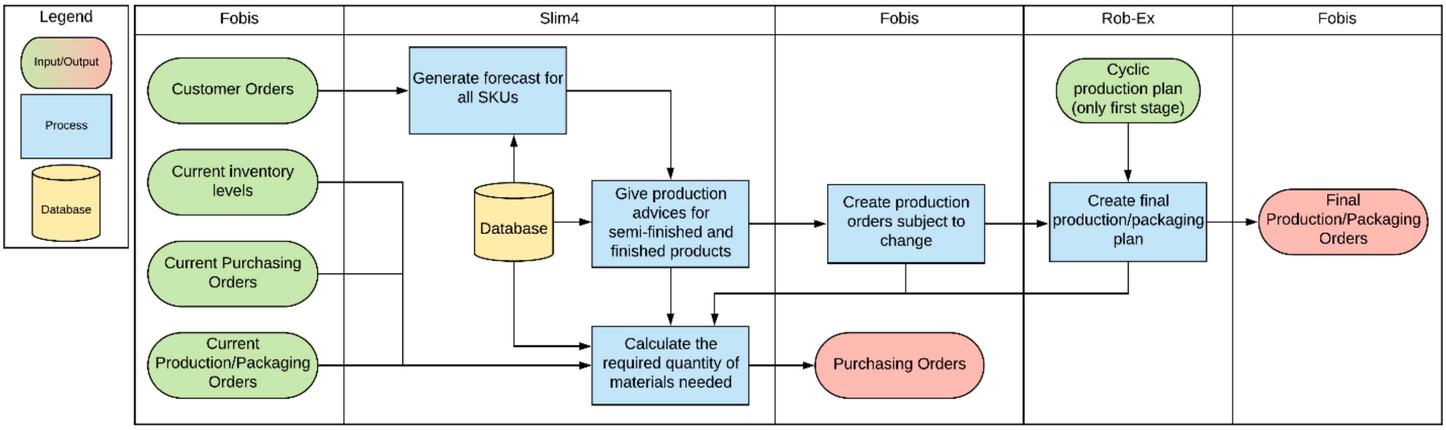

Figure 6: Relationships between the systems

2.3.2 Cyclic production plan

Section 2.3.1 explains the different systems that the supply chain department uses. Production plans are based on the production advice of Slim4 or from an external input. The supply chain department also uses production plans that are created in Excel. This production plan is based on a cyclic production plan. The cyclic plan is a fixed plan that repeats every four weeks. The cyclic production plan is based on a demand forecast from Slim4, batch sizes, capacity, and line speeds. The batch sizes are based on a half or full-day production capacity. Table 1 illustrates an example of a 4-week cyclic production plan.

Product	Week 1	Week 2	Week 3	Week 4	Total
55750	15,000 kg	0	15,000 kg	0	30,000 kg
55760	0	10,000 kg	0	10,000 kg	20,000 kg
55770	0	0	10,000 kg	0	10,000 kg

Table 1: 4-week cyclic production plan

A cyclic production plan has several advantages according to Company X. It reduces the complexity of creating a production plan, it reduces planning costs and it could give more stability in the supply chain. However, cyclic production plans need to be revised after a certain period and there is not a procedure for this.

2.4 Current production planning

Production planning is an administrative process and it is a function of establishing an overall level of output which is called a production plan. The production planner is in charge of production planning. In this process, several actions are taken by a production planner for establishing a production plan. Section 2.4.1 explains the current process of production planning. Business Process Modelling Notation (BPMN) (OMG, 2010) is used to make a graphical representation of the process. BPMN is a standardization for describing and visualizing business processes. Next, Section 2.4.2 explains production scheduling at Company X.

2.4.1 Production planning overview

Production planning is executed every week. Every week a production plan is created for week+4. For example, if the current week is week number 20, the production planner makes a production plan for week 24. In this process, several actions are taken by the production planner to establish a production plan. Figure 7 illustrates the BPMN model of production planning. This model has two subprocesses which are illustrated in Figure 9 and Figure 10. We divide the explanation into 4 subsections. Section 2.4.1.1 explains the check of the production advice. Section 2.4.1.2 explains the planning methods. Section 2.4.1.3 explains the capacity check. Section 2.4.1.4 provides a conclusion.

2.4.1.1 Check production advice

Figure 7, underneath Section 2.4.1.4, illustrates all the steps of the production planner. The first task in production planning is to check the production advice that is given by Slim4 in Rob-Ex. In this advice, the quantity of the semi-finished (S/F) product is given and also a due date and the plan window. The due date is the date before which the order needs to be produced. If it is produced after this date there is a likely chance that the semi-finished product will go out of stock in a short time. The plan window is the date when there are sufficient raw materials to produce. So the due date and plan window gives the time interval in which production can and should take place. The check of the production advice is done to find any urgent production orders, so with a due date that is earlier than week+4. When there is an urgent order the production planner will choose if the product should be made earlier than week+4. This means that the frozen period of the production plan is violated, so most of the time this will not be done.

2.4.1.2 Choose planning method

After the checks, the production planner chooses a method to create a production plan. The production planner can choose between the cyclic planning and planning based on Slim4. Each plan method has both its advantages and disadvantages. With the cyclic plan method the semi-finished products, quantities and schedule are already determined and only have to be loaded into the planning system which is less time-consuming. However, because the products and quantities are already determined it is more difficult to change this plan in the systems. Production advice of Slim4 has the advantage that the production planner can create a production plan that is more flexible but it is also more time-consuming. The production planner mentioned that both methods are for now not optimal.

When the cyclic production plan is used as a planning method it will be loaded into the planning system. The cyclic production plan does not cover the capacity of a full week, so there is some capacity left for products that are not in the cyclic production plan for that week. Therefore the production planner waits a day and Slim4 will calculate new production advice. Calculation of new production advice is done through the night and therefore the production planner needs to wait until the next day. The next day Slim4 has generated new production advice for certain semi-finished products and the production planner will loop through these products in Slim4 to see what impact the advice has on inventory in combination with the forecast. This is modelled as a subprocess in Figure 9 and loops until all the product advices are checked.

This subprocess is executed because the production advice is not always in line with the real situation. This can have multiple causes. For example, the actual due date is later or earlier. This means that production needs to take place earlier than the suggested due date. Also, the given forecast is not accurate and therefore it needs a check to validate if there are no strange deviations. The production planner first looks if the advised quantity is sufficient. It is sufficient when it covers demand with a maximum of 4 weeks of inventory. If not, the production planner changes the advised quantity of the products and also the underlying components. This task is done manually. This means that the production planner needs to determine the new quantity that needs to be produced. Also, the quantity of underlying components needs to calculated again. If the quantity is sufficient then the production planner checks the forecast and the input parameters. For example, if the forecast deviates too much, the production planner can adjust the forecast. After this, the production planner will choose if the product needs to be planned in week+4 or not. Input parameters are MOQ and IOQ. When the forecast is low it is not efficient to have a high MOQ because leads to higher inventories.

Scheduling is modelled as a subprocess and it is a loop until all the products are scheduled. Figure 10 illustrates this subprocess. Scheduling is done based on the constraints, preferences of the processing department and if it is produced at Company Z facility or Company X facility. A fixed number of products are produced at the Company Z facility or the Company X facility. Section 2.4.2 provides more information on production scheduling at Company X.

When the production planner chooses to plan based on Slim4 advice the production planner does not need to wait till the next day and can start to plan. The production planner will check for every semi-finished product the development in Slim4. This is the same subprocess as explained in the paragraph above. However, now more products need to be checked so the number of loops is larger in the subprocess. This step requires a lot of time. After the checks to products are scheduled.

2.4.1.3 Capacity check

When the production plan is determined and the products are scheduled on the production lines at Company Z or Company X, a total overview is generated. This overview gives the amount of kg that is produced in week+4. This amount of kg is checked in the capacity plan of Company X. The capacity plan gives for every week the forecasted required amount of kg, the currently planned amount of kg and the impact on the inventory development. The operational management set the bandwidth of total kg inventory of semi-finished products between the 750,000 and the 800,000 kg. This range is based on following starting points: target of 98% delivery performance and 3 to 4 weeks of safety stock per semi-finished product. Aggregating this safety stock minus the forecasted sales gives this range. In this research, we refer to this range as the capacity plan. The objective is to stay in between this range. So when the total amount of kg of the production plan of week+4 does violate the capacity plan, the production plan is changed to a certain extent. Therefore, the production planner needs to check again if it is possible to change the quantities of some semi-finished products.

When the production plan is according to the capacity plan, then the production plan and schedule is communicated with the different stakeholders, such as the Manager Processing and the team leaders of the processing departments. When the schedule is sufficient, then production planning is finished. If it is not sufficient some changes will be done in the schedule until the schedule is sufficient. A schedule is not sufficient when, for example, a product is scheduled after a product with a different allergen when there are better options. This results in a long setup time.

2.4.1.4 Conclusion of production planning

Both production plan methods have time-consuming tasks in the process. The subprocess of checking every semi-finished product development is time-consuming. This is because the production advice of Slim4 is not always reliable. It is not always reliable because Slim4 does not take into account capacity, due dates can appear to be earlier or later, and the forecast is not accurate.

The production plan needs to take into account the capacity of Company X. It is difficult to control this capacity level because there are no real-time insights from systems and the systems do not take into account the capacity level. Therefore the capacity is manually controlled by checking the production plan every time. According to Company X, the cyclic production plan can help in controlling the capacity. However, the cyclic production plan is not so extensive that takes capacity into account.

Choosing a planning method is also challenging for the production planner because both plan methods have their advantages and disadvantages. There is no fixed decision rule so the production planner needs to choose based on his interpretation. For the production planner, the ideal situation is a fixed planning method where the production planner does not need to validate every decision each time. Also, preferably, the planning method needs to take into account constraints such as the capacity level or give insight into the capacity level.

The current production planning does not give insight into the impact of the production plan. Insights in inventory development, capacities and cost are hard to determine and also time-consuming. Section 2.4.2 explains some KPIs that are used in production planning.

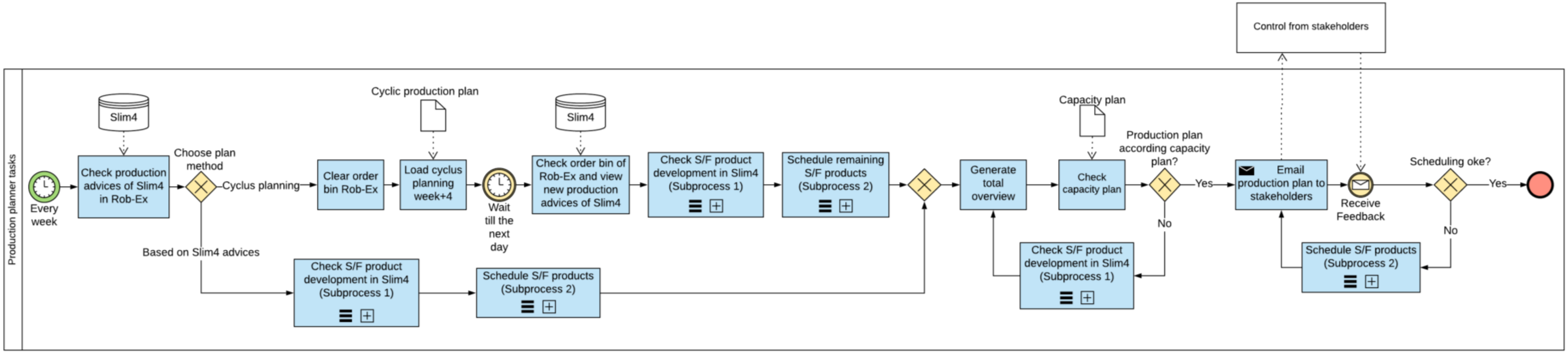

Figure 7: Production planning

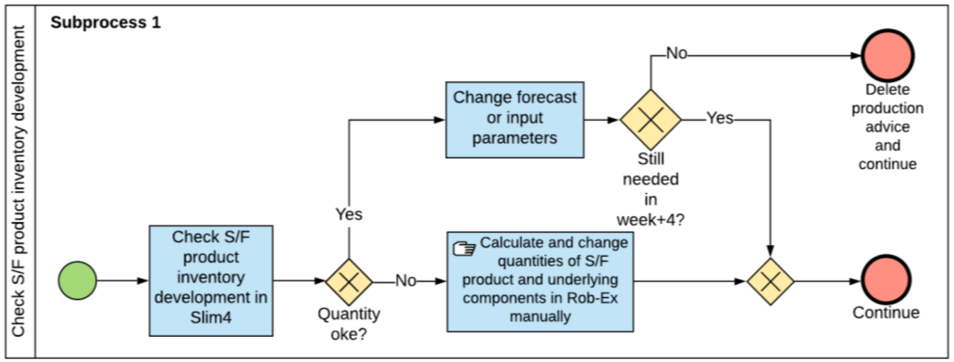

Figure 9: Subprocess 1, Check

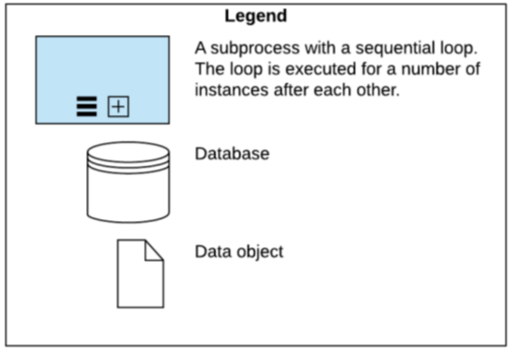

Figure 8: Legend

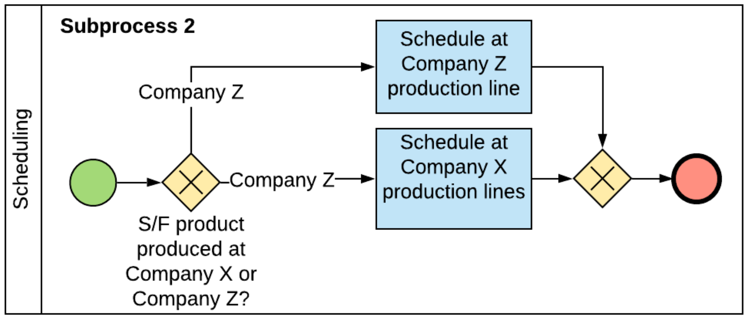

Figure 10: Subprocess 2, scheduling

2.4.2 Production scheduling

Production scheduling is part of production planning. After a production plan is set for week+4, the production planner makes a schedule for the production lines. The production planner takes the following into account when scheduling:

1. Allergens. Semi-finished products are scheduled based on allergen combinations to prevent allergen contamination. It is only possible to follow a specific order. This allergens order is illustrated in Appendix A. Switching to an allergen that is not in the specified order requires a cleaning. Cleaning the production line takes 5 to 6 hours.
2. Within these allergen combinations, semi-finished products are also categorized on product characteristics. For example, round formed products are categorized as "balls" and hamburgers as "patty". Switching between these products categorizations takes additional setup times because a switch between machines is needed.
3. Preferences of the processing department. The processing department has preferences about the sequence of production and allocations of the products on a production line.

The production planner is required to take allergens (point 1) into account. Point 2 is important for efficiency. The production planner wants to have a schedule with the highest efficiency, so without long setup times. Point 3 is not specifically necessary but the production planner tries to fulfil all the desired preferences.

Section 2.4.1 describes the process of production planning. In this process, the schedule is validated by different stakeholders. Stakeholders have the opportunity to advise on changes in the schedule. The production planner decides whether to accept these changes or not.

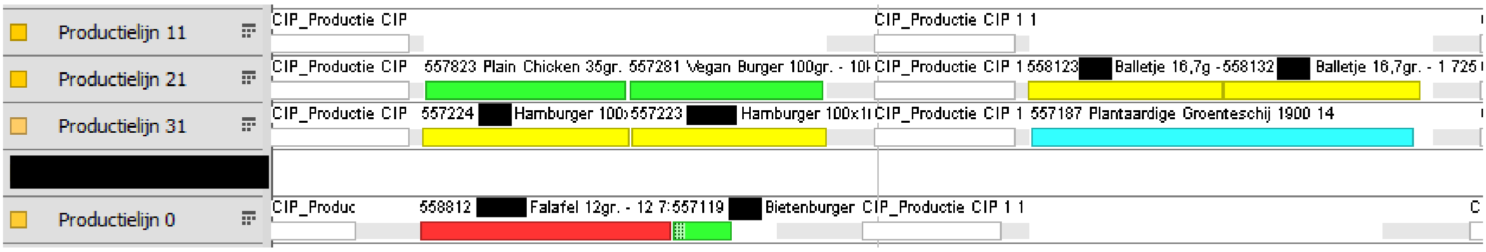

Figure 11: Production schedule

To give more detail on the schedule, we illustrate a schedule that is made in Rob-Ex. Figure 11 shows a Gantt schedule of 2 production days for the different production lines. The colours are related to the specific allergen, which is illustrated in Appendix A. The white blocks with "CIP_Production" illustrate the cleaning time during the night. "Productielijn 0" is the production line at Company Z.

2.5 Key Performance Indicators

Key performance indicators are performance measurements to evaluate a business activity. Production planning has also KPIs to evaluate the process. Section 2.5.1 describes the current KPIs for production planning. Section 2.5.2 explains the relationships between KPIs and the production plan.

2.5.1 Current KPIs for production planning

The supply chain department has several KPIs to evaluate certain processes within the supply chain. The most important objective for the supply chain is the delivery performance. The delivery performance depends on a lot of different processes of which production planning is one. When a semi-finished product is out of stock the packaging department cannot pack a finished product which leads to non-delivery. This results in lower delivery performance. Therefore, it is important that production planning and packaging planning are well aligned.

Another important KPI that influences the supply chain department is the forecast accuracy of finished products. In production planning forecasts are used by Slim4 to give production advice to optimize inventory and reduce chances of non-deliveries. Therefore, it is important to have a good forecast accuracy. However, the forecast accuracy is not very good at the moment. A forecast influences the production advice of Slim4 and the KPIs. From week 1 to week 20 in 2020 the average forecast accuracy was 50%. This means that the forecasted quantities deviate from the real ordered quantity with on average 50%. The production planner takes this forecast accuracy into account but this is difficult because the forecast is measured for finished products. Forecast accuracy for semi-finished products is not possible at the moment. The supply chain department is investigating if it would be possible to also measure the forecast accuracy for semi-finished products. Measuring the forecast accuracy for semi-finished products will give a better indication in the reliability of the production advices of Slim4.

Within production planning, there are two KPIs used by the production planner. One KPI that is reported weekly and one that is reported daily. Daily, the production planner reports the percentage of planned versus the real output. This could influence production planning because with a low percentage the production plan may need to revise or rescheduled. Rescheduling occurs 2 to 3 times a week depending on the situation.

Every week the total inventory of semi-finished products in days is displayed. This is the coverage of the inventory in days relative to the forecasted orders. Figure 12 illustrates this KPI. The target is to have a coverage level between 20 and 29 days.

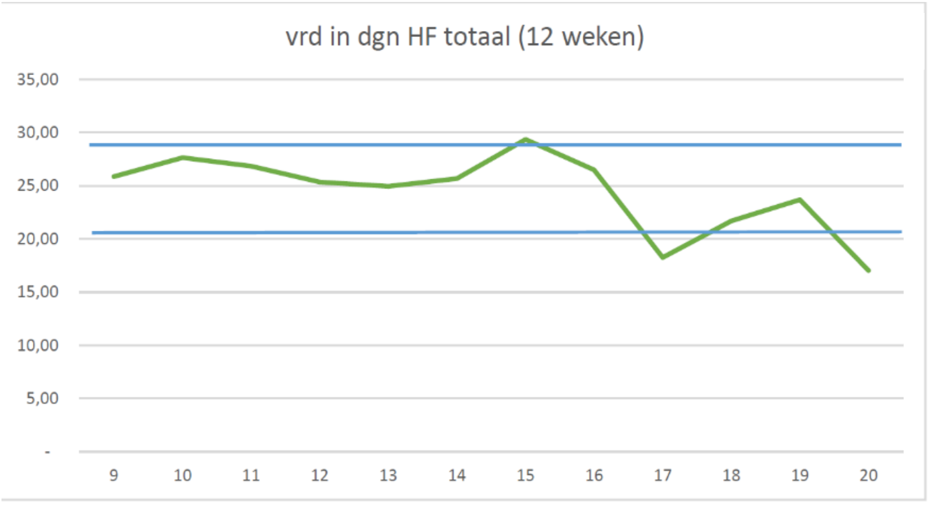

Figure 12: KPI Inventory in days

2.5.2 Relationship between KPIs and the production plan

From the current KPIs, it is not possible to see the direct influence on the production plan. The delivery performance is an important KPI but the supply chain department has no performance measure to see the influence of the production plan on the delivery performance. Therefore we do this performance measure with the available data of the supply chain department. From the current information, it is possible to find the percentage of non-deliveries that were caused by an out of stock of semi-finished products relative to the ordered volume. Figure 13 illustrates the percentage of non-deliveries that were caused by an out of stock of semi-finished products relative to the ordered volume. At the beginning of the year, a lot of non-deliveries were caused by out of stock of semi-finished products produced at Company X or Company Z. However, from week 10 it is very stable and below 1%. This is because the production planner evaluates the production plan and checks the development of the inventory of semi-finished critically. Also, the target to have a safety stock of 3 to 4 weeks for semi-finished products helps to prevent non-deliveries.

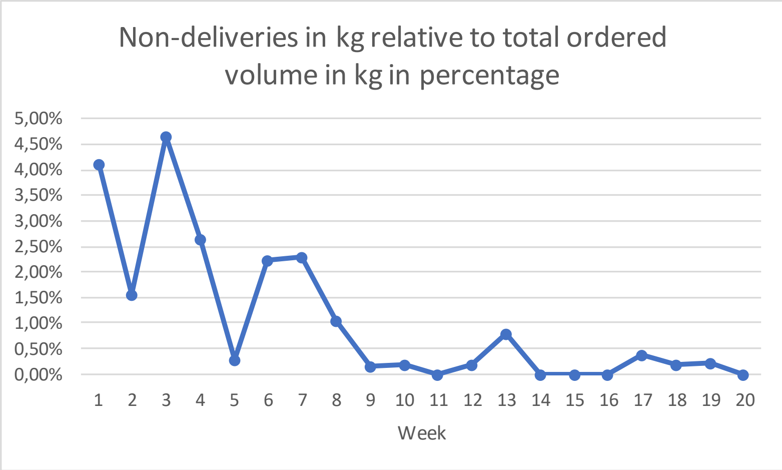

Figure 13: Volume non-deliveries relative to ordered volume

2.6 Conclusion

The production system of Company X consists of a two-stage production system. The first stage is the processing department which makes semi-finished products. The second stage is the packaging department which makes finished products. Production planning at Company X is concerned with the planning of semi-finished products at Company X and the facility of Company Z. For production planning, three different systems are used which are connected. The main systems that are used for production planning are Slim4 and Rob-Ex.

Every week the production planner will make a production plan for week+4. To create a production plan, the production planner can choose between two plan methods. The two plan methods are a cyclic production plan or a production plan created from the advice of Slim4. The cyclic production plan is an almost fixed production plan which is easy to control and plan. However, because it is fixed it is hard to change the plan. Planning based on Slim4 is more flexible because the production planner can create a plan from scratch and can, therefore, take into account preferences from stakeholders. However, to create this plan it is also time-consuming.

In the process of production planning, the production planner always needs to take two things into account. The inventory development and forecast of individual semi-finished products and the total inventory development of all semi-finished products, also known as the capacity plan. The check of individual semi-finished products is done in Slim4. Advises from Slim4 are not always reliable because of a forecast accuracy of 50%. Therefore the advices need to be checked. The capacity plan cannot be integrated into Slim4 and therefore Slim4 does not take into account capacity. This check is done in a separate file and therefore it is difficult and time-consuming to make a production plan that takes into account the capacity plan.

The goal for the production planner is to prevent non-deliveries that are caused by having an out-of-stock of semi-finished products that are produced at Company X or Company Z. To prevent non-deliveries it requires more time to critically check inventory and forecast for every semi-finished product. In combination with the capacity plan and controlling the KPI inventory in days, production planning is very time-consuming.

3 Literature review

This chapter reviews the literature for the research questions formulated in Chapter 1. Section 3.1 reviews the literature for a two-stage production system. Section 3.2 explains the considerations in make-to-order and make-to-stock in the food processing industry. Section 3.3 provides literature for scheduling with sequence-dependent setup. Section 3.4 defines performance measures for production planning that are found in the literature. Last, Section 3.5 provides a conclusion of the chapter.

3.1 Two-stage production planning

Production planning at Company X needs to take into account the two-stage production system with capacitated intermediate storage between the stages. The output from the first stage is input for the second stage and the other way around. We divide the literature of this section in 3 subsections. Section 3.1.1 explains the literature about food processing systems. Next, Section 3.1.2 describes literature about two-stage food processing systems. Last, Section 3.1.3 explains literature about hierarchical production planning.

3.1.1 Food processing systems

Food processing systems are widely analysed and described by researchers as Akkerman, Soman, and Donk. Donk presents a framework for determining the customer order decoupling point (CODP) in the food processing industry (Donk, 2001). This framework helps managers to make decisions and find influences of the factors in changing the decoupling point. Van Wezel, Donk & Gaalman (2006) review the planning flexibility bottleneck in the food processing industry. Potential profits are lost because organizations do not know how to respond to unexpected events. They present a framework that analyses unexpected events in planning. Also, the framework presents a way to reason about reconsiderations of planning decisions within a planning hierarchy.

3.1.2 Two-stage food processing systems

Akkerman, Donk, and Gaalman (2007) describe the influence of capacity- and time-constrained intermediate storage in two-stage food production systems. Perishable products and shared resources, such as storage tanks, are characteristics that suggest the presence of capacity- and time-constrained intermediate storage. Time constraints occur when the products have a short shelf-life. In their research, the researchers describe a situation with the presence of capacity- and time-constrained intermediate storage in a two-stage production system. The first stage concerns a batch process. Batch processing is used for efficiency reasons and technical reasons. Efficiency reasons are, for example, minimizing setup-times. Technical reasons in the processing are often concerning non-discrete products and processing technologies that implies the need for batching. The researchers present a cyclic scheduling approach for the first stage. Cyclic scheduling is often used in flow lines with limited intermediate storage (Akkerman, Donk, & Gaalman, 2007). Also, it is an attractive approach because it will periodically supply different intermediate products to the second stage of the production system. Soman, Donk, and Gaalman (2004) described earlier an approach for economic lot scheduling with shelf life considerations. In this approach, the researchers provide a procedure to find the common cycle time which takes shelf life into account. The cycle time is from the procedure of Doll and Whybark (1973). This cycle time is modified to take into account shelf life considerations.

3.1.3 Hierarchical production planning

Hierarchical production planning in a two-stage production system is also a well-described topic in production planning. Bitran et al. (1982) describe this two-stage hierarchical production planning (HPP). HPP model provides a hierarchy of decisions that have to be made. Aggregate decisions (e.g. strategic and tactical) are made first and lay down constraints for making more detailed (operational) decisions. For a complete description of HPP see Bitran et al. (1982). Tsubone et al. (1991) elaborate on HPP in a two-stage system by analysing the relationship between the production planning rules and the role of buffer inventory level in terms of production system performances.

Aghezzaf et al. (2011) use the HPP model to propose a production planning approach. HPP approaches typically consider holding costs at the aggregate level and setup cost at a detailed level. However, in the proposed production planning approach this is not the case. The first stage is considered as the aggregate level and the second stage as the detailed level which is disaggregated with a coupling plan that connects the two planning levels. Setup costs in the first stage are significantly higher than in the setup cost in the second stage, which is taken into account. Also, the demands of semi-finished products in the first stage is relatively stable due to aggregation and therefore a cyclic planning model is proposed. The researchers use the procedure of Doll and Whybark (1973) to find a fundamental cycle period. The fundamental cycle period is the length of a single cycle. Also, this procedure gives the production frequencies of each semi-finished product. Together with the fundamental cycle period and the production frequencies, it is possible to determine the total cycle length.

Earlier, Aghezzaf and Landeghem (2002) present a two-stage production model that is not based on HPP. The first stage is a processing production system and the second stage a job-shop production system. The two stages are decoupled with an intermediate warehouse. The inventory policy at the intermediate warehouse is determined based on the semi-finished products' demands behaviour. This research is not to propose a new heuristic but use the available results reported in the literature to achieve excellent performance in solving the case described in the research.

The objective of the proposed models is to minimize cost for production while maintaining target performance. However, in production planning, the input parameters can be uncertain. Input parameters such as demand and production. Data uncertainty can be taken into account by applying robust optimization (Rahmani et al., 2013). The researchers present a model for a multi-period multi-product multi-machine two-stage production system. The researchers use robust optimization to create a robust production plan that is less sensitive to the change in the uncertain data.

3.2 Make-to-order and make-to-stock in the food processing industry

In the last decades, food processing industries are expected to deliver a greater variety of products and meet higher logistical demand while keeping costs as low as possible. Therefore, food processing companies are looking for flexibility to deal with these market demands. As a consequence, food processing companies operate often under a hybrid MTO-MTS strategy (Soman et al., 2004a). MTO systems offer a high variety of customer-specific products which are typically more expensive. Production planning focus on customer orders. On the other hand, MTS systems provide a low variety of customer-specific products which are typically less expensive. In this system, production planning focusses on anticipating the forecasted demand (Soman et al., 2004a). The main problem in the MTS system is inventory capacity, lot sizing, and demand forecasting. According to Soman et al. (2004a), many previous articles use simplistic rules to tackle issues in MTO/MTS. Therefore, they provide a hierarchical planning framework for managing main problems in a combined MTO-MTS system. This hierarchical framework encourages the use of the customer order decoupling point to make MTO/MTS decisions. The customer order decoupling point distinguish order-driven activities and forecast driven activities and it is the main point from which deliveries to customers are made. The concept of the customer order decoupling point in the food processing industry is extensively described by Van Donk (2001). The decision level for MTO/MTS is often in the second stage of the production system where semi-finished products are disaggregated into multiple different finished products variations.

Later, Soman et al. (2006) describe a hybrid MTO-MTS production situation with capacity restrictions and stochastic demand. In this article, they compare four different dynamic scheduling methods for a combined MTO-MTS situation. First, a target cycle time is pre-calculated by using an economic manufacturing quantity or the procedure described by Doll and Whybark (1973). To deal with demand uncertainty safety stocks and order up-to-levels are pre-calculated based on the mean and standard deviation of the demand. After the determination of the target cycle times, a scheduling heuristic is used to find the sequence of production. The methods perform well for pure MTS situations but not necessarily for hybrid MTO-MTS situations.

Soman et al. (2007) describe a case study for capacitated planning and scheduling for combined MTO-MTS production in the food industry. They use the framework for combined MTO-MTS production situation of Soman et al. (2004a). Additionally, they identify areas of improvements and suggest analytical decision aids. According to Soman et al. (2007), demand variability analysis forms the main activity to segregate MTO and MTS products. Companies often categorise products into either A, B, or C categories. In category A are MTS products while in the B and C category are MTO items. However, the researchers find this too simplistic. They describe an analysis by looking at the average weekly demand and variability. Typical MTO candidates are products with low set-up times, products with high holding costs, customized products, and highly perishable products. MTO and MTS decisions are strategically orientated and are complicated because of the complex trade-offs between demand and product-process characteristics.

3.3 Sequence-dependent setup scheduling

Scheduling in the food processing industry is a challenging task. Food processing industry deals with sequence-dependent setups due to the required cleaning times between different product families. Also, within product families there exist additional sequence-dependent setups. Section 3.2 already reviews the hybrid MTO-MTS production systems described by Soman et al. (2006, 2007). They give insight into scheduling methods for MTO-MTS production systems. However, these researchers do not provide a detailed method for sequencing.

Gupta and Magnusson (2005) describe a capacitated lot-sizing and scheduling problem (CLSP) with sequence-dependent setup costs and setup times. When one or more machines are used to meet forecasted demand for multiple products over multiple periods encounters a CLSP. CLSP with sequence-dependent setup times is related to the travelling salesman problem and the vehicle routing problem and these problems are NP-hard (Gupta & Magnusson, 2005). Problems that are NP-hard are difficult to solve and have long computational times when the problem increases. Therefore, they provide next to an algorithm also a heuristic to make the CLSP more practical. The goal of the heuristic is to find a near-optimal solution that minimizes cost with consideration of capacity.

The well-known travelling salesman problem is a popular heuristic for sequence-dependent scheduling. Ozgur and Brown (1995) provide a well-described procedure to find a near-optimal solution for sequence-dependent scheduling. The travelling salesman heuristic consists of two-stages. In the first stage, a changeover setup time matrix is used to cluster product families and sequence the products within the product families. The second stage determines the sequence of the product families. The heuristic can quickly find good solutions to the scheduling problem.

Group scheduling of product families is also described by Gupta and Chantaravapan (2008). They use the total tardiness as a performance measure for scheduling. First, they apply a greedy heuristic to generate an initial sequence. After this, the sequence is improved by applying a swap heuristic or simulated annealing. The swap heuristic is recommended for problems with a few families, tighter due dates, a large number of products and/or large family setup times (Gupta & Chantaravarapan, 2008). In other cases, simulated annealing is the recommended option.

Other heuristics that are described for sequence-dependent scheduling are local search heuristics. Crauwels et al. (1997) investigate the performance of several local search heuristics. They start by testing the "standard" version of each method and improve the methods if the solutions are not of sufficiently high quality. The local search heuristics that they use are neighbourhood search, simulated annealing, threshold accepting, and tabu search. Simulated annealing, threshold accepting and tabu search all generate solutions of high quality.

3.4 Production planning performance

Production planning has certain objectives. To measure these objectives it is important to have performance measurement. Section 2.4.2 explains the current key performance indicators. The production planner takes into account the delivery performance and the inventory in days of semi-finished products. At the moment there are no other KPIs that measure production planning and the production plan. To find potential performance measures for production planning the performance measures of the models in Section 3.1 are described and analysed.

The different models described in Section 3.1 have a particular objective function to improve particular performances. HPP models are mostly cost-based (Tsubone, Matsuura, & Tsutsu, 1991) and aim to minimize the total cost. Total cost is an important performance measure but it does not capture all the effects of production planning on the production performance. For example, opportunity loss due to capacity.

This is also partly the case in the model of Aghezzaf et al., (2002, 2011) but they take service level into account. Tsubone et al. (1991) use the following four performance measures: unfilled rate, the average inventory levels, the ratio of set-up time to total processing time, and the deviation in production rate. Rahmani et al., (2013) also take total cost as performance measures. However, the total cost is extended with regular cost and overtime cost, subcontracting cost, backorder cost, labor cost, hiring cost, and downsizing cost.

3.5 Conclusion

Akkerman et al. (2007) described a model that takes the influences of capacity- and time-constrained intermediate storage into account in a two-stage food production system. The first stage is a batch process which has multiple advantages. In a batch process, a cyclic schedule is often used.

Additionally, a widely described model for production planning in a two-stage production system is an HPP model. An HPP model gives divides the decisions into aggregate decisions (i.e. strategic and tactical level) and detailed (i.e. operational) decisions.

Aghezzef et al., (2011) use the HPP model to propose an alternative production planning approach in a two-stage system. The first stage is considered as the aggregate level and the second stage as the detailed level. The two stages are disaggregated with a coupling plan. In the first stage, the demand for semi-finished is relatively stable and therefore a cyclic planning model is proposed. Planning in the second stage is based on a periodic review policy.

All the described models use certain performance measures to reach a certain objective. HPP models are mostly cost-based and aim to minimize total cost. Performance measures that are often used in production planning are cost, set-up, utilization, average inventory levels and unfilled rate for market demand. The total cost can be divided into different categories such as overtime cost, backorder cost and labour cost.

Food processing companies often operate under a hybrid MTO-MTS strategy due to the changes in market characteristics. A demand variability analysis helps to segregate MTO and MTS products. However, strategically decisions about MTO and MTS is complicated because of the complex trade-offs between demand and product-process characteristics.

Scheduling in the food processing industry is a complex task because of the sequence-dependent setups and the required cleaning times. Most scheduling problems are NP-hard which means that they are hard to solve and to compute. Instead of these algorithms heuristics provide a practical procedure to solve the problem and find a near-optimal solution. Gupta and Magnusson (2005) describe a heuristic for capacitated lot-sizing and scheduling problem (CLSP) with sequence-dependent setup costs and setup times.

Ozgur and Brown (1995) describe a heuristic based on the travelling salesman problem. This heuristic consists of two stages. In the first stage, a changeover setup matrix is used to cluster product families and sequence the products within the product families. The second stage determines the sequence of the product families.

Group or family scheduling is also described by Gupta and Chantaravapan (2008). The heuristic minimizes the total tardiness of the schedule. First, a greedy heuristic is used to generate an initial sequence. They improve the schedule by using the swap heuristic or simulated annealing. The swap heuristic is recommended for problems with a few families, tighter due dates, a large number of products and/or large family setup times.

4 Solution design

This chapter describes a production planning model and a heuristic for finding a feasible schedule. Section 4.1 looks at the implications of production planning in the first stage of a two-stage production system. Section 4.2 describes the considerations of make-to-order and make-to-stock in production planning. Section 4.3 describes a procedure to find the fundamental cycle period in an economic lot scheduling problem. Next, Section 4.4 provides a heuristic to find a feasible schedule by taking into account the cycle length from Section 4.3. Section 4.5 gives an overview of the solution design. Furthermore, Section 4.6 explains the production planning performance for the solution design. Finally, Section 4.7 provides a conclusion of the chapter.

4.1 First stage production planning

We focus on the first stage of a two-stage production model. We use the demand from the second stage as input for the first stage. Most of the two-stage production models provide a feasible plan for both stages. However, the scope of this research is the first stage and we focus only on production planning and scheduling in the first stage.

Section 3.1 mentions HPP as a widely described model in a two-stage production system. HPP decomposed the problem into subproblems. Aghezzaf et al., (2010) use this to describe the first stage of a two-stage production system as the aggregate level and the second level as the disaggregated level. We can find this structure of data already at Company X. Slim4 calculates the forecast for the finished products (disaggregated level) and aggregate this to a forecast for semi-finished products (aggregated level).

In the solution design, we use cyclic production planning. Aghezzaf et al. (2010, 2011) and Akkerman et al. (2007) describe the advantages and implications of a cyclic planning model in the first stage. Aghezzaf et al., (2011) use a procedure by Doll and Whybark (1973) to find the fundamental cycle period and lot-size for every product and the total cycle length.

Aghezzaf et al. (2011) use the fundamental cycle period in a linear programming model to minimize the cost and to take into account capacity. On the other hand, Akkerman et al. (2007) use cyclic planning that takes into account the capacity and time constraint. The capacity constraint applies to a limited number of storage tanks as intermediate storage. This means that production is not possible when a storage tank is filled. However, at Company X the intermediate storage is a large warehouse where the storage of multiple semi-finished products is possible. Also, a shelf life constraint does not necessarily apply because of the one-year shelf life of semi-finished products. However, we can apply a time constraint to limit the storage time of semi-finished products in the intermediate storage. Semi-finished products are stored at the warehouse of Company X and in an external warehouse. Especially the external warehouse gives relatively high holding costs. Therefore, it could be beneficial to shorten the inventory time. Soman et al. (2004) use a shelf-life constraint when calculation the fundamental cycle period. We use this shelf-life constraint for limiting the duration a semi-finished product is in inventory.

4.2 Make-to-order and make-to-stock

Section 3.2 describes literature about the importance and decision-making in MTO and MTS in the food processing industry. However, most of the decision-making in MTO and MTS is considered for finished products and not necessarily for semi-finished products. Still, we provide an analysis of the demand variability, which is considered as the main activity to segregate MTO and MTS products (Soman et al., 2007). We use the analysis described by Soman et al. (2007). We analyse the semi-finished products on the average weekly demand and the demand variability. For the demand variability, we use the coefficient of variation

(CoV). In Section 4.1 we state that demand at the aggregated level is often stable over time. Company X already calculates the aggregated forecast for semi-finished products with the help of Slim4. We use the data availability in Slim4 to do a demand variability analysis.

Next to the analysis of demand variability, we also do a product-process analysis. Products with low-setup times, high holding costs, customized products, and perishable products are candidates for MTO.

4.3 Fundamental cycle period and MTO/MTS considerations

First, Section 4.3.1 describes the procedure to determine the fundamental cycle period in Section. Second, Section 4.3.2. discuss the MTO and MTS considerations for the fundamental cycle period.

4.3.1 Fundamental cycle period

In Section 3.1 and Section 4.1, we mention procedure by Doll and Whybark (1973) to find the fundamental cycle period, in other words, the length of a single cycle. Soman et al. (2004) modify the procedure to take into account the shelf life of products. We use the procedure by Doll and Whybark (1973) and of Soman et al. (2004) to find the fundamental cycle period. To apply this procedure we make multiple assumptions. These assumptions are:

1. The demand rate is deterministic for each semi-finished product and all demand needs to be fulfilled. According to Aghezzaf et al. (2010), in a two-stage system demands of semi-finished products are relatively stable even though the demands of finished products are random.
2. The production rate is constant. In a given time the machine produce always the same number of units.
3. The setup time and cost are sequence-independent.
4. The holding costs are constant for each semi-finished product in inventory.
5. The semi-finished products have a maximum inventory storage duration.
6. The semi-finished products are used on a first-in-first-out basis.

We work with the following parameters for each semi-finished product:

1. d_j: demand rate in kg per unit time of product j.
2. p_j: the production rate in kg per unit time of product j.
3. s_j: setup cost (€) per production lot of product j.
4. u_j: setup time per production lot of product j.
5. h_j: inventory holding cost (€) per kg per time unit of product j.
6. w_j: maximum inventory holding time of product j.
7. IOQ_j: incremental order quantity (IOQ) of product j. The incremental order tells us the quantity when we want to increase our order. For example, when the IOQ is 100 we increase our order with a multiple of 100 quantities.

Now we can apply the procedure of Soman et al. (2004) to find the fundamental cycle period for each production line. The formulas that we use are described by Soman et al. (2004), however, we change the notations in the formulas because we have multiple production lines instead of a single production line. Also, we add a formula for calculating the number of batches.

The cost for each semi-finished product j produced on production line i per unit time is given by:

(1) $$C_{ij} = \frac{s_j}{T_{ij}} + \frac{1}{2} h_j T_{ij} d_j (1 - \frac{d_j}{p_j}).$$

T_{ij} is the cycle period of product j produced on production line i. We can obtain T_{ij} from the formula:

(2) $$T_{ij} = k_{ij} T_i^*.$$

T_i^* is the fundamental cycle period of production line i and k_{ij} are the production frequencies of product j produced on production line i. For the production frequencies, we use integers that are of the power of two, i.e. (1, 2, 4, 8, 16,…). We use integers of the power of two because it becomes easier to define the total cycle length. According to Soman et al. (2004), it is common to use the power of two in economic lot-sizing problems. The use of integers of the power of two results in a 6% costlier solution in the worst case. We explain later how we determine the total cycle length.

Now we can define the total cost for all the production lines per unit time:

(3) $$C = \sum_{i=1}^{4} \sum_{j=1}^{N} C_{ij} = \sum_{i=1}^{4} \sum_{j=1}^{N} \{ \frac{s_j}{k_{ij} T_i^*} + \frac{1}{2} h_j k_{ij} T_i^* d_j \left(1 - \frac{d_j}{p_j}\right) \}$$

In (3), N is the set of semi-finished products produced on production line i.

The maximum duration of a semi-finished product in inventory is: $T_{ij}(1 - \frac{d_j}{p_j})$ (4). When we set an inventory duration constraint we have the following condition:

(5) $$T_i^* \leq \left\{ \frac{w_j}{k_{ij}(1 - \frac{d_j}{p_j})} \right\}$$

From (5) we can set an upper bound for a given set of products j produced on production line i by:

(6) $$T_i^* \leq \min_j \left\{ \frac{w_j}{k_{ij}(1 - \frac{d_j}{p_j})} \right\}$$

Equation (6) gives the maximum duration a product is in inventory. We take the lowest value from a given set of products produced on production line i. The fundamental cycle period must be smaller or equal to this duration.

We can also set a lower bound. There must be sufficient time to handle the average number of setups required for all semi-finished products. The lower bound is defined by:

(7) $$T_i^* \geq \frac{\sum_{j=1}^{N} u_j / k_{ij}}{(1 - \sum_{j=1}^{N} \frac{d_j}{p_j})}$$

To obtain a feasible plan for every production line we define a plan with a length that is equal to the least common multiple (LCM) of k_{ij} values times the fundamental cycle period T_i^*. The LCM is the smallest positive integer that is divisible by the values k_{ij}. With the production frequencies k_{ij} that are equal to integers of the power-of-two, i.e. (1, 2, 4, 8, 16,…), we can find easily the least common multiple because *LCM*(k_{ij}) is $max(k_{ij})$. Now we can define the total cycle length on production line i by $LENGTH_i = LCM(k_{ij}) \times T_i^*$ (8).

Soman et al. (2004) describe a 7 step procedure to find the values for the fundamental cycle period. We provide a slightly modified procedure of Soman et al. (2004) in Appendix B to find the fundamental cycle period for every production line by taking into account a maximum inventory duration constraint.

The fundamental cycle period values T_i^* together with the production frequency integer multiples k_{ij} we have a good indication and the starting point of a production plan. We can define the total processing time per lot by $PT_{ij} = T_{ij}d_j/p_j$ (9) where $T_{ij} = k_{ij}T_i^*$ (2) the cycle time for product j on production line i. From this formula, we see those semi-finished products with a low ratio of d_j/p_j result in a relatively short processing time per lot. For the processing department of Company X, very short processing times per lot are not favourable. We can increase the processing time by increasing the maximum inventory waiting time or increasing the production frequency integer multiple k_{ij} values to obtain a higher fundamental cycle period. Increasing the production frequency reduces the fundamental cycle period.

Also, semi-finished products are produced in batches. Therefore, we need to take into account the batch size of semi-finished products. To find the next batch size we define the formula: $BATCH_j = \frac{PT_{ij}p_j}{IOQ_j}$ (10) where $BATCH_j$ are the number of batches for semi-finished product j and where IOQ_j is the incremental order quantity for product j. In this formula, we multiply the processing time with the production rate. This will give the total quantity that we produce. When we divide by the incremental order quantity we have the number of batches.

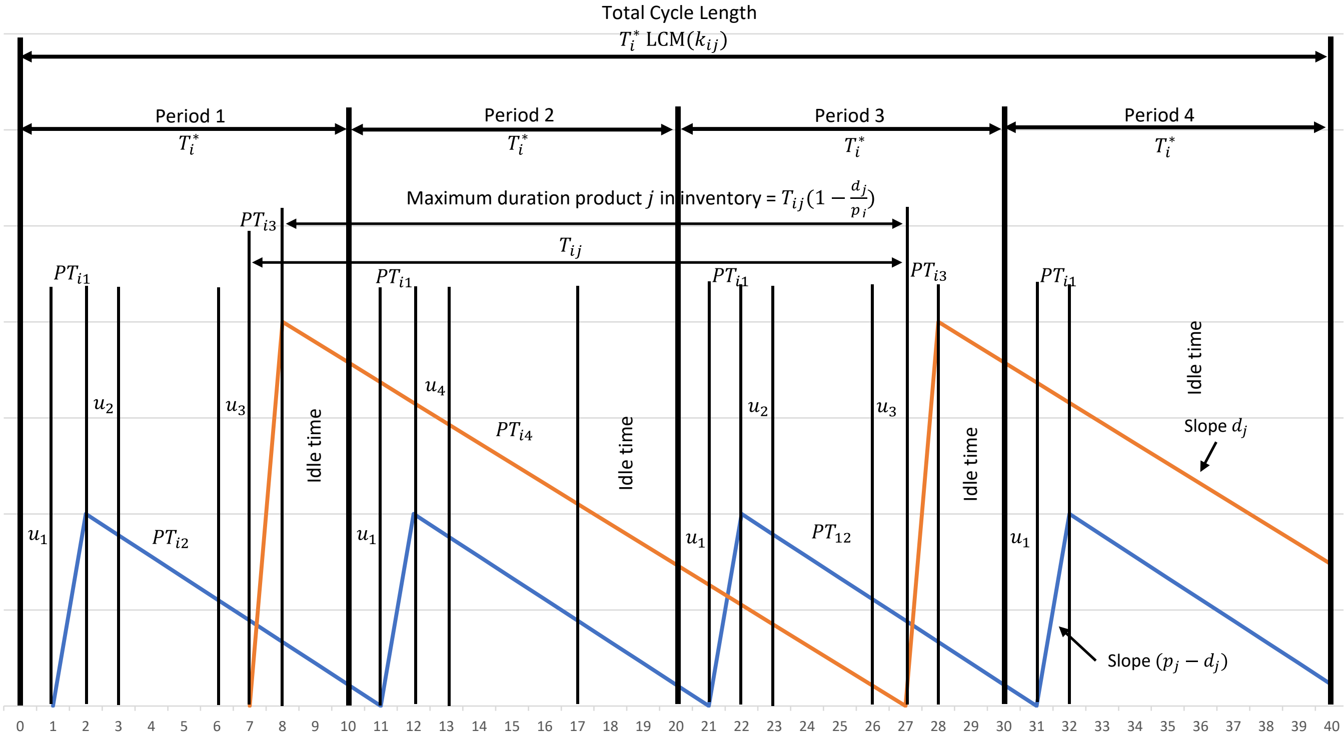

Figure 14: Example production plan with the fundamental cycle period. Applied from Soman et al. (2004) but modificated

Figure 14 illustrates a graph to give a better understanding of the fundamental cycle period. In this graph, we have a production plan for semi-finished products 1, 2, 3, 4 with a fundamental cycle period of T_i^* and k_{ij} values of 1, 2, 2, 4 respectively. We indicate the processing times PT_{ij}, the setup times u_j. Semi-finished product 1 is produced every period while semi-finished products 2 and 3 are both produced in the first and third period. Semi-finished product 4 is produced only in the second period. We also illustrate the inventory development over time for semi-finished products 1 and 3, the colours blue and orange respectively. Next to this, we also show the cycle time and the maximum duration in the inventory of semi-finished product 3.

4.3.2 MTO and MTS considerations in the fundamental cycle period

The decision for MTO and MTS for semi-finished products is complex and requires close relationships with the packaging department and the customers. We decide to not use MTO products in the calculation of the fundamental cycle period. Soman et al. (2007) suggested to reserve capacity for MTO products in each cycle or use the idle time.

Another consideration is the relatively low demand for semi-finished products. From formula 9 we see that low demands lead to short processing times. We can handle semi-finished products as MTO products and leave these products out of the calculation of the fundamental cycle period. When we reserve capacity for MTO products we can produce these products when they are needed. With a combination of inventory management software, like Slim4, it is possible to let the software decide when to produce an MTO product.

4.4 Production scheduling

Scheduling is a complex task, especially when we have sequence-dependent setups between products. Section 4.4.1 describes a heuristic to find a feasible schedule for every production line in every fundamental cycle period. We do not consider MTO products in the schedule because they are not produced regularly. We want to first create a relatively fixed schedule for MTS products. For MTO products, we advise using human interaction and decision-making in scheduling.

4.4.1 Scheduling heuristic

First, we define a setup matrix for product families. The product families are the corresponding allergen codes of the semi-finished products. Appendix A provides an allergen flow scheme. Semi-finished products need to follow a specific order to avoid allergen contamination. When we switch to an allergen that is not in the determined order, a cleaning time of 6 hours is required. Table 2 specifies the setups between allergen codes from the overview of the allergen flow scheme.

		To										
		1	2	3	4	5	6	7	8	9	10	11
From	1	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	6	6	0	0	0	0	0	0	0
	3	0	6	0	6	6	6	6	0	6	6	0
	4	0	6	6	0	6	0	6	6	0	0	0
	5	0	6	6	6	0	6	6	0	0	6	0
	6	0	6	6	6	6	0	6	6	0	0	0
	7	0	6	6	6	6	6	0	0	6	0	0
	8	0	6	6	6	6	6	6	6	6	6	0
	9	0	6	6	6	6	6	6	6	0	6	0
	10	0	6	6	6	6	6	6	6	6	0	0
	11	0	6	6	6	6	6	6	6	6	6	0

Table 2: Allergen setup matrix

Gupta and Magnusson (2008) describe a scheduling heuristic named: Initialize, Sequence, and Improve (ISI). We describe the steps Initialize, Sequence, and Improve in Section 4.4.1.1, Section 4.4.1.2, and Section 4.4.1.3 respectively. This scheduling heuristic finds a feasible solution for sequence-dependent products without exceeding capacity and minimizing setup cost. In the heuristic, it is allowed to have overtime when it is not possible to schedule all products within the available time. However, we do not want overtime because it violates cycle planning. Section 4.4.1.3 describes the suggestions for eliminating overtime.

Besides the possibility of overtime, the heuristic is easily adaptable and provides a good structure. Therefore, we apply some general guidelines from this heuristic to find a feasible schedule.

4.4.1.1 Initialize

Section 4.3 describes a procedure to find a feasible production plan for MTS products. From this procedure, we find an optimal cycle length for every production line which cover all the product cycles. Applying the algorithm from Section 4.3 we find the fundamental cycle period T_i^*, the total cycle length $LENGTH_i$, and the production frequencies k_{ij}. We illustrate an example with simplistic numbers to give an impression of the first step in finding a feasible schedule.

i, j	k_{ij}
1,1	1
1,2	1
1,3	2
1,4	2
1,5	4

Table 3: Production frequency example

We have semi-finished products $j = 1, \dots, 5$ to be produced on production line $i = 1$. The corresponding production frequencies k_{ij} are:

The total cycle length is $LENGTH_1 = 4$ weeks and the fundamental cycle period is $T_1^* = 1$ week.

Product	Week 1	Week 2	Week 3	Week 4
1	100	100	100	100
2	100	100	100	100
3	0	50	0	50
4	50	0	50	0
5	25	0	0	0

Table 4: Production plan example

Table 3 gives the production frequency of the products. So, we produce product 1 and 2 every week ($k_{ij} = 1$), product 3 and 4 once in two weeks ($k_{ij} = 2$) and product 5 once in four weeks ($k_{ij} = 4$). Table 4 illustrates an example of the production plan based on the production frequencies.

Therefore, we already determined which product we produce in a cycle period. Products with values $k_{ij} > 1$ are more flexible to schedule. However, we need to take into account the cycle period and the production frequencies of these products.

In the first step of initializing the schedule, we ignore setup times. We start with all products where $k_{ij} = 1$. We need to produce these products every period. We sequence the products in order of decreasing processing time during a cycle period. So we start with products with the highest processing time. The idea is that it is easier to generate a possible schedule by scheduling products with longer processing times first. We fill the gaps in the sequence by producing products with shorter processing times. After all products with $k_{ij} = 1$, we take values of $k_{ij} = 2$. Also here, we start with the product with the highest demand. When the product exceeds the capacity constraint in the given period we shift that product to the next period. We continue increasing k_{ij} until we have scheduled all the products. We need to take into account the cycle times of k_{ij}. So when $k_{ij} = 2$ we schedule that product once every two cycle periods.

In a cycle period we have a capacity constraint. The capacity constraint is defined by the total processing hours that are available in a cycle period. We do not use the demand as a constraint because every product has a different production rate. Therefore, some products can have a shorter processing time with equal demand. The capacity constraint is given by $\sum_{j \in N} \frac{T_{ij} d_j}{p_j} \leq K_{T_i^*}$ (11) for all $i = 1, \ldots, 4$ with $K_{T_i^*}$ the available processing time per cycle period and N the set of semi-finished products.

Now we have allocated production of all period we compute the potential capacity that is required to meet the schedule by taking into account possible setup time between products with different allergen codes.

Next, we work backwards from the end of the planning horizon to the first period. The objective is to not violate the capacity constraint in each period. When the capacity constraint is violated we move the remaining products to the next period. Keep in mind that we need to produce products with $k_{ij} = 1$ in every cycle period. This means we cannot move these products to different cycle periods. We continue until we reach period 1. We can use the remaining available processing time at the end of each period for production MTO products. We believe that the production planner can decide what to do with the remaining production time. Therefore, we do not fill the gap by the heuristic.

If we do not have sufficient capacity in the first period we do the procedure again. We concentrate on the products with production frequency larger than 1, i.e. $k_{ij} > 1$. We check if we can produce some products in different cycle periods that have processing time available. If we do not find a feasible schedule after the second check then the heuristic stops and conclude that it is not possible to generate a feasible schedule given the available capacity.

4.4.1.2 Sequence

We have now determined which products we need to produce in each period. For sequencing, we start with the first product in each period with the longest processing time. We have categorized families based on the allergen of the products. Appendix A illustrates the allergen flow scheme. We continue to look for a product with an allergen code that is ranked highest in the allergen flow scheme. In our situation allergen numbers 2, 3, or 4 are ranked highest. It is more ideal to start at the top of the flow scheme and work downwards. The advantage of working from top to bottom is the reduced number of allergen switches that require additional cleaning.

The next product to be sequenced is the one with the lowest setup time. The lowest setup time is a product of the same family. Therefore, we look for products from the same family. After all the products from the same family are scheduled we look for a product with the lowest setup time. Keep in mind that we work from top to bottom in the allergen flow scheme. So, we can go from allergen code 6 to allergen code 11 without additional setup time. However, we first look for products with allergen code 9 or 10. We continue until we have scheduled all products in a given period. We go to the next period and start the sequencing procedure again. We do this until we have scheduled all periods.

In the initialize step we do not take into account the setup times. We have only a limit available processing time per cycle. When the setup time is included we may have overtime in a cycle. Section 4.4.1.3 provides solutions for improving the schedule and eliminate overtime.

4.4.1.3 Improve

Gupta and Magnusson (2008) apply an improvement step to the feasible solution obtained from the first two steps. They test whether it is possible to lower cost by shifting production in two different periods to a single period. This results in fewer setups but higher inventory levels thus higher holding costs. This improvement step is reasonable when the setup cost is significantly higher than the holding cost per product. Section 4.4.1.2 mentions the possibility of having over time in a cycle. However, we do not want overtime because this violates the cycle planning. Therefore, we provide some solutions for eliminating overtime.

First, we can change the production frequency k_{ij} from the calculation of the fundamental cycle period. Increasing these values will result in longer processing times and fewer setups. After changing the production frequency we need to apply the procedure of the fundamental cycle period and the scheduling heuristic again. We change the production frequencies until we find a feasible schedule with the elimination of overtime.

Second, it is possible to shift products to a different production line. Most of the products have an alternative production line. However, this is mostly not the most efficient production. We can shift products to a production line with sufficient available processing time. When we shift products to a different production line we need to calculate the procedure of the fundamental cycle period and the scheduling heuristic again.

4.5 Overview of fundamental cycle period and scheduling

Figure 15 illustrates all the steps of the solution design in a flow scheme. This flow scheme will help to execute the solution design. We divide the flow scheme is in 3 sections. We start with MTO-MTS considerations. We continue to the calculation of the fundamental cycle period. Last, we apply the ISI scheduling heuristic. When we do not have sufficient processing time available we change the production frequencies of the semi-finished products.

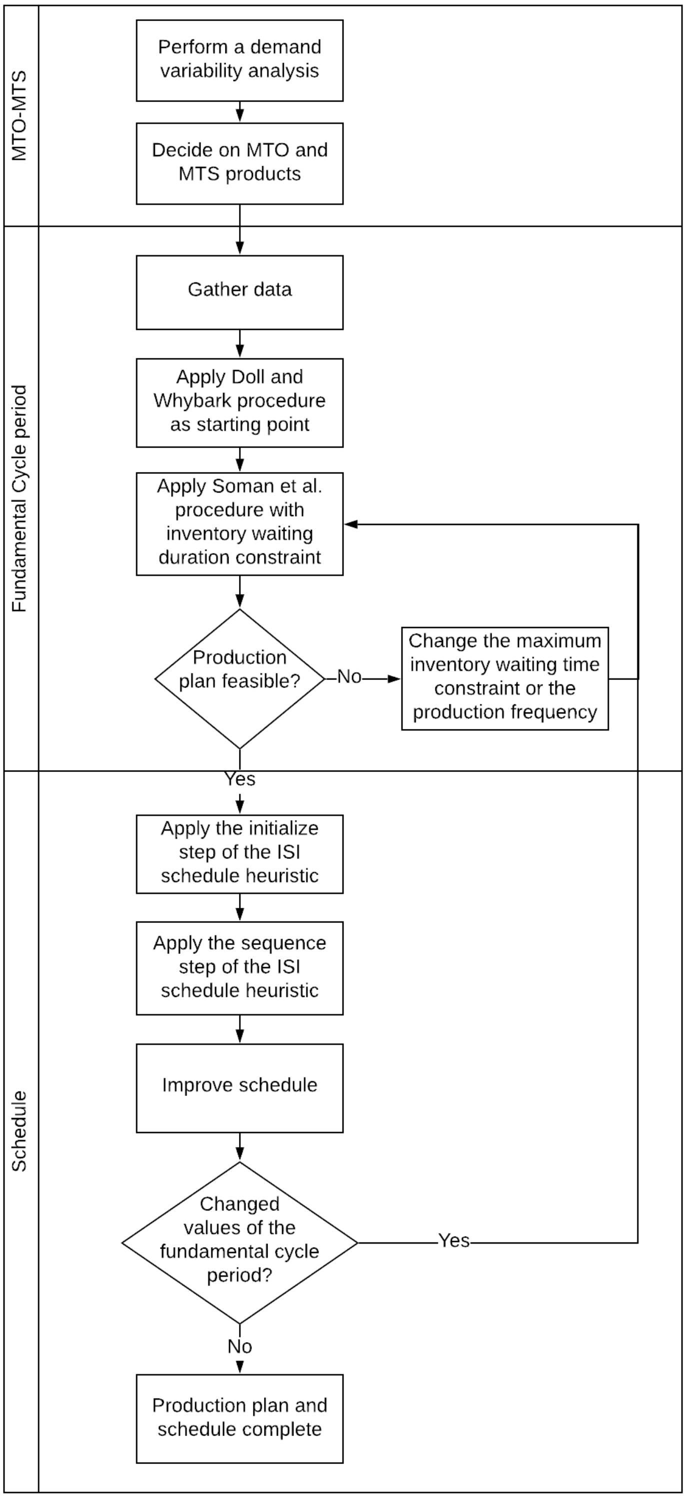

Figure 15: Solution design overview

4.6 Production planning performance

Section 3.4 describes performance measurements for production planning. The models that we find for two-stage production systems are mostly focused on total costs. For Company X the delivery performance is one of the most important KPIs. However, because we only focus on the first stage of a two-stage production system it becomes difficult to measure the delivery performance from our proposed solution design. From the proposed models in our solution design we can measure the following performances:

- Total costs. This is the setup and the holding costs.
- Average processing times. Take the average of the results from equation 9 from Section 4.3.1.
- Average inventory duration. Take the average of the results from equation 4 from Section 4.3.1.
- Number of required cleanings in the schedule

We use these performance measures for the solution design. Also, Company X is already using the KPI inventory in days to measure the total inventory time of semi-finished products.

4.7 Conclusion

In this chapter describes a solution design based on the literature of Chapter 3. We look at how we can improve production planning in the first stage of a two-stage production system. In the first stage often a cyclic production planning is used. The procedure described by Doll and Whybark (1973) is a well know procedure for cyclic production planning. Soman et al. (2004) use this procedure in combination with a shelf-life constraint.

We use and modify the procedures described by Doll and Whybark (1973) and Soman et al. (2004) for creating a cyclic production planning with a fundamental cycle period. We define the parameters in the formulas of the procedure. Before we execute this procedure we describe the MTO and MTS considerations in the calculation of the fundamental cycle period. We do not include MTO products in this procedure. By reserving capacity in the cycle planning we can produce MTO products.

We use the fundamental cycle period as input for the schedule. We create a schedule by the means of the ISI heuristic. The ISI heuristic has three steps, namely: Initialize, Sequence, and Improve. This heuristic takes into account the sequence dependency between the products. In the initialize step we create a schedule based on the production frequencies and the available processing time per cycle. In the sequence step, we sequence the products in each cycle based on the allergens of the semi-finished products. The allergens are defined by the means of an allergen flow scheme. We require a setup when we switch to an allergen that is not in the order of this flow scheme. The improve step is for looking for opportunities to improve the schedule. There may be overtime in the schedule. The overtime is not allowed because this violates the cycle planning. We provide a solution to eliminate overtime. Next to this, we provide an overview of all the steps of the solution design.

Last, we look at the production planning performances. We use the total cost, average processing times, average inventory duration, and the number of required cleanings in the schedule as performance measurements.

5 Implementation

In this chapter implements the solution design that is described in Chapter 4. Section 5.1 explains the data availability at Company X. Next, Section 5.2 explains the execution of the solution design from Chapter 4. Section 5.3 performs a demand variability analysis to check for MTO and MTS products. Furthermore, Section 5.4 calculates the fundamental cycle period for every production line. Section 5.5 applies the scheduling heuristic to transform the production plan into a feasible schedule. Section 5.6 explains the performance measurements. Section 5.7 performs a sensitivity analysis. Section 5.8 gives the validation of the results. Last, Section 5.9 provides a conclusion.

5.1 Data availability

The first step is to get the required information that is needed for the solution design. Section 2.3 explains the systems that are used in production planning. The main systems are Slim4 and the ERP system Fobis. We use the data of Slim4 to derive the forecast for the semi-finished products. This forecast is an aggregated forecast from the finished products. Unfortunately, it is not possible to retrieve accurate historical data for the demand of semi-finished products. Therefore, we only consider the forecast for the upcoming 52 weeks. We use the data from the date 14-08-2020.

We use Fobis to retrieve the data for the bill of materials and other specific information. For example, we retrieve the production rates, IOQ, and MOQ.

We retrieve the information about costs, such as holding cost and setup cost, from the financial department of Company X.

5.2 Execution of the solution design

To execute the solution design, we program the models in Visual Basic. Visual Basic is built into Excel. We choose Visual Basic because it is a relatively easy programme language and it works with Excel. Excel is easily accessible for other persons and is also widely used by employees of Company X. The programme is executed based on the visual illustration of the solution design that we present in Section 4.5.

5.3 MTO and MTS considerations

Section 4.2 discusses the consideration of MTO and MTS products. We perform a demand variability analysis to check for MTO and MTS products. We use the average weekly forecasted demand based on the coming 52 weeks. We retrieve this forecast from Slim4. Also, we calculate the coefficient of variation for the variability in the demand. Several semi-finished products have an average weekly demand of zero. This means that the product is already MTO or is in the phased-out. Therefore, we exclude these products in the analysis.

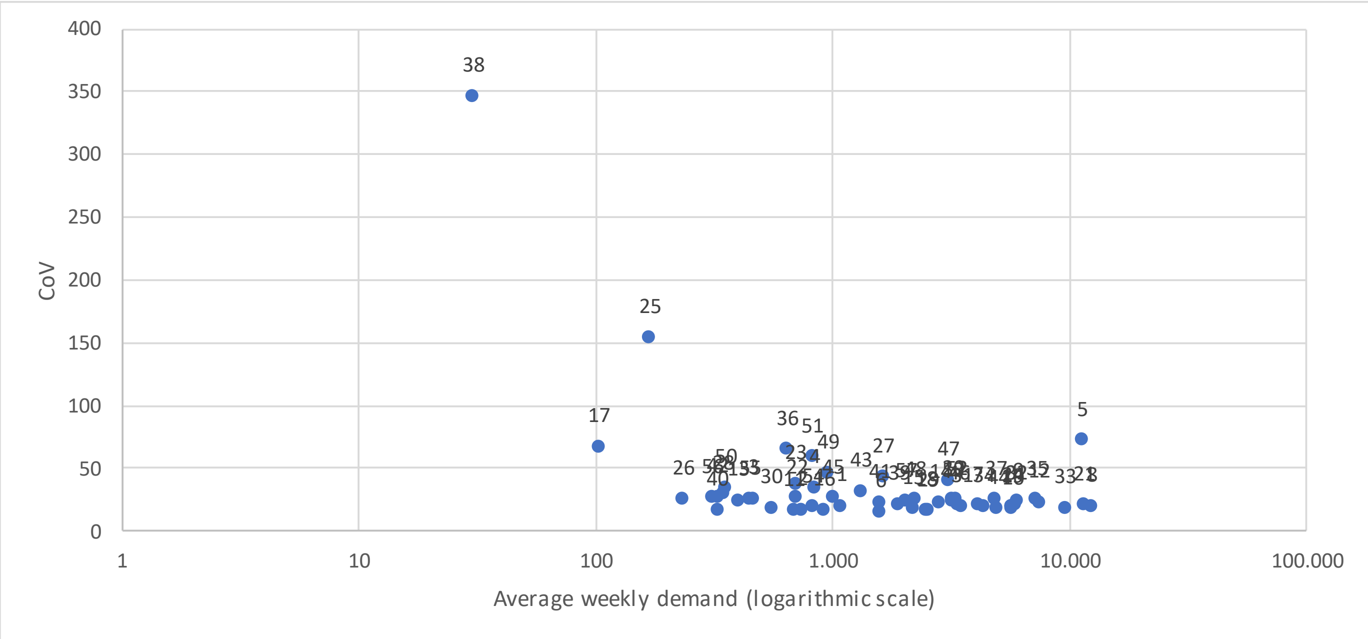

Figure 16: Demand variability analysis

Figure 16 illustrates the analysis. On the X-axes, we have the average weekly demand on a logarithmic scale and on the Y-axes the coefficient of variance. Semi-finished products with high-volume and low variability are candidates for MTS. Products with low volume and high variability are candidates for MTO.

Products 17, 25, and 38 are good candidates for MTO. The remaining products have relatively low variability. However, several products do not have a high volume. We can consider semi-finished products with very low volume as MTO. As a guideline, we decide to exclude products with demand lower than the incremental order quantity. This will exclude the products in the calculation of the fundamental cycle period. Appendix C illustrates an overview of the semi-finished products together with the required information.

The advantage of excluding MTO products is the reduced number of cycle periods and longer processing times. Also, Slim4 is a powerful tool to advice when to produce an MTO product based on actual information, such as new customer orders.

5.4 Fundamental cycle period calculation

We apply the algorithm from Section 4.3. We have an Excel file that calculates the fundamental cycle period for every production line. We use the products that remain after the constraints that we set in Section 5.3. This gives a list of a total of 39 semi-finished products that we include and we exclude 19 semi-finished products.

For the holding cost, we use a fixed holding cost per kg per week for every product. We do not have enough detailed information for the calculation of the holding cost for every semi-finished product. However, because the semi-finished products are stored on pallets with 320 kg each, we assume that the holding costs are equal for all semi-finished products. For the setup cost, we perform an analysis of the average setup time for every semi-finished product from year to date. With this time, we use a cost price per time unit. For the maximum duration in inventory, we consider a maximum of 6 weeks. The supply chain has as target an inventory level of 3 to 4 weeks. However, with 6 weeks we have a sufficient maximum inventory duration for all the production lines. Preferably, the maximum duration can change to a lower level. Appendix D presents all the input data. We use weeks as time unit were one week is 5 working days.

We apply the algorithm with the given data. After applying the procedure of Soman et al. (2004), which is explained in Section 4.3 and Appendix B, we have the following results for the lower bound, upper bound, fundamental cycle period, least common multiple of the production frequency, the total holding and setup cost, total cost, and the total cycle length. Table 5 illustrates these results. The total cost for the 4 production lines is €6,369.08. Table 6 illustrates the results of 5 semi-finished products. The results for every semi-finished product are illustrated in Appendix E.

	Production line 11 ($\boldsymbol{i} = \mathbf{1}$)	**Production line 21 ($\boldsymbol{i} = \mathbf{2}$)**	**Production line 31 ($\boldsymbol{i} = \mathbf{3}$)**	**Production line Company Z ($\boldsymbol{i} = \mathbf{4}$)**
#Products	16	13	7	3
Lower bound T* in weeks	0.1412	0.0531	0.0258	0.0067
Upper bound T* in weeks	3.0192	1.5132	3.0446	3.0744
Fundamental cycle period $\boldsymbol{T_i^*}$ in weeks	0.89	0.69	0.79	0.63
Least common multiple of $\boldsymbol{k_{ij}}$	2	4	2	2
Total Cycle Length in weeks	1.78	2.76	1.58	1.27
Holding cost for the total cycle length	€ 1,211.24	€ 1,031.14	€ 638.24	€ 303.91
Setup cost for the total cycle length	€ 1,211.24	€ 1,031.14	€ 638.24	€ 303.91
Total cost for the total cycle length	€ 2,422.48	€ 2,062.28	€ 1,276.49	€ 607.83

Table 5: Initial plan

Product nr	**Art. Code**	**Production line**	**Demand per week in kg**	**Processing time in hours**	**Duration in inventory in weeks**	**LOT size in kg**	**#Batches**	**Production frequency**
38	557356	11	690	1.21	1.77	1,231	2.37	2
36	557311	11	760	1.79	1.76	1,355	2.14	2
16	557822	11	3,630	3.75	0.84	3,237	2.59	1
12	557122	11	5,130	3.81	0.84	4,575	3.63	1
13	557145	11	4,910	3.86	0.84	4,379	2.28	1

Table 6: Results of 5 semi-finished products from the initial plan

We give some explanation for Table 5. The lower bound and upper bound of T* are determined by equations 6 and 7 from Section 4.3.1 respectively. The fundamental cycle period or the cycle length needs to be higher than the lower bound and lower than the upper bound. The LCM is the smallest positive integer that is divisible by the values k_{ij}. With the LCM and the fundamental cycle period we can determine the total cycle length, see equation 8 in Section 4.3.1. We determine the total cost with equation 3.

We notice that the total cycle length is not practical to use, i.e. 1.78 weeks is 8.9 working days. Section 5.8.1 explains the practical use of the results.

After examining the processing time per lot for the semi-finished products, we decide to try to increase the processing time to a minimum of around 3 to 4 hours processing time. Shorter processing times are not favourable for the processing department. We do this by increasing the production frequencies. Section 4.3.1 mentions the use integers of the power-of-two for the production frequencies, i.e. 1, 2, 4, 8, 16. However, we do not increase the production frequency higher than the 8. Therefore, we only change the production frequency to 1, 2, 4, or 8. We choose to go no higher than 8 because increasing the production frequency higher than 8 will result in too many cycles with short fundamental cycle periods.

Table 7 illustrates the result after changing the production frequencies and Table 8 the results of 5 semi-finished products. The results of all the semi-finished products are given in Appendix E.

	Production line 11 ($i = 1$)	**Production line 21 ($i = 2$)**	**Production line 31 ($i = 3$)**	**Production line Company Z ($i = 4$)**
#Products	16	13	7	3
Lower bound T* in weeks	0.0466	0.0162	0.0100	0.0028
Upper bound T* in weeks	0.7548	0.7566	1.5223	1.5372
Fundamental cycle period T_i^* in weeks	0.6460	0.4997	0.6786	0.5482
Least common multiple of k_{ij}	8	8	4	4
Total Cycle Length in weeks	5.17	4.00	2.71	2.19
Holding cost for the total cycle length	€ 1,266.28	€ 1,062.51	€ 643.89	€ 316.82
Setup cost for the total cycle length	€ 1,266.28	€ 1,062.51	€ 643.89	€ 316.82
Total cost for the total cycle length	€ 2,532.55	€ 2,125.02	€ 1,287.78	€ 633.63
Feasibility	Feasible	Feasible	Feasible	Feasible

Table 7: Results after changing the production frequencies

Product nr	**Art. Code**	**Production line**	**Demand in kg**	**Processing time in hours**	**Duration in inventory in weeks**	**LOT size in kg**	**#Batches**	**Production frequency**
4	558203	11	9,680	8.17	0.54	6,253	3.42	1
28	557172	11	1,960	2.22	1.26	2,532	4.62	2
34	557853	11	850	3.63	2.54	2,196	3.72	4
38	557356	11	690	3.50	5.12	3,566	6.86	8
37	557139	11	760	3.27	5.13	3,928	6.99	8

Table 8: Results of 5 semi-finished products after changing the production frequencies

The total cost for the 4 production lines is €6578.98 which is 3.3% higher than before the change. The fundamental cycle period is reduced but the total cycle length is increased. So, we have shorter cycles over a longer planning horizon. The fundamental cycle period is still feasible which means all the semi-finished products have an inventory duration shorter than 6 weeks. Also here, we have total cycle lengths that are not practical for production line 11, 31 and Company Z. Section 5.8 explains the practical use of the results.

The average processing times per production line is:

Production line	**Average processing time in hours**	**Average inventory duration in weeks**
Production line 11	3.78	1.89
Production line 21	3.37	1.57
Production line 31	4.04	1.11
Production line Company Z	4.55	1.04

5.5 Scheduling

Section 5.4 describes a feasible production plan. We schedule this production plan over the planning horizon. For every production line, we find a fundamental cycle period. This cycle period is the length of a single cycle. We have the following results for the fundamental cycle period:

	11	**21**	**31**	**Company Z**
Fundamental cycle period T_i^* in weeks	0.6460	0.4997	0.6786	0.5482

This is not a practical number. Therefore we choose to round the fundamental cycle period to the nearest value that gives whole production days. In Section 5.8 we provide further explanation of the practical use of the results. We transform the results from weeks to working days. We have 5 working days in a week, so the results are now:

	11	**21**	**31**	**Company Z**
Fundamental cycle period T_i^* in days	3 days	2 days	3 days	3 days

Multiplying the fundamental cycle period by the least common multiple of the production frequencies we find the total cycle length. See Figure 14 in Section 4.3 for an example of a cyclic production plan. We start by arranging the semi-finished products in order of long processing times to short processing times. Then we work backwards from the last cycle to the first cycle to make sure we do not violate the capacity.

After we have a schedule that does not violate the capacity in every cycle we continue with sequencing. First, we look for the products with an allergen that is at the top of the allergen flow scheme. We continue by working from top to bottom in the allergen flow scheme. When we reach the bottom and still have semi-finished products to schedule then cleaning is required. After the cleaning, we can start again at the top of the allergen flow scheme and work downwards until all semi-finished products are scheduled.

Production Line 11																
Cycle	1	1	1	1	1	1	New Cycle	2	2	2	2	2	2	2	2	2
Art. code	557616	558203	557122	557822	Cleaning Required	557851	Cleaning R	557616	558203	557343	558234	557591	557122	557822	Cleaning R	557145
Allergen	2	6	10	11	Cleaning Required	5	Cleaning R	2	6	6	6	6	10	11	Cleaning R	8
Number of batches	2,189361	3,1149272	2,394945	1,7109636	N/A	2,020686	N/A	2,189361322	3,114927	2,964097	2,394064	4,297971032	2,394945035	1,7109636	N/A	3,008562
Processing Time	2,597886	7,6703341	2,698026	2,671391867	6	7,115516	6	2,597886105	7,670334	4,725139	3,291747	2,745544142	2,69802562	2,671391867	6	5,386084
Cumulative Required Time in hours	2,597886	10,26822	12,96625	15,63763772	21,63763772	28,75315		2,597886105	10,26822	14,99336	18,28511	21,03065025	23,72867587	26,40006774	32,40007	37,78615
Production line																
Cycle	1	1	1	1	New Cycle	2	2	2	2	2	2	2	New Cycle	3	3	3
Art. code	558105	557354	558132	558123	Cleaning Required	558119	557405	557329	558105	557354	558123	558132	Cleaning Required	558164	558105	557354
Allergen	6	6	10	10	Cleaning Required	6	6	6	6	6	10	10	Cleaning Required	6	6	6
Number of batches	2,752771	2,8269599	3,26281	3,273888792	N/A	3,582969	1,94587	1,801007126	2,752771	2,82696	3,273889	3,262809643	N/A	6,054391501	2,752771	2,82696
Processing Time	2,308192	4,5540631	3,625858	5,047236347	6	2,774152	3,17172	3,090586083	2,308192	4,554063	5,047236	3,625858291	6	3,803118381	2,308192	4,554063
Cumulative Required Time in hours	2,308192	6,862255	10,48811	15,5353496		2,774152	5,945872	9,036458078	11,34465	15,89871	20,94595	24,57180768		3,803118381	6,11131	10,66537
Production Line 31																
Cycle	1	1	1	1	New Cycle	2	2	2	2	2	2	New Cycle	3	3	3	3
Art. code	557627	557281	557223	557224	Cleaning Required	557225	557627	557281	557224	557223	557123	Cleaning Required	557627	557281	557223	557224
Allergen	6	6	10	10	Cleaning Required	6	6	6	10	10	10	Cleaning Required	6	6	10	10
Number of batches	4,757726	4,2466605	1,699302	3,31929388	N/A	5,523724	4,757726	4,246660483	3,319294	1,699302	2,578532	N/A	4,757726057	4,246660483	1,699302	3,319294
Processing Time	3,989557	4,6250778	4,596209	4,573835835	6	5,347349	3,989557	4,625077751	4,573836	4,596209	3,18856	6	3,989557101	4,625077751	4,596209	4,573836
Cumulative Required Time in hours	3,989557	8,6146349	13,21084	17,78467967		5,347349	9,336906	13,96198413	18,53582	23,13203	26,32059		3,989557101	8,614634852	13,21084	17,78468
Production Line Z																
Cycle	1	1	1	New Cycle	2	2	2	New Cycle	3	3	3	New Cycle	4	4	4	4
Art. code	558812	Cleaning Re	557187	Cleaning Required	558812	Cleaning R	557187	Cleaning Required	558812	Cleaning R	557187	Cleaning Required	558812	557152	Cleaning R	557187
Allergen	2	Cleaning Re	4	Cleaning Required	2	Cleaning R	4	Cleaning Required	2	Cleaning R	4	Cleaning Required	2	6	Cleaning R	4
Number of batches	5,129364	N/A	2,836934	N/A	5,12936435	N/A	2,836934	N/A	5,129364	N/A	2,836934	N/A	5,12936435	8,689221747	N/A	2,836934
Processing Time	6,495301	6	3,2239	6	6,495300983	6	3,2239	6	6,495301	6	3,2239	6	6,495300983	4,401898089	6	3,2239
Cumulative Required Time in hours	6,495301	12,495301	15,7192		6,495300983	12,4953	15,7192		6,495301	12,4953	15,7192		6,495300983	10,89719907	16,8972	20,1211

Figure 17: Schedule

Figure 17 shows the outcome of the scheduling heuristic for the 4 production lines. For every production line, we start at the first cycle. We start producing the product with the highest position in the allergen flow scheme. We continue to look for products with the same allergen code. If there is no product with the same allergen code than we go to the next allergen code in the allergen flow scheme. We repeat these steps until we have scheduled every product that belongs to the cycle or until we reach the capacity.

	Production line 11	Production line 21	Production line 31	Production line Company Z
#Products	16	13	7	3
Total cycle length in days	24	16	12	12
Total number of required cleanings over the total cycle length	16	0	0	4
Total available time	384	256	192	192
Total processing time with cleaning time	461.79	197.22	91.61	67.28
Total remaining processing time	-23.08	58.78	100.39	124.72

Table 9: Summary of the initial schedule

Table 9 gives a summary from the schedule. This summary gives the number of required cleanings, the total processing time of all cycles and the total time that is available after processing. We see that we have still processing time available for production line 21, 31 and Company Z. We fill this time by producing MTO products or increasing the number of batches of the current MTS products.

5.5.1 Feasibility check

We do have overtime for production line 11. When we do not take into account cleaning time we have enough processing time available. Section 4.4.1.3 provides solutions for eliminating overtime in the schedule.

We want to have a schedule that has sufficient available processing time for all the production lines. We choose to change some production frequencies for semi-finished products produced on production line 11. Increasing the production frequency results in fewer setups. We change the production frequency of the product with the lowest processing time. We do this until we have a schedule with sufficient available processing time. However, this procedure also changes the results of the procedure of the fundamental cycle period. Table 10 presents the new results of the fundamental cycle period.

	Production line 11 ($i = 1$)	**Production line 21 ($i = 2$)**	**Production line 31 ($i = 3$)**	**Production line Company Z ($i = 4$)**
Lower bound T* in weeks	0.0416	0.0162	0.0100	0.0028
Upper bound T* in weeks	0.7548	0.7566	1.5223	1.5372
Fundamental cycle period T_i^* in weeks	0.5882	0.4997	0.6786	0.5482
Least common multiple of k_{ij}	8	8	4	4
Total Cycle Length in weeks	4.71	4.00	2.71	2.19
Holding cost for the total cycle length	€ 1,263.58	€ 1.062,51	€ 643.89	€ 316.82
Setup cost for the total cycle length	€ 1,263.58	€ 1,062.51	€ 643.89	€ 316.82
Total cost for the total cycle length	€ 2,527.17	€ 2,125.02	€ 1,287.78	€ 633.63
Feasibility	Feasible	Feasible	Feasible	Feasible

Table 10: Results of the fundamental cycle period with a feasible schedule

Table 11 shows the effect on the average processing time and the average inventory duration.

Production line	**Average processing time in hours**	**Average inventory duration in weeks**
Production line 11	3.71	1.83
Production line 21	3.37	1.57
Production line 31	4.04	1.11
Production line Company Z	4.55	1.04

Table 11: Results of the new measurements

After changing the results we find a lower cost for production line 11. The total cost is now €6,573.60. However, the average processing time and the average inventory duration is slightly reduced. Table 12 presents the new summary of the results after applying the scheduling heuristic.

	Production line 11	Production line 21	Production line 31	Production line Company Z
#Products	16	13	7	3
Total cycle length in days	24	16	12	12
Total number of required cleanings over the total cycle length	14	0	0	4
Total available time in hours	384	256	192	192
Total processing time with cleaning time in hours	377.90	197.22	91.61	67.28
Total remaining processing time in hours	6.10	58.78	100.39	124.72

Table 12: Final results of the schedule

We see that we now have sufficient time available for scheduling all the semi-finished products. With the remaining processing time, we can produce 19 MTO products. The production planner can divide the products over the production lines. We do not create a schedule with the MTO products because we do not have sufficient information when to produce an MTO product.

When it is not possible to create sufficient processing time it is possible to shift products to a different production line. For example, production line 31 has 100 hours of remaining processing time. So we can shift products from production line 11 to production line 31.

5.6 Production planning performance

Section 4.6 presents several performance measurements for the solution design. The total costs, average processing time, and the number of required cleanings are already given in Section 5.4 and Section 5.5.

	Production line 11 ($i = 1$)	Production line 21 ($i = 2$)	Production line 31 ($i = 3$)	Production line Company Z ($i = 4$)
Total cost	€ 2,527.17	€2,125.02	€1,287.78	€633.63
Average processing time in hours	3.71	3.37	4.04	4.55
Average inventory duration in weeks	1.83	1.57	1.11	1.04
Total number of required cleanings	14	0	0	4

Table 13: Summary performance measurements

Table 13 summarises the performance measurements. Company X can use these performance measurements to validate the solution design after implementing this solution design in production planning. Section 5.7 performs a sensitivity analysis to see the change in total costs and average processing time when we change some parameters.

5.7 Sensitivity analysis

Section 5.3 calculates the fundamental cycle period for every production line. We perform a sensitivity analysis to see the impact on the result when we change certain parameters. We decide to do a sensitivity analysis for the following scenarios:

1. Calculate the fundamental cycle period with inventory duration constraints with a maximum of 2, 3, 4, 5, 6, 7, 8, 9, and 10 weeks.
2. Increasing the demand for semi-finished products with 10%, 20%, 30%, and 40%.
3. Reduce the production rates of the semi-finished products to 90%, 80%, and 70%.

We will look if we can create a feasible production plan and schedule without changing the production frequencies. Section 5.7.1 explains scenario 1. For scenario 1, we look at the total cost and the average processing time.

Next, Section 5.7.2 explains scenario 2. In scenario 2, we keep the maximum inventory time on 6 weeks and increase the demand with the given percentages. We look at the impact on the total cost and the average processing time.

Last, Section 5.7.3 explains scenario 3. In scenario 3, we reduce the production rates per hour from 100% to the given percentages. We keep the demand at the same level as in the original situation. We look at the impact on the total cost and the average inventory time.

5.7.1 Scenario 1

In this scenario, we change the maximum inventory duration. We start with a maximum of 2 weeks and we increase this to a maximum of 10 weeks for every semi-finished product. We do not start with 1 week because it does not guarantee a feasible outcome and it is also not realistic to have maximum inventory duration of 1 week given the weekly demands of the semi-finished products.

Appendix F: Scenario 1, we have illustrated 4 graphs of the different production lines. In this section, we explain the results for production line 11, which we illustrate in Figure 18. For explanation and remarks for production line 21, 31, and Company Z consult Appendix F.

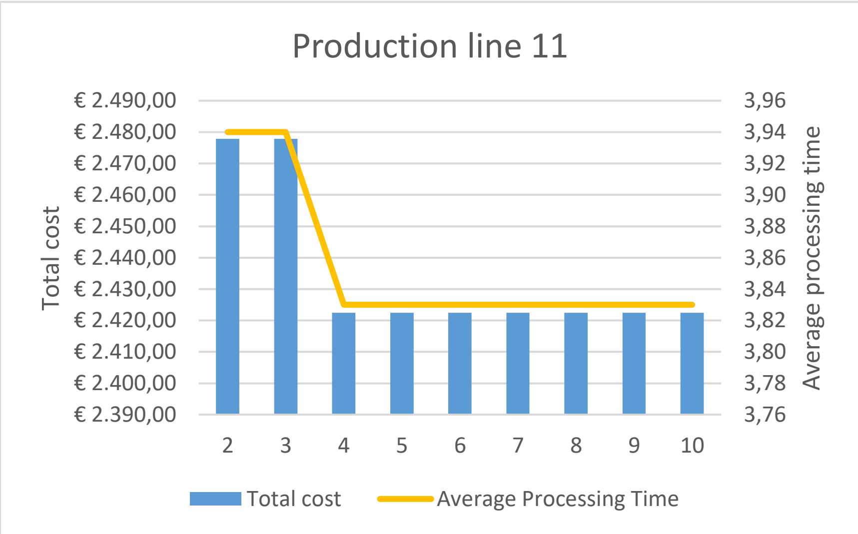

Figure 18: Result production line 11 scenario 1

Figure 18 presents the total cost and the average processing times. We see that that the total cost and the average processing changes when we increase the maximum inventory duration.

Section 4.3.1 sets an upper bound T_i^* with equation 6. When we have a short maximum inventory duration, we need to reduce the production frequencies k_{ij} of some products to generate a feasible plan. By reducing the production frequencies of some products we increase the upper bound that we set for T_i^*.

When we do not have a relatively short maximum inventory duration the procedure looks for opportunities to reduce the total cost. The procedure finds a lower total cost with a lower fundamental cycle period. In equation 2 and 9 we see that the fundamental cycle period influences the calculation of the processing times. With a lower fundamental cycle period, we have shorter processing times.

When the maximum inventory duration is greater or equal than 4 weeks, the total costs and the average processing time do not change. This is because with 4 weeks the calculated upper bound of T_i^* is sufficient to cover all productions. We do not have to change the production frequencies to create a feasible plan. Also, the procedure cannot find a solution for lower total costs.

5.7.2 Scenario 2

In this scenario, we increase the demand for semi-finished products. We do not change the production rate and the maximum duration of 6 weeks in inventory. In our calculation, we assume that the demand is constant. However, we perform a check to see the influence in the cost and the processing times when we increase the demand. We expect to see an increase in the total cost and the average processing times because we need to produce more.

Figure 19 illustrates the result of production line 21. Consult Appendix F for the illustration of the results for production line 11, 31, and Company Z.

We see that the cost and the average processing times increase when we increase the demand for all the production lines. The total cost and the average processing times increase at a constant rate. When we increase the demand, the ratio $\frac{d_j}{p_j}$ increase with a constant rate. The increase in cost from the base to a 40% increase is 16.92% which is around 4% increase per 10% increase in demand.

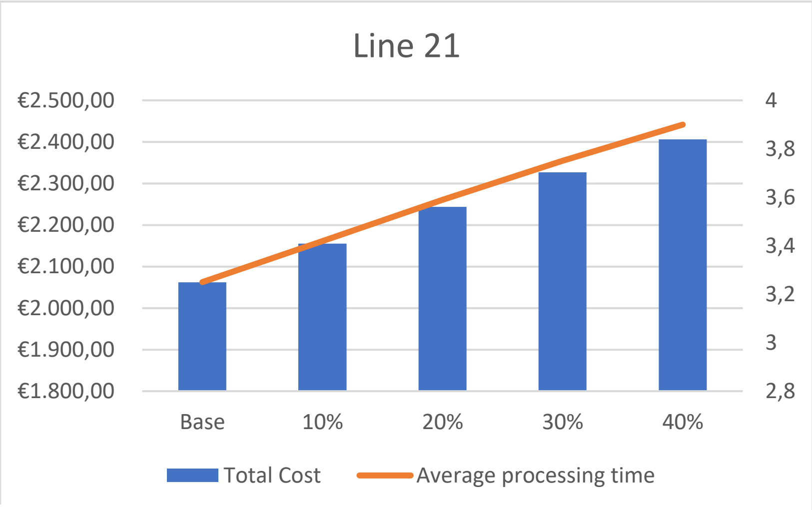

Figure 19: Result production line 21 scenario 2

5.7.3 Scenario 3

In this scenario, we decrease the production rate. During the calculation of the fundamental cycle period we assume that the production rate is constant over time. However, decreasing production rates is realistic. For example, Company X can choose to reduce the rate of improving product quality or improving machine reliability. In this section, we explain the results for production line 11. Figure 20 illustrates the results of production line 11. In Appendix F: Scenario 3, we illustrate the 3 graphs of production line 21, 31, and Company Z. We use the demand and the maximum inventory duration from the base scenario.

We see that the total costs reduce when we decrease the production rate. This makes sense because the fraction $\frac{d_j}{p_j}$ will increase. The total cost is given by (1) $C_{ij} = \frac{s_j}{T_{ij}} + \frac{1}{2} h_h T_{ij} d_j (1 - \frac{d_j}{p_j})$. Now we see that $1 - \frac{d_j}{p_j}$ will become smaller. The processing time increase because we need to meet demand with a lower production rate. When we go further into details we see that the fundamental cycle period T_i^* only

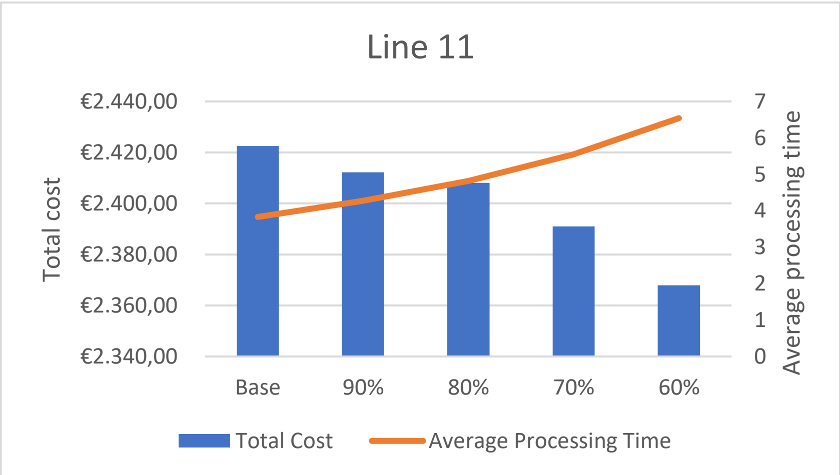

Figure 20: Result production line 11 scenario 3

increase slightly. It looks attractive to have a lower production rate because of the lower cost. However, because the fundamental cycle period only slightly increases we come to a moment where we do not have sufficient processing time available. This results in a production plan and schedule that is not feasible.

The slope of the average processing time increases after 70% production rate. From equation (9) $PT_{ij} = T_{ij}d_j/p_j$ together with equation (2) $T_{ij} = k_{ij}T_i^*$ we calculate the processing time per semi-finished product. When we look at the results we see that some production frequencies k_{ij} increase at a production rate of 60%. The fundamental cycle period T_i^* only slightly increase. Because of the increase of some production frequencies the slope of the average processing time increases.

5.8 Validation

This section explains the validation of the results. We divide this section into three subsections. First, Section 5.8.1 explains the results of the calculation for the fundamental cycle period. Second, Section 5.8.2 looks at the results of the schedule. Third, Section 5.8.3 uses historical data to compare the results with the current situation.

5.8.1 Results of the fundamental cycle period

We have some remarks on the results of the calculation of the fundamental cycle period and the schedule. The outcome of the calculation of the cycle periods we get a fundamental cycle period that is not equal to the whole day and/or week. In practice, a fundamental cycle period of 0.5882 weeks or 2.941 days (based on a week with 5 production days) is not practical. We could decide to change this fundamental cycle period to full working days. This will create more practical results. We have the results from Section 0:

	11	**21**	**31**	**Company Z**
Fundamental cycle period T_i^*	0.5882	0.4997	0.6786	0.5482

In Section 5.5 we already did a modification on the fundamental cycle period to make a more practical result for the schedule. When we round these to the nearest full working day based on 5 working days. So we have:

	11	**21**	**31**	**Company Z**
Fundamental cycle period T_i^*	3 days	2 days	3 days	3 days

We need to choose if we round up or down to a full working day. In the results above we round up or down based on the nearest full production day. These results create a feasible production plan and schedule. However, we may not have sufficient processing time available per cycle when we round up or down because the fundamental cycle period influences the processing times. We execute both scenarios and examine the results. When we round down the fundamental cycle period we do not have sufficient processing time available for processing all the products on production line 11. When we round up the fundamental cycle period we do have enough processing time available for all production lines. Also, for production line 21, 31, and Company Z the remaining processing time increases. Because we want to have a feasible schedule for all production lines we decide to round up the fundamental cycle period.

	Production line 11 ($i = 1$)	**Production line 21 ($i = 2$)**	**Production line 31 ($i = 3$)**	**Production line Company Z ($i = 4$)**
Lower bound T* in weeks	0.0416	0.0167	0.0100	0.0028
Upper bound T* in weeks	0.7548	0.7579	1.5223	1.5372

Fundamental cycle period T_i^* in weeks	0.6000	0.6000	0.8000	0.6000
Least common multiple of k_{ij}	8	8	4	4
Total Cycle Length in weeks	4.80	4.80	3.20	2.40
Holding cost for the total cycle length	€ 1,288.86	€ 1,228.46	€ 759.13	€ 346.75
Setup cost for the total cycle length	€ 1,238.80	€ 906.68	€ 546.15	€ 289.46
Total cost for the total cycle length	€ 2,527.66	€ 2,135.15	€ 1,305.27	€ 636.22
Feasibility	Feasible	Feasible	Feasible	Feasible

Table 14: Results when rounding up fundamental cycle period

Table 14 shows the results after changing rounding the fundamental cycle period. When we convert the fundamental cycle period from weeks to working days we have:

	Production line 11	**Production line 21**	**Production line 31**	**Production line Company Z**
Fundamental cycle period T_i^* in working days	3	3	4	3

The total cost is €6,604.30 in Table 14. When we compare the results of Table 14 with the results of Table 7 in Section 0 we see that the total cost increases with 0.38%.

	Production line 11	**Production line 21**	**Production line 31**	**Production line COMPANY Z**
#Products	16	13	7	3
Number of required cleanings	14	0	0	4
Total available time in hours	384	384	256	192
Total Processing time with cleaning time in hours	383.49	235.34	107.28	71.23
Total available processing time after processing in hours	0.51	148.66	148.72	120.77

Table 15: Summary schedule after rounding fundamental cycle period

Table 15 presents a summary of the new result of the schedule. When we compare these results with Table 12 we see that the available processing time after processing reduces for production line 11 and Company Z. However, for production line 21 and 31 it increases.

When we look at the number of batches of the semi-finished products we see that these are not of type integer. The production planner can decide to round up or down the number of batches based on factors like current inventory level or demand. This will influence the processing time slightly. However, this will not be a problem when the fundamental cycle period has extra capacity available.

5.8.2 Results of the schedule

The fundamental cycle period assumes that the setup is sequence-independent. However, the procedure set a lower bound that makes sure that there is sufficient time for producing all the semi-finished products based on the given setup times. We provide these setup times based on historical information of Company X. Nevertheless, these setup times are not based on the sequence dependency. Sequence dependency results in longer setup times between products. However, when we include sufficient time processing time in the fundamental cycle period it is possible to make a schedule with sequence-dependent setups.

Also, in the schedule, we present a feasible schedule based on the allergen of the semi-finished products. However, we do not take into account product specifications in the schedule. For example, switching to different types of machines takes more time than continue producing on the same machine. Also, we have a long setup time if we switch to an allergen that is not in order of the allergen flow scheme. However, in the current situation, Company X cleans the processing department every night. This means that it is possible to switch to a different allergen without loss of available processing time. There are some opportunities for further research on the schedule.

5.8.3 Comparison with the current situation

We look if we can compare some results of the fundamental cycle period with the current situation. First, we find the average processing times on the production lines from the beginning of the year. Second, we look at the average inventory time from the beginning of March 1 2020.

		Production line 11	**Production line 21**	**Production line 31**	**Production line Company Z**
Current situation	Average processing times in hours	8.38	7.85	9.02	6.01
Results fundamental cycle period	Average processing times in hours	3.71	3.37	4.04	4.55
	Percentage change current situation versus results fundamental cycle period	-55.7%	-57.1%	-55.2%	-24.3%

Table 16: Average processing times in hours

First, we look at the average processing times. We take the data from March 2nd to August 14th. Table 16 illustrates the results from the historical situation together with the results from Table 13. We see that the results from the fundamental cycle period drastically decrease the average processing times for production line 11, 21, and 31. For production line Company Z we see a more moderate decrease.

		Production line 11	**Production line 21**	**Production line 31**	**Production line Company Z**
Current situation	Average inventory duration in weeks	1.75	1.45	1.66	1.63
Results fundamental cycle period	Average inventory duration in weeks	1.83	1.57	1.11	1.04

	Percentage change current situation versus results fundamental cycle period	4.6%	8.3%	-33.1%	-36.2%

Table 17: Average inventory duration in weeks

For the average inventory duration, we took historical data from March 1st to August 13th. Table 17 illustrates the results per production line. We also give the results of the fundamental cycle period which is adapted from Table 13. When we compare these results we see that for production line 11 and 21 the average inventory duration is longer than in the current situation. However, these values are relatively close. For production line 31 and Company Z, we have in the current situation a high average inventory duration compared to the results of the fundamental cycle period.

When we want to compare the total costs with the current situation it becomes fairly difficult. We need to gather more data and we need to do a more in-depth analysis in the data of the current situation. We are not going to do this because of the available time we have for this research.

5.8.4 Reduction time for production planning

The previous sections of this chapter give the results after implementation of the solution design. However, we do not have the answer yet for the core problem of this research. With the solution design, we want to reduce the time that is needed for production planning at Company X. We already mentioned the advantages of a cyclic production plan in Chapter 2 and 3. A cyclic production plan reduces the complexity of creating a production plan. With the presented solution design, the cycle length, production frequencies, quantities, and cycle lengths are already determined.

Together with the stakeholders at Company X, we evaluated the solution design and the implementation of the solution design. They mention that the solution design helps in reducing the time for production planning. Also, it gives a fixed planning method. Section 2.4 mentions two different production planning methods. With this solution design, the production planner does not have to choose a planning method. Also, the quantities, production frequencies, and cycle lengths are determined by the solution design. Therefore, the production planner only has to control and improve the procedure of the fundamental cycle period and the scheduling heuristic.

When we want to measure the reduction of time needed for production planning we need to implement the results of this research in the current environment of Company X. Due to the time limits we have for this research, it becomes very hard to have good measurements. However, all the stakeholders expect that the time will significantly reduce because the production planner has only one plan method and only needs to control and improve the production planning and schedule.

5.9 Conclusion

We apply the solution design that we describe in Chapter 4. Before applying the procedure of the fundamental cycle period we perform a demand and variability analysis. From this analysis, it is possible to separate the MTO and MTS products. Only the MTS products are included in the calculation of the fundamental cycle period. This means 39 MTS products are included and 19 MTO products are excluded.

We execute the fundamental cycle period that is described in Section 4.3. The procedure gives an initial result. We want to have processing times of around 3 hours. The initial result does not satisfy this. Therefore, we decide to increase the production frequencies which increases the processing times. We find a feasible result after changing the production frequencies.

The results of the fundamental cycle period are applied in the ISI heuristic. After applying the initialize and the sequence step we do not find a feasible schedule for production line 11 because there is not sufficient processing time available. Therefore, we reduce the production frequencies of some semi-finished products. This leads to fewer setups and therefore more available time for processing. Changing the production frequencies also leads to a change in the results of the fundamental cycle period. After changing some production frequencies we find a feasible schedule.

We provide a validation of the solution design. We do not find a practical result in the final result of the fundamental cycle period. Therefore, we change the fundamental cycle period to make it more practical. This results in slightly different outcomes of the procedure and the heuristic of the schedule.

Next to this, the final results of the fundamental cycle period are compared with the current situation at Company X. The average processing times decrease with ± 55% for production line 11, 21, and 31. For production line Company Z the average processing time decreases with 24%. The average inventory duration slightly increases for production line 11 and 21. However, for production line 31 and Company Z it decreases with 33% and 36% respectively.

Finally, we discuss whether the solution design decreases the time that is needed for production planning. With this solution design, the production planner only has one plan method. Also, the quantities, production frequencies, and cycle lengths are already determined by the solution design. The production planner only needs to control and improve the production plan and the scheduling heuristic. Therefore, the stakeholders of Company X foresee a significant reduction of time for production planning. Unfortunately, we cannot give calculate the time reduction because we have limited available time for this research.

6 Conclusion, recommendation and further research

This chapter provides a conclusion of this research, gives recommendations, limitations, and possibilities for further research. Section 6.1 gives the conclusion of this research. Section 6.2 provides recommendations. Section 6.3 gives a contribution to the theory. Last, Section 6.4 describes the limitations and possibilities for further research.

6.1 Conclusion

The core problem in this research is: "*The production planning takes too much time*". In the current situation, production planning takes around 1.0 FTE (38 hours). The supply chain department wants to reduce production planning with 50% to 0.5 FTE (19 hours).

For reducing the time for production planning we describe a cyclic production plan based on the research of Doll and Whybark (1973) and Soman et al. (2004). A cyclic production plan in a two-stage production system has the advantage that it will periodically supply semi-finished products to the packaging stage. This reduces the capacity in the intermediate warehouse. Also, the quantities, production frequencies, processing times, and cycle length are already given. The solution design describes a procedure to find the fundamental cycle period with maximum inventory duration for every production line. The fundamental cycle period is the length of a single cycle. Also, this procedure gives the production frequencies of the semi-finished products. The production frequencies are the total number of production occurrences over a given total cycle length. With the least common multiple of the production frequencies and the fundamental cycle period, we can calculate the total cycle length. Next to this, the procedure tries to find a feasible cyclic production plan with maximum inventory duration. Before we execute the procedure of the fundamental cycle period we look at the MTO and MTS considerations for production planning. We do a demand variability analysis to decide which product are MTO or MTS orientated. We leave the MTO products in the calculation of the fundamental cycle period. The procedure of the fundamental cycle period gives the following result:

	Production line 11	**Production line 21**	**Production line 31**	**Production line Company Z**
Fundamental cycle period in weeks	0.6460	0.4997	0.6786	0.5482
Total cycle length in weeks	5.17	4.00	2.71	2.19

The total cost is €6,578.98. From this result, we create a schedule. This schedule takes into account the processing capacity per fundamental cycle period and the allergens of the products. On production line 21, 31, and Company Z we have sufficient processing time available after scheduling the products. With this available time, it is possible to produce MTO products. For production line 11 we do have overtime. We do not want overtime because this violates the cycle planning. As a solution, we improve the schedule by changing the production frequencies until we have sufficient processing time for production line 11. Changing the production frequencies also influences the results of the fundamental cycle procedure and therefore we apply the procedure again. The new results are:

	Production line 11	**Production line 21**	**Production line 31**	**Production line Company Z**
Fundamental cycle period in weeks	0.5882	0.4997	0.6786	0.5482

Total Cycle Length in weeks	4.71	4.00	2.71	2.19

This gives a total cost of €6,573.60. The results of the final schedule are:

	Production line 11	**Production line 21**	**Production line 31**	**Production line Company Z**
Total available time in hours	384	256	192	192
Total processing time with cleaning time in hours	377.90	197.22	91.61	67.28
Total remaining processing time in hours	6.10	58.78	100.39	124.72

We use the performance measurements total cost, average processing time in hours, average inventory duration, and the total number of required cleanings. These performance measurements can Company X help to keep track of the solution design after implementing. Especially the average processing time and the average inventory duration are helpful.

We do a sensitivity analysis to find the impact on the total cost and the average processing time when we change certain parameters. In three different scenarios, we change the maximum inventory duration, demand, and the production rate respectively. We see that the maximum inventory duration only has a large influence when we set a short maximum inventory duration. When we increase the demand we see a linear growth in the average processing time. Also, the total cost shows almost linear growth. If we decrease the production rate we see an almost linear growth in the average processing time. The total cost will decrease. It is tempting to reduce the production rate because of lower cost, however, at a certain point, we do not have sufficient processing time available.

We comment on the practical results of the fundamental cycle period. It is better to have a fundamental cycle period in full production days. We look at the scenario of rounding up or down the fundamental cycle period to the nearest full production day. We have better results when we round up to the nearest full production day. From this, we calculate the new results of the procedure of the fundamental cycle period. We see that the cost slightly increase, however, we have a sufficient solution and a more practical solution.

We also compare the average processing times and the average inventory duration with the current situation. We see that the average processing times decreases significantly with ± 55% for production lines 11, 21, and 31. For the average inventory duration, we see that the procedure of the fundamental cycle period gives slightly higher results for production line 11 and 21. For production line 31 and Company Z, it is the opposite. The average inventory duration is reduced by ± 35%.

The solution design is evaluated with the stakeholders of Company X. They foresee a serious reduction in the time that is needed for processing. First of all, the production planner only has one planning method. Also, the quantities, production frequencies, and cycle lengths are already determined. The production planner only needs to control and improve production planning and schedule. Unfortunately, it is not possible to do measure the time reduction specifically.

6.2 Recommendations

Based on our solution design and the conclusions from Section 6.1 we would recommend the following to Company X:

- Do a demand variability analysis for the semi-finished products regularly. This will give insight into the demand and the variability of the semi-finished products. This can help in assigning products as MTO or MTS.
- Use a cyclic production plan for semi-finished products. A cyclic production plan is easy to use and it creates stability in production planning and the supply chain department. A cyclic production plan reduces the time for production planning because a large part of the planning is already determined. Use the remaining capacity for producing MTO products or extra MTS productions. With the Excel file that we developed, it becomes relatively easy to calculate the fundamental cycle periods and the planning horizon. It also gives insight into total costs, processing times, and the number of batches. When the initial results are not feasible or favourable it is possible to change the fundamental cycle period by changing the production frequencies.
- We advise revising the calculation of the fundamental cycle period after the total cycle length. Mainly the change in demand is important. The sequence in the schedule can remain the same as long the total processing time is not larger than the available capacity. The processing times and the number of batches can change.
- Look constant for opportunities to improve the schedule. When the sequence of some semi-finished products is not favourable, try to change and improve the sequence. This is a continues process and does not have to stop after applying it once. When semi-finished products are shifted to another production line, the fundamental cycle period needs to be calculated again.
- To keep track of the performance of the cycle, we advise using the average inventory duration and the average processing times. These two performance measurements are fairly easy to calculate. Also, Company X is already using the KPI inventory in days for semi-finished products.

6.3 Contribution to theory

The solution design is created for the situation at Company X. However, we have findings that are useful for the theory. This research connects different practical findings from the literature into one research. Also, we have changed some findings from the literature that will be useful for further research. We present an overview of findings that a have a contribution to the theory.

- At first, we provide a summary of practical solutions for a two-stage production system. Hierarchical production planning is useful in a two-stage production system. Together with a coupling plan to couple the first-stage and the second-stage, it is possible to create a robust production plan for both stages.
- We provide a demand variability for the first-stage. This demand variability gives insight into the MTO and MTS considerations for semi-finished products. MTO and MTS considerations are mostly focused on finished products and not on semi-finished products. This analysis can give insight into how these considerations are adopted in production planning in the first stage of a two-stage production system.
- We use the procedure of Doll and Whybark (1973) and Soman et al. (2004) to calculate the fundamental cycle period with maximum inventory duration. These calculations are based on a single production line and therefore change it for the use of multiple production lines. We apply this procedure to calculate the fundamental cycle period for 4 production lines. Also, we first look at the considerations of MTO and MTS products. With these results, we determine if we include a product in the calculation of the fundamental cycle period.
- We use the results of the fundamental cycle period to create a schedule. We use a scheduling heuristic from Gupta and Magnusson (2008). We change this heuristic to apply it to the food industry. We take into account the available processing time at a

production line. Also, for sequencing, we use allergens of the semi-finished products based on a setup matrix.

6.4 Limitations and further research

We explain the limitations of the research and we have some suggestions for future research for Company X based on the conclusions and the recommendations. We mention all the suggestions below.

- The first limitation is data availability. Company X has sufficient data available. However, Company X stores the data at different places, for example, in the ERP system and Slim4. This makes the search for data complicated and sensitive to errors, for example, when Company X changes the data.
- The second limitation was the availability of time. We scope the research to improving production planning for the first stage. However, the first stage and second stage depend on each other. The second-stage gives input for the first-stage. Therefore, for further research, we would advise looking further into the relations between the two stages to create a better solution design for the first stage. Also, this solution design could help to improve production planning in the second-stage.
- Also, due to time availability, it is not possible to implement the solution design in the systems of Company X. Therefore, it is difficult to measure the decrease in the time that is needed for production planning.
- We do not include MTO products in the calculation of the fundamental cycle period. Having MTO products in de first-stage is more difficult because the semi-finished products are disaggregated to multiple finished products. To switch completely to an MTO product we advise to do further research on how to deal with MTO products in production planning.
- In the heuristic of scheduling, we define product families based on the allergens of the semi-finished products. However, the products also have different product specifications in processing. For example, products are produced at different types of machines. We could extend the heuristic with an extra setup matrix for scheduling within a product family based on the product specifications. Therefore, we would advise doing further research on extending the scheduling heuristic for scheduling within product families.
- Finally, we advise researching the other potential core problems from Section 1.3. These problems also help in improving the performance of production planning. For example, forecast accuracy is a potential problem for further research. With a better forecast accuracy, the demand is better predictable. This can help in improving production planning.

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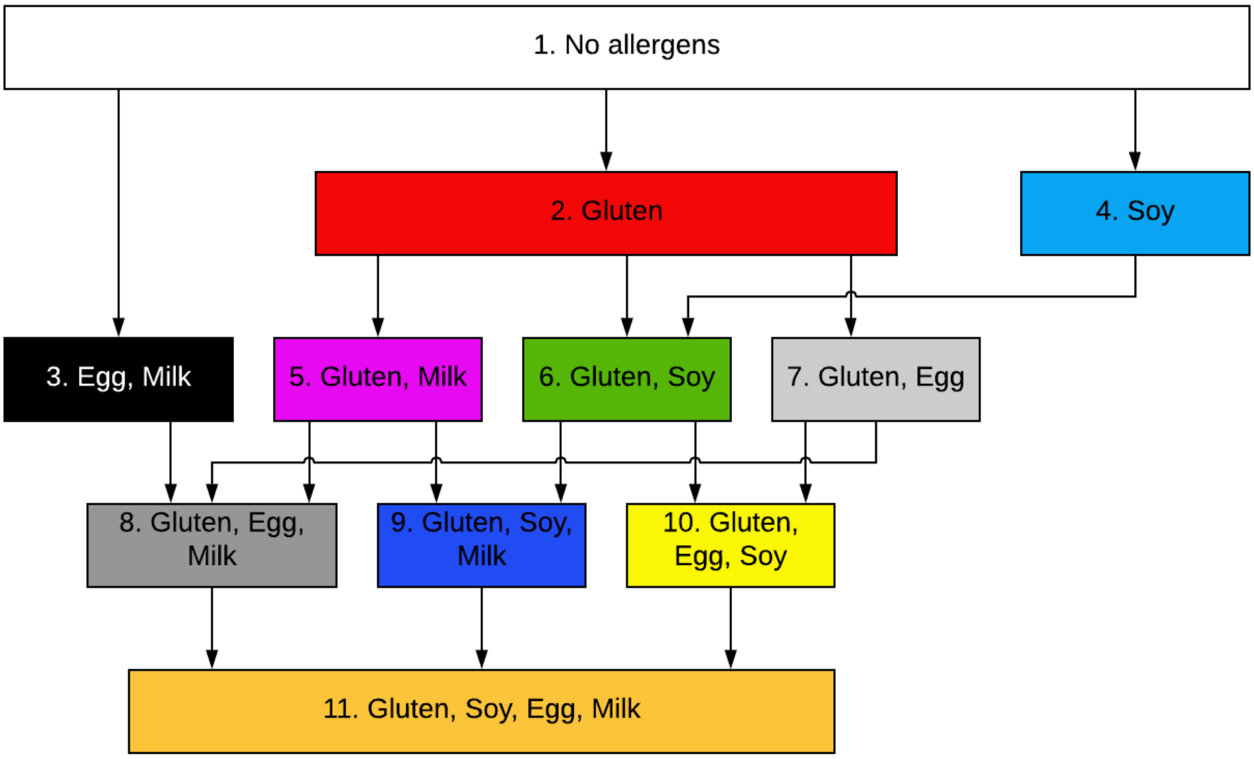
Appendix A: Allergen flow scheme



Appendix B: Fundamental cycle period procedure

Step 1: Execute the procedure of Dolby and Whybark (1973) with the power of two policy. This gives good starting points of T_i^* and k_{ij}. We further information about this procedure we refer the reader to the research of Doll and Whybark (1973).

Step 2: Check if T_i^* satisfy the constraint given by (7).

$$T_i^* = \max\{T_i^*, \frac{\sum_j s_j/k_{ij}}{1-\sum_j d_j/p_j}\}$$

Step 3: Check if T_j^* satisfy the maximum inventory time.

$$T_i^* = \min\{T_i^*, \min_j[\frac{w_{ij}}{k_{ij}(1-d_j/p_j}]\}$$

Check if a feasible plan can be made with fundamental cycle period equal to $T_i^* = \min_j\{w_j/k_{ij}(1-\frac{d_j}{p_j})\}$. If this is possible go to step 4. If not. go to step 5.

Step 4: The T_i^* of step 2 is systematically increased until a feasible plan can be made or till it reaches $\min_j\{w_j/k_{ij}(1-\frac{d_j}{p_j})\}$. The plan has a feasible solution when it generates a lower cost for so far. We safe this solution as ‘the current best solution’ and go to step 5.

Step 5: (a) if $\max\{k_{ij}\} = 1$. go to step 7.

(b) for each semi-finished product with $k_{ij} > 1$. halve the value of k_{ij} and calculate the lower cost bound of the cost per unit time using (7).

where $T_i^* = \{\frac{2\left[\sum_j \frac{s_j}{k_{ij}}\right]}{\left[\sum_j h_j d_j k_{ij}(1-\frac{d_j}{p_j})\right]}\}^{1/2}$.

(c) Sort the products in ascending order of their cost and store this in a list.

(d) if there is a ‘current best solution’ stored in step 4 then ignore semi-finished products which give a higher minimum cost than the ‘current best solution’ and update the list. If the list is empty the procedure terminates and the ‘current best solution’ is the solution.

(e) choose the first semi-finished product in the list.

(f) Use equation (6) to calculate the upper bound of the new k_{ij} values for every i. The k_{ij} value of the first product is halved while other k_{ij} from step 2 remain the same. Store these k_{ij} in vector K_i.

(g) Check if is possible to generate a feasible plan for new vector K_i and T_i^* equal to the new upper bound from (f). If a feasible plan can be made, go to step 6. If not, go to (h)

(h) Choose the next semi-finished product in the list and go to (f). If the end of the list is reached, choose the first semi-finished product and go to Step 6.

Step 6: Halve the value of k_{ij} that is obtained in Step 5. If $\max(k_{ij}) > 1$ go to Step 2, otherwise go to Step 7.

Step 7: Stop the procedure. If there is a 'current best solution' this is the final solution. Otherwise use the common cycle approach that is described by Silver (1989)

Appendix C: Demand analysis

Nr	code	Average weekly demand	Standard deviation	CoV	IOQ	Include or Exclude
1	558165	1078.04	235.64	21.86	1804	Exclude
2	557311	735.69	137.39	18.67	633	Include
3	558221	459.02	127.28	27.73	487	Exclude
4	557866	829.22	299.89	36.17	1147	Exclude
5	558812	11158.59	8220.97	73.67	1253	Include
6	557420	1577.65	269.11	17.06	815	Include
7	557343	4045.10	896.76	22.17	1667	Include
8	557354	12241.37	2620.25	21.40	2220	Include
9	557187	5991.76	1508.71	25.18	1200	Include
10	558132	5686.67	1087.52	19.12	902	Include
11	557356	679.22	120.32	17.72	520	Include
12	557281	7340.98	1815.98	24.74	1200	Include
13	557182	395.10	103.06	26.08	475	Exclude
14	558234	2811.57	680.88	24.22	1430	Include
15	557823	2162.55	423.43	19.58	342	Include
16	557523	909.02	167.03	18.37	513	Include
17	558696	102.12	70.31	68.85	339	Exclude
18	557232	2456.08	445.60	18.14	645	Include
19	557224	5658.82	1176.84	20.80	1200	Include
20	558105	3182.75	862.88	27.11	599	Include
21	558123	11362.75	2528.79	22.26	1804	Include
22	557139	700.00	195.28	27.90	562	Include
23	557583	690.78	272.57	39.46	1728	Exclude
24	557223	5672.55	1208.57	21.31	2340	Include
25	557824	167.84	260.67	155.31	947	Exclude
26	558129	231.96	62.75	27.05	344	Exclude
27	558164	1615.49	719.64	44.55	548	Include
28	557119	341.37	105.70	30.96	351	Exclude
29	557591	2497.25	441.06	17.66	698	Include
30	557146	544.90	110.66	20.31	500	Include
31	557822	3471.37	730.14	21.03	1248	Include
32	557627	5885.29	1366.66	23.22	870	Include
33	558203	9453.73	1902.19	20.12	1828	Include
34	557616	4284.90	911.01	21.26	1158	Include
35	557851	7189.80	1918.92	26.69	2160	Include
36	557675	637.06	422.67	66.35	2100	Exclude
37	557145	4833.14	1295.14	26.80	1920	Include
38	557301	30.20	104.89	347.36	2532	Exclude
39	557172	1890.20	436.78	23.11	548	Include
40	557004	322.94	58.59	18.14	378	Exclude
41	557153	1563.53	379.60	24.28	1800	Exclude
42	558152	323.14	93.32	28.88	3786	Exclude

43	557151	1302.35	435.96	33.47	420	Include
44	557122	4929.80	961.27	19.50	1260	Include
45	558126	992.16	278.25	28.04	615	Include
46	557225	3365.49	772.97	22.97	855	Include
47	558119	3042.94	1287.65	42.32	873	Include
48	557123	2201.96	582.56	26.46	1200	Include
49	557336	947.25	450.94	47.61	1152	Exclude
50	557865	350.20	126.89	36.23	1548	Exclude
51	557853	811.37	489.40	60.32	590	Include
52	557405	3291.57	875.23	26.59	1741	Include
53	557329	3180.20	806.90	25.37	1820	Include
54	557009	817.65	169.12	20.68	555	Include
55	557323	443.33	120.78	27.24	506	Exclude
56	557601	308.24	87.17	28.28	487	Exclude
57	557152	2018.63	504.97	25.02	535	Include

Appendix D: Input data

Art. code	Line*	Average weekly demand in kg	Production rate in kg per hour	Production rate per week in kg**	Holding cost per kg per week	Set-up cost per run	Set-up time in weeks	Max inventory time in weeks	IOQ in kg	Allergen Code
557311	11	836.00	756.00	60,480.00	€ 0.05	€ 73.82	0.00082	6	633	6
558812	51	12,896.40	1014.00	81,120.00	€ 0.05	€ 77.19	0.00093	6	1,253	2
557420	21	1,782.00	918.00	73,440.00	€ 0.05	€ 80.32	0.00104	6	815	11
557343	11	4,620.00	1,080.00	86,400.00	€ 0.05	€ 75.99	0.00089	6	1,667	6
557354	21	13,816.00	1,440.00	115,200.00	€ 0.05	€ 83.93	0.00117	6	2,220	6
557187	51	6,831.00	1,110.00	88,800.00	€ 0.05	€ 77.19	0.00093	6	1,200	4
558132	21	6,479.00	840.00	67,200.00	€ 0.05	€ 71.18	0.00073	6	902	10
557356	11	759.00	1,020.00	81,600.00	€ 0.05	€ 58.66	0.00030	6	520	6
557281	31	8,261.00	1,155.00	92,400.00	€ 0.05	€ 86.90	0.00127	6	1,200	6
558234	11	3,201.00	1,128.60	90,288.00	€ 0.05	€ 94.76	0.00154	6	1,430	6
557823	21	2,431.00	960.00	76,800.00	€ 0.05	€ 93.31	0.00149	6	342	6
557523	21	1,023.00	1,110.00	88,800.00	€ 0.05	€ 145.29	0.00327	6	513	6
557232	11	2,761.00	756.00	60,480.00	€ 0.05	€ 113.53	0.00218	6	645	8
557224	31	6,457.00	901.80	72,144.00	€ 0.05	€ 77.19	0.00093	6	1,200	10
558105	21	3,630.00	760.50	60,840.00	€ 0.05	€ 74.26	0.00083	6	599	6
558123	21	13,002.00	1,200.00	96,000.00	€ 0.05	€ 71.74	0.00075	6	1,804	10
557139	11	836.00	1,200.00	96,000.00	€ 0.05	€ 77.43	0.00094	6	562	5
557223	31	6,446.00	901.80	72,144.00	€ 0.05	€ 82.37	0.00111	6	2340	10
558164	21	1,826.00	900.00	72,000.00	€ 0.05	€ 70.21	0.00069	6	548	6
557591	11	2,805.00	1,158.30	92,664.00	€ 0.05	€ 76.95	0.00093	6	698	6
557146	11	616.00	1,101.60	88,128.00	€ 0.05	€ 99.09	0.00169	6	500	8
557822	11	3,993.00	864.00	69,120.00	€ 0.05	€ 84.65	0.00119	6	1248	11
557627	31	6,710.00	1,080.00	86,400.00	€ 0.05	€ 77.19	0.00093	6	870	6
558203	11	10,648.00	765.00	61,200.00	€ 0.05	€ 89.34	0.00135	6	1828	6
557616	11	4,741.00	1,050.00	84,000.00	€ 0.05	€ 81.76	0.00109	6	1158	2
557851	11	8,162.00	624.00	49,920.00	€ 0.05	€ 70.93	0.00072	6	2160	5
557145	11	5,401.00	1,134.00	90,720.00	€ 0.05	€ 100.63	0.00174	6	1920	8
557172	11	2,156.00	1,140.00	91,200.00	€ 0.05	€ 147.02	0.00333	6	548	9
557151	31	1,430.00	1,110.00	88,800.00	€ 0.05	€ 87.54	0.00129	6	420	6
557122	11	5,643.00	1,200.00	96,000.00	€ 0.05	€ 81.76	0.00109	6	1260	10
558126	21	1,199.00	881.40	70,512.00	€ 0.05	€ 60.68	0.00037	6	615	10
557225	31	3,828.00	924.00	73,920.00	€ 0.05	€ 90.91	0.00141	6	855	6
558119	21	3,443.00	1,260.00	100,800.00	€ 0.05	€ 100.53	0.00174	6	873	6
557123	31	2,508.00	1,050.00	84,000.00	€ 0.05	€ 91.87	0.00144	6	1200	10
557853	11	935.00	604.80	48,384.00	€ 0.05	€ 77.19	0.00093	6	590	9
557405	21	3,729.00	1,140.00	91,200.00	€ 0.05	€ 84.65	0.00119	6	1741	6
557329	21	3,608.00	1,080.00	86,400.00	€ 0.05	€ 59.63	0.00033	6	1820	6
557009	21	913.00	1,188.00	95,040.00	€ 0.05	€ 104.86	0.00188	6	555	10
557152	51	2,332.00	1,095.12	87,609.60	€ 0.05	€ 77.19	0.00093	6	535	6

*Line 51 is the production line at the facility of Company Z.

**Production rate based on 5 days a week with 16 hours of production per day.

Appendix E: Results of the fundamental cycle period

Results initial plan

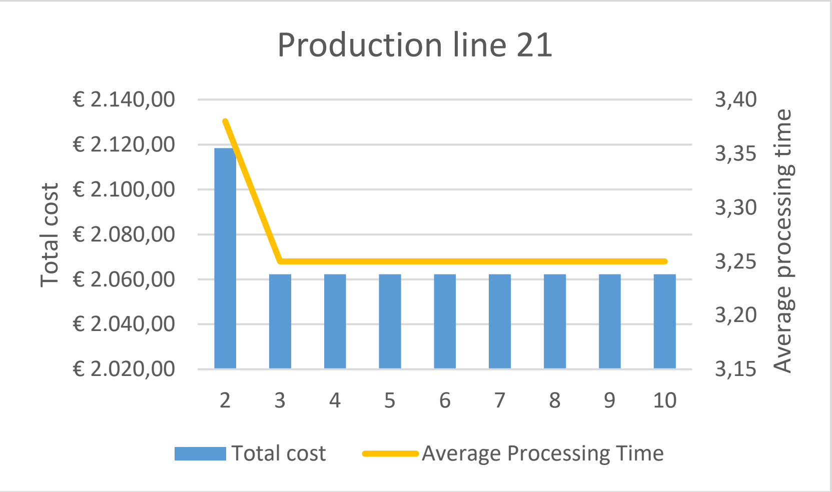
Product nr	Art. Code	Production line	Demand in kg	Processing time in hours	Inventory duration in weeks	LOT size in kg	#Batches	Production frequency
38	557356	11	690	1.21	1.77	1,231	2.37	2
36	557311	11	760	1.79	1.76	1,355	2.14	2
37	557139	11	760	1.13	1.77	1,355	2.41	2
34	557853	11	850	2.51	1.75	1,516	2.57	2
39	557146	11	560	0.91	1.77	999	2.00	2
23	557591	11	2,550	1.96	0.87	2,274	3.26	1
22	558234	11	2,910	2.30	0.86	2,595	1.81	1
24	557232	11	2,510	5.92	1.71	4,477	6.94	2
16	557822	11	3,630	3.75	0.84	3,237	2.59	1
15	557343	11	4,200	3.47	0.85	3,745	2.25	1
14	557616	11	4,310	3.66	0.85	3,844	3.32	1
28	557172	11	1,960	3.07	1.75	3,496	6.38	2
12	557122	11	5,130	3.81	0.84	4,575	3.63	1
13	557145	11	4,910	3.86	0.84	4,379	2.28	1
6	557851	11	7,420	10.60	0.76	6,617	3.06	1
4	558203	11	9,680	11.28	0.75	8,632	4.72	1
32	558126	21	1,090	1.70	1.36	1,502	2.44	2
35	557009	21	830	1.93	2.73	2,287	4.12	4
29	558164	21	1,660	2.54	1.35	2,287	4.17	2
33	557523	21	930	2.31	2.73	2,563	5.00	4
30	557420	21	1,620	2.43	1.35	2,232	2.74	2
20	557329	21	3,280	2.09	0.66	2,260	1.24	1
26	557823	21	2,210	3.17	1.34	3,045	8.90	2
19	558105	21	3,300	2.99	0.65	2,274	3.80	1
18	557405	21	3,390	2.05	0.66	2,336	1.34	1
21	558119	21	3,130	3.42	1.34	4,313	4.94	2
9	558132	21	5,890	4.83	0.63	4,058	4.50	1
2	558123	21	11,820	6.79	0.60	8,144	4.51	1
1	557354	21	12,560	6.01	0.61	8,654	3.90	1
31	557151	31	1,300	1.85	1.56	2,054	4.89	2
25	557123	31	2,280	3.43	1.54	3,603	3.00	2
17	557225	31	3,480	2.98	0.75	2,749	3.22	1
10	557224	31	5,870	5.14	0.73	4,638	3.86	1
11	557223	31	5,860	5.13	0.73	4,630	1.98	1
8	557627	31	6,100	4.46	0.73	4,819	5.54	1
5	557281	31	7,510	5.14	0.73	5,933	4.94	1
27	557152	51	2,120	2.46	1.24	2,692	5.03	2
7	557187	51	6,210	3.55	0.59	3,943	3.29	1
3	558812	51	11,724	7.34	0.54	7,444	5.94	1

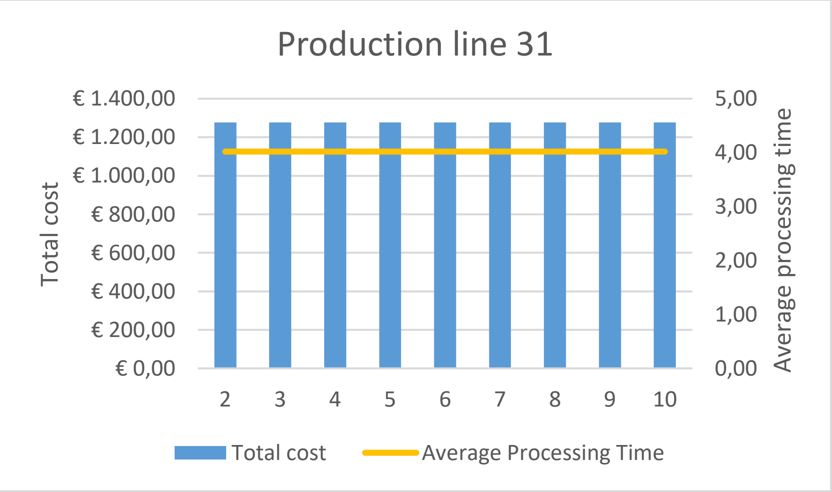
Results after changing the values

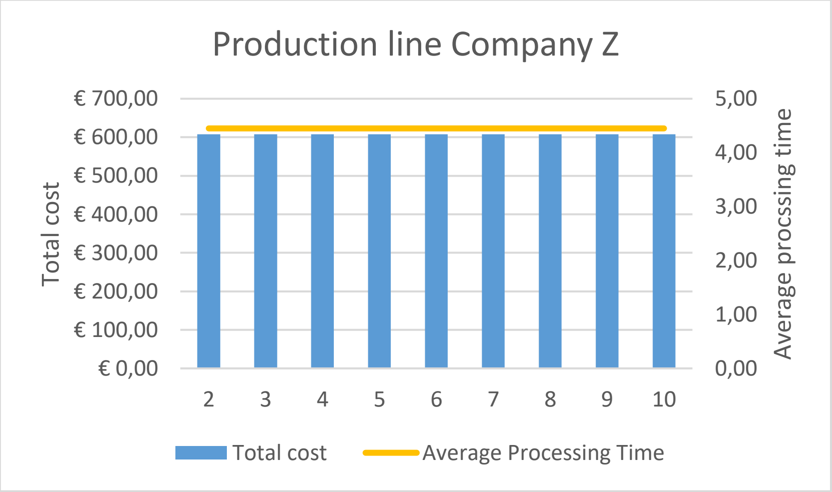
Product nr	Art. Code	Production line	Demand in kg	Processing time in hours	Inventory duration in weeks	LOT size in kg	#Batches	Production frequency
38	557356	11	690	3.18	4.67	3,247	6.24	8
36	557311	11	760	2.37	2.32	1,788	2.83	4
37	557139	11	760	2.98	4.67	3,576	6.36	8
34	557853	11	850	3.31	2.31	2,000	3.39	4
39	557146	11	560	2.39	4.68	2,635	5.27	8
23	557591	11	2,550	2.59	1.14	3,000	4.30	2
22	558234	11	2,910	3.03	1.14	3,424	2.39	2
24	557232	11	2,510	3.91	1.13	2,953	4.58	2
16	557822	11	3,630	2.47	0.56	2,135	1.71	1
15	557343	11	4,200	4.58	1.12	4,941	2.96	2
14	557616	11	4,310	2.41	0.56	2,535	2.19	1
28	557172	11	1,960	4.05	2.30	4,612	8.42	4
12	557122	11	5,130	2.51	0.56	3,018	2.39	1
13	557145	11	4,910	5.09	1.11	5,776	3.01	2
6	557851	11	7,420	6.99	0.50	4,365	2.02	1
4	558203	11	9,680	7.44	0.50	5,694	3.11	1
32	558126	21	1,090	2.47	1.97	2,179	3.54	4
35	557009	21	830	2.79	3.96	3,318	5.98	8
29	558164	21	1,660	3.69	1.95	3,318	6.05	4
33	557523	21	930	3.35	3.96	3,718	7.25	8
30	557420	21	1,620	3.53	1.95	3,238	3.97	4
20	557329	21	3,280	3.04	0.96	3,278	1.80	2
26	557823	21	2,210	4.60	1.94	4,417	12.92	4
19	558105	21	3,300	2.17	0.47	1,649	2.75	1
18	557405	21	3,390	2.97	0.96	3,388	1.95	2
21	558119	21	3,130	2.48	0.97	3,128	3.58	2
9	558132	21	5,890	3.50	0.46	2,943	3.26	1
2	558123	21	11,820	4.92	0.44	5,906	3.27	1
1	557354	21	12,560	4.36	0.45	6,276	2.83	1
31	557151	31	1,300	3.18	2.67	3,529	8.40	4
25	557123	31	2,280	2.95	1.32	3,094	2.58	2
17	557225	31	3,480	5.11	1.29	4,723	5.52	2
10	557224	31	5,870	4.42	0.62	3,983	3.32	1
11	557223	31	5,860	4.41	0.62	3,976	1.70	1
8	557627	31	6,100	3.83	0.63	4,139	4.76	1
5	557281	31	7,510	4.41	0.62	5,096	4.25	1
27	557152	51	2,120	4.24	2.14	4,649	8.69	4
7	557187	51	6,210	3.07	0.51	3,404	2.84	1
3	558812	51	11.724	6.34	0.47	6,427	5.13	1

Appendix F: Sensitivity analysis graphs

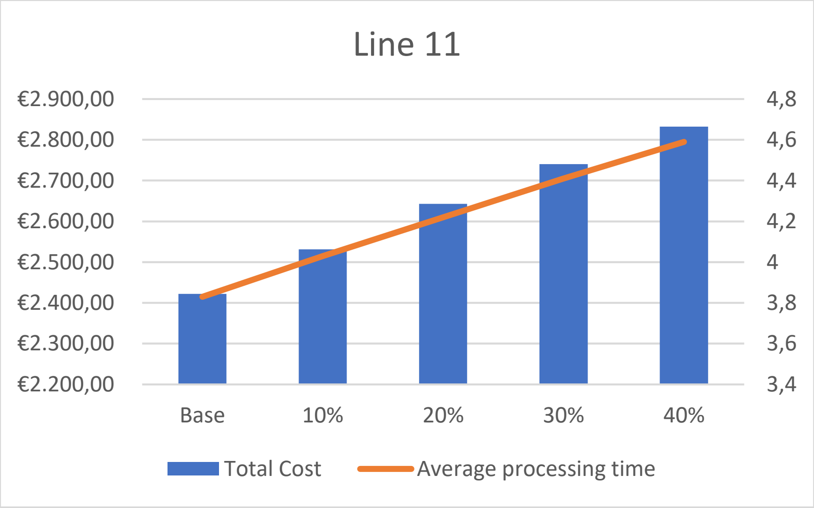
Scenario 1

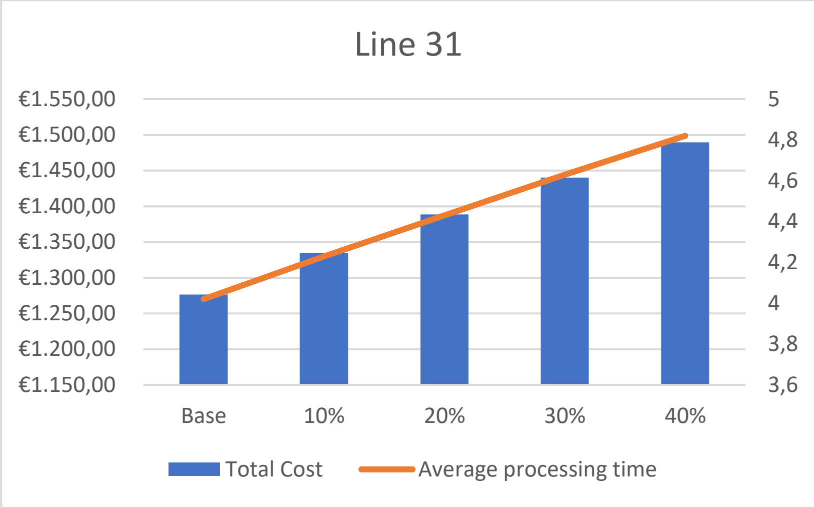


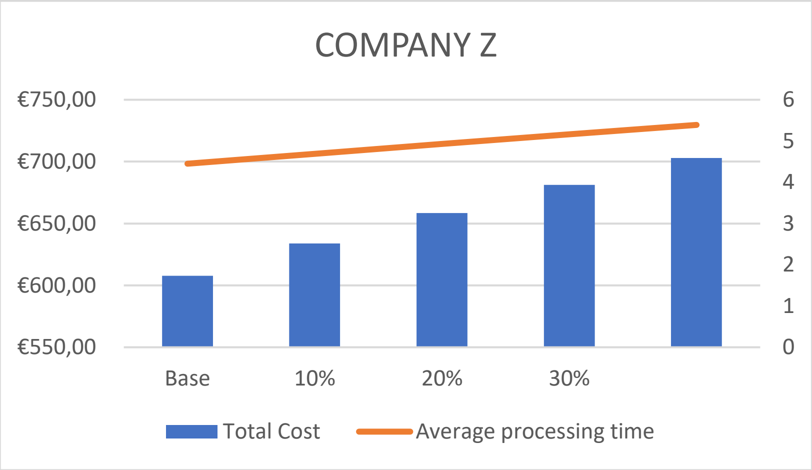




Scenario 2

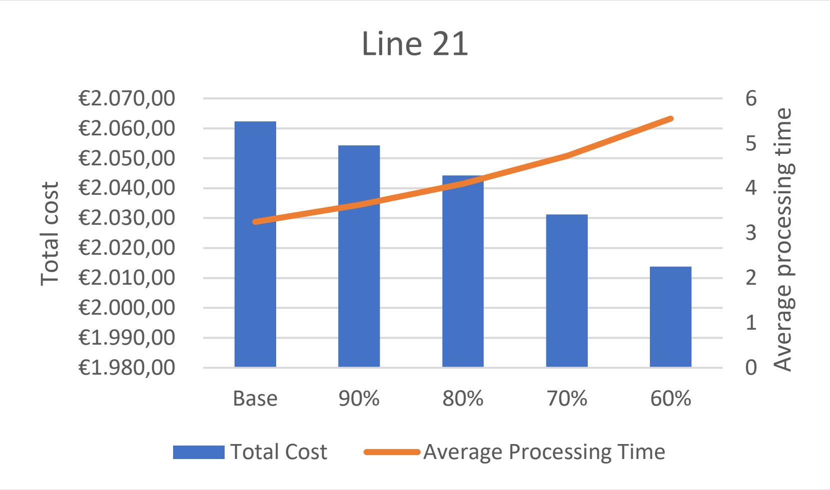




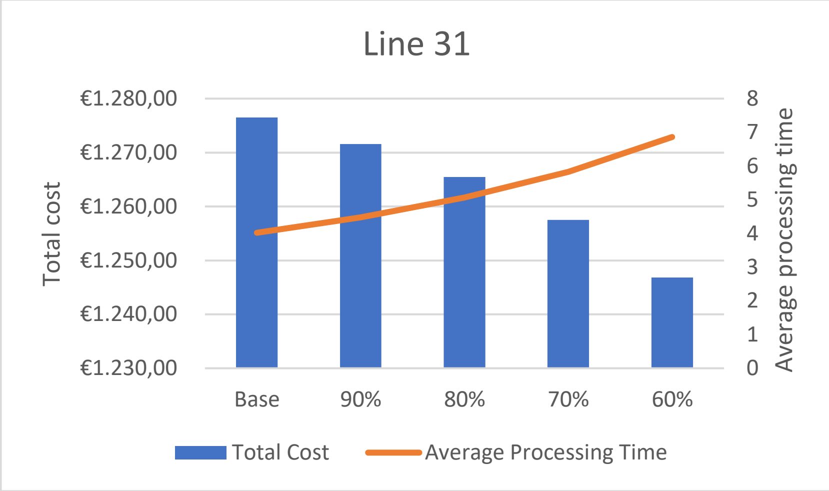


In all the three graphs we see a linear increase in the average processing time. Also, the total cost is almost increasing linearly.

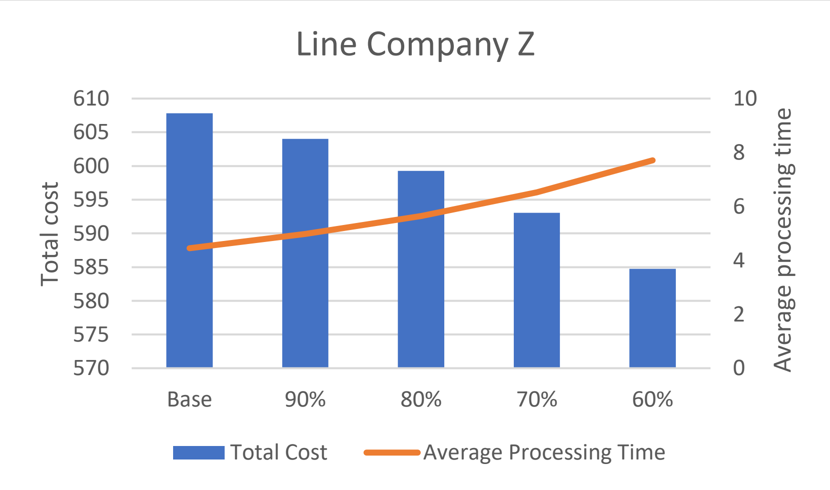
Scenario 3



Line 21
€2.070,00
€2.060,00
€2.050,00
€2.040,00
€2.030,00
€2.020,00
€2.010,00
€2.000,00
€1.990,00
€1.980,00
Total cost
6
5
4
3
2
1
0
Average processing time
Base
90%
80%
70%
60%
Total Cost
Average Processing Time



Line 31
€1.280,00
€1.270,00
€1.260,00
€1.250,00
€1.240,00
€1.230,00
Total cost
8
7
6
5
4
3
2
1
0
Average processing time
Base
90%
80%
70%
60%
Total Cost
Average Processing Time



Line Company Z
610
605
600
595
590
585
580
575
570
Total cost
10
8
6
4
2
0
Average processing time
Base
90%
80%
70%
60%
Total Cost
Average Processing Time

In scenario 3 see an increase in the average processing time after 70% from the base production rate. Some production frequencies change after 70% which affect on the average processing times. The total cost will reduce because of the fraction $\frac{d_i}{p_i}$.