UNIVERSITY OF TWENTE

MASTER THESIS

Using Mixed Integer Linear Programming for providing insight into structural improvements in the production planning process at a food production company

Non-confidential version

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

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GENERAL INFORMATION

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Using Mixed Integer Linear Programming for providing insight into structural improvements in the production planning process at a food production company

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PREFACE

In front of you lies a report that is the result of my graduation project to acquire my master's degree in Industrial Engineering and Management, with the specialisation in Production and Logistics Management. I would like to use this preface as an opportunity to thank the people who made it possible for me to realise this thesis.

Within the context of this master thesis executed at FrozenBakery, I entered the world of mass production. A world with a great focus on efficiency, where millions of products roll out of the factory every day and where departments, despite their different individual goals, work towards one goal together. I would like to thank FrozenBakery for giving me the opportunity to graduate here and experience this. Despite this exceptional year in which the Coronavirus meant that a great part of my assignment had to be done from home and in which FrozenBakery was busy coping with sudden changes as a consequence of this virus, all the people who helped me took the time to do so. I am very grateful to them for that. I would also like to thank my supervisor Sander for guiding me through this thesis and for the nice conversations that broadened my view on production management in particular and on other relevant subjects.

Furthermore, I would like to thank both my UT supervisors Marco Schutten and Leo van der Wegen. Even though we had to do all of our meetings online, I received the guidance whenever I needed it. I am convinced that their commitment and the extensive feedback sessions have led to a better result and for that I am thankful.

Finishing this thesis also embodies the start of a final phase of my student time in Enschede at the University of Twente. I would like to thank my fellow students, with whom I executed dozens of interesting projects. Working together with so many different people, with different backgrounds and opinions has learned me more than I can imagine. In this year in which the Coronavirus makes it harder to do so for all new students, I realise that this is something to really appreciate. I would like to say a special thank you to my IEM master buddy Ellemijn for making all the hours of working on projects so much fun. Also, I would like to say a special thank you to Nicole for all the brainstorms, help and support in the model development phase of this thesis.

Finally, I would like to express great gratitude to the people who are most dear to me. My mom wisely pointed to me, during the difficult pieces in this thesis, that I cannot and should not want to do it all alone. This advice has been given to me by my UT supervisors as well and stated that I should ask for help when I need it. This is something that I will take with me in my next adventures. Without the great conversations and brainstorm sessions at my parents' kitchen table, the critical eye on the entire thesis from my little sister, and the sweet unconditional mental support of my boyfriend, I would not have been able to finish my master's thesis.

Ever since I can remember, me and my sister were often asked "Who invented this?!" by my dad whenever we ran into an interesting product or artefact, with the intention that we shouted out in choir: "Engineers!". This would make him, engineer in brain and soul, proud of his profession and would make us roll our eyes because we had to hear this for the hundredth time. I am proud that, thanks to completing this master's thesis, I can add myself to this group of people and hope to be able to add value to the world of tomorrow!

Laura Nieuwmeijer
Enschede, December 2020

MANAGEMENT SUMMARY

We perform this research at FrozenBakery in Overijssel. FrozenBakery is an international producer and leader in the frozen bakery dough sector. The location in Overijssel opened in 2015 and since then, FrozenBakery has grown rapidly. Three production lines opened in 2015, 2016 and 2017 respectively and there are plans for more in the near future as well. Working methods were copied from the headquarters in the southern of Europe and focus was mainly on running the lines successfully and delivering the products in time. After 5 years of successfully doing business, the next step is to focus on improving current processes and decreasing total costs associated with the operational process. In this research, we aim to find an answer on the following main research question: "***How can the production planning process of FrozenBakery be structurally improved in order to save total associated costs, while maintaining a service level of 99.5%?***".

Currently, the planner at FrozenBakery makes weekly production schedules by using batch run lengths of 8 hours in general. Between different recipes, setup time is incurred due to cleaning of the line and setup of machines. Currently, batch run lengths of 8 hours are used due to the desire to minimise overall setup time, as this is seen as a time loss which has to be minimised. However, producing in large batches currently lead to high inventory levels and the need for external storage. The first problem that we identify is that a product on average stays 31 days in the warehouse, while the goal is to achieve a dwell time of 25 days on average. The second problem is that high setup costs are incurred due to the current way of planning. The current planning process is executed manually by one person in which main focus is on actualities of today, rather than focussing on achieving efficient schedules over the entire planning horizon. Moreover, planning decisions are currently mainly based on subjective opinions rather than on quantified cost factors. This makes it challenging to consider the best possible schedule of the entire planning horizon and can cause production costs due to setups to be higher than desired. The third problem concerns the high uncertainty in customer demand and production output. Main part of the planning process is based on customer forecasts that highly deviate from actual demand. Based on intuition, the planner keeps inventory for a number of products on occasion, but no strategy for this is used. Since FrozenBakery aims to achieve a 99.5% service level, this causes last-minute changes in the production schedule often. This causes costs to be higher than desired as well.

From our literature review, we find that methods exist for solving lotsizing and scheduling problems. These methods aim to find an optimal trade-off between setups in production on the one hand and inventory on the other hand. Furthermore, we find that inventory control policies can be used for keeping inventory in order to prevent for uncertainties in the process.

We use our literature as input for developing a mathematical method that is able to create production schedules under different parameter settings. We test different settings for the batch run length, inclusion of inventory control parameters, and the usage of available capacity in order to gain insight into the impact of these individual planning factors on total costs and on the service level. In our solution design, we evaluate two alternative methods for creating production schedules: 1) a MILP-based Simultaneous Lotsizing and Scheduling method that simultaneously determines the optimal production sequence, production quantities and the timing of production and 2) a MILP-based Block Planning method that assumes a predefined production sequence and determines optimal production quantities and the timing of production. For the Block Planning method, we use another method for determining the optimal production sequence by finding the optimal sequence of recipes that incurs the shortest total setup time. We find from our method comparison that both methods show comparable solution values, but that the Block Planning method performs better in terms of computation time. We therefore elaborate further on the Block Planning method. Based on a number of input parameters such as forecasted demand and processing times and based on the optimal trade-off between setup costs and inventory holding costs, our Block Planning method is able to create production schedules. Moreover, we develop an inventory control policy that uses minimum and maximum inventory levels with the goal to provide protection against uncertainties and to prevent high inventory levels. We use the Block Planning method in combination with our inventory control policy for running scenarios that include a combination of three planning factors in different settings: batch production (standard batch run lengths of 8 hours, of 4 hours, and free batch run lengths), capacity usage (using all available capacity and using only needed capacity) and inventory control parameters (free inventory levels, including minimum inventory levels and including minimum and maximum inventory levels) and we analyse the usage of a predefined fixed production sequence compared to the optimal

weekly production sequence. By running these scenarios, we gain insight in the impact of every planning factor on our key performance indicators (KPIs): service level, inventory holding costs, setup costs, production costs.

We conclude from our results that a direct link exists between the batch run lengths, the inventory levels in the warehouse and the setup time in production. We find that shifting from using a standard batch run length of 8 hours to 4 hours can provide for yearly cost savings of €675,948. This is mainly possible due to a decrease in needed weekly production time of 5% and a decrease in inventory holding costs of 21%. Using free batch runs over using 8-hour batches result in even higher yearly cost savings of €940,108. This cost saving is mainly possible due to a decrease in production time of 9% as batch runs are not restricted to a length of 8 hours.

Furthermore, we conclude from the results in our research that taking into account minimum inventory levels in the planning process are successful in achieving a customer service level of 99.5%. This means that there is less need for last-minute changes in the production schedule and therefore inefficient last-minute setup costs can be prevented. Using minimum inventory levels also provide more certainty in processes that are dependent on the planning such as raw material procurement and deployment of temporary personnel. However, the usage of minimum inventory levels also involves higher inventory levels and costs. Compared to the current situation, our results show increases in yearly inventory holding costs of €484,172 (44%) in case of using 8-hour batches and €193,284 (18%) in case of using 4-hour batches. In case of using free batches we find a decrease in yearly inventory holding costs of €17,836 (2%).

Furthermore, based on comparing the production schedules made by our Block Planning model and the production schedules made by the planner of FrozenBakery, we find that our Block Planning model is able to realise total yearly cost savings of €1,313,728 when using 8-hour batches, €1,471,496 when using 4-hour batches and €1,997,320 for using free batches in combination with using minimum inventory levels and a predefined fixed production sequence. This is mainly possible because the model performs well in finding the optimal combination of stock-keeping-units (SKUs) and recipes that need to be produced in a week. This results in an overall decrease in needed setup and production time. Finally, our results show possible yearly savings of €161,200 when using the optimal weekly production sequence over using a standard fixed weekly sequence. This corresponds to total weekly setup time of 2.95 hours for the three lines together.

Based on the results and other relevant findings in our research, we recommend FrozenBakery to:

- Shift from using standard batch run lengths of 8 hours to using standard batch run lengths of 4 hours. In cases where recipes need a comparable number of personnel and only small machine changes are needed, even smaller batches can result in a further decrease of costs.
- Shift from using a reactive method to cope with uncertainty by changing the production planning last-minute, towards including minimum inventory levels in the planning process for critical make-to-stock products in order to increase certainty in the planning process and the ability to achieve the aimed service levels of 99.5%.
- Conduct further research on the demand side of the planning process by 1) focussing on ways to make sure that customer forecasts become more reliable and 2) by focussing on classifying make-to-stock products based on importance and uncertainty in demand and production and consider to shift highly uncertain products from make-to-stock to make-to-order. Better forecasts decrease the safety stock levels and thereby inventory levels and a clear classification of products imposes a better balance between keeping safety stocks for critical make-to-stock products and risking stockouts for less critical ones.
- Start using a production planning model that can serve as supportive tool to help the planner in making initial production schedules. We emphasise that the model should be used in its strength for computation power and that the planner should be used in its strength as well: dealing with uncommon circumstances and situations by intuition and experience.
- Make the production planning process more future-proof by paying more attention to documenting important planning decisions that are crucial in making production plans, because a company should not be dependent on one person for doing this in a good way. In addition, we advise to use recipe-dependent setup times in the production schedules, because this allows for better performance and bottleneck analyses in production in order to improve changeover activities. Shorter changeover times result in more time being available for value-adding production and result in more flexibility in the production process as decision-making for changeovers become less critical.

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LIST OF ABBREVIATIONS

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OEE	Overall Equipment Effectiveness	3
SKU	Stock keeping unit	7
MTS	Make to stock	8
MTO	Make to order	8
DC	Distribution centre	10
ERP	Enterprise resource planning	11
COPD	Customer order decoupling point	23
GSLPST	General lotsizing and scheduling problem with sequence-dependent setups	25
CLSD	Capacitated lotsizing and scheduling problem with sequence-dependent setups	28
BP	Block planning	28
MIP	Mixed integer programming	30
MILP	Mixed integer linear programming	30
TSP	Traveling salesman problem	31
SLSM	Simultaneous lotsizing and scheduling method	34
SD	Sequence determination	36
KPI	Key performance indicators	52

1. INTRODUCTION

In the context of completing the Master Industrial Engineering and Management, we conduct this research. We execute the research FrozenBakery Overijssel, a food production company in Overijssel. The location in Overijssel opened in 2015 and is part of FrozenBakery International. FrozenBakery Overijssel mainly produces dough products to the frozen bakery dough sector worldwide. After the realisation of the factory in Overijssel, working methods used in other facilities of FrozenBakery International were brought to Overijssel. However, due to a rapid growth, no sufficient time was taken to adopt these working methods to make it fit their own situation. In addition, FrozenBakery Overijssel finds it increasingly important to express their vision in the operational field as well: delivering high quality products and service and being innovative. This has led to the need for improvement in their way of planning production. This research focuses on providing insight in structural improvements in the production planning process of FrozenBakery Overijssel by integrating inventory, lotsizing and scheduling techniques.

This chapter provides an introduction to gain a clear insight into the context of this research. Section 1.1 provides relevant information about the company and Section 1.2 provides more information about the context of the problem. Thereafter, we describe the problem by means of a problem bundle in Section 1.3. We discuss the research objective in Section 1.4, followed by the research sub questions in Section 1.5. Section 1.6 covers the scope of the research.

1.1 Context information

FrozenBakery is an international producer and leader in the frozen bakery dough sector for bread, savoury and sweet pastries. In total, FrozenBakery International has over 20 production plants worldwide. Since 2015, one of them is located in Overijssel, the Netherlands; FrozenBakery Overijssel (from now on called FrozenBakery). FrozenBakery attempts to express their vision more and more, also on operational level: to value the tradition of baking and combine this with innovation to continuously improve processes and products in order to deliver a high-quality product and service. For FrozenBakery, a high quality product means a food safety compliant product that looks, tastes and smells good and neat. A high quality service means reliable delivery and being flexible to meet the needs and wishes of the market.

FrozenBakery has grown fast in the past few years. This has led to the construction of three production lines in 2015, 2016 and 2017 respectively and plans for more lines are already present. As can be seen in Figure 1.1, FrozenBakery International, of which FrozenBakery is a part, has grown from € 380 million to € 729 million in turnover over the past 7 years. After the instantiation of the factory in Overijssel, working methods that are developed by the headquarters of FrozenBakery in Europe were copied to this location as well. However, partly due to this rapid growth, insufficient time was taken to adapt working methods to the Dutch culture and working standards.

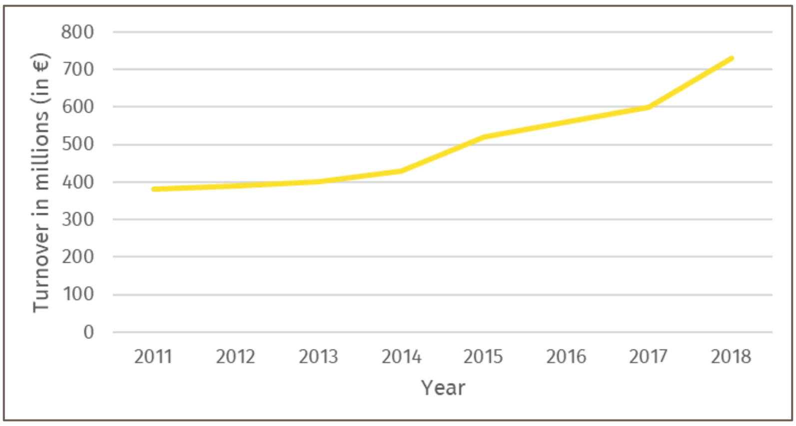

Figure 1.1: Turnover FrozenBakery International 2011-2018

1.2 The problem context

In the initial start-up phase of FrozenBakery, the focus was mainly on running the production lines successfully and getting the products to the customers in time. After 5 years of successfully doing business, more focus is being paid to improving current processes and decrease total costs associated with the operational process. This desire arose because realised costs turn out to be higher than expected. This results in a lower sales margin than desired. Furthermore, the market of today forces FrozenBakery to differentiate themselves from competitors and come up with original, innovative products in the market. This comes along with an increasing need in the market for greater variety in products and packaging. An example on how FrozenBakery reacts to this is the introduction of the BAKER product range. This product range includes sweet pastry products which are produced on one of the production lines that are currently underutilised.

An increase in the total number of product types to produce also leads to an increase in the complexity of planning production and organising setups and product switches on the production lines. Therefore, there is need for improvement in the organisation of production and alignment of the supply chain to reduce the costs generated and making sure FrozenBakery is able to fulfil customer wishes and demands in the future.

1.3 Problem description

We develop a problem bundle in order to represent the problem context given by FrozenBakery. In a problem bundle, different problems with their underlying relations are depicted (Heerkens & van Winden, 2012). The goal of making a problem bundle is to bring structure in the problem context. In this way, the core problem can be found.

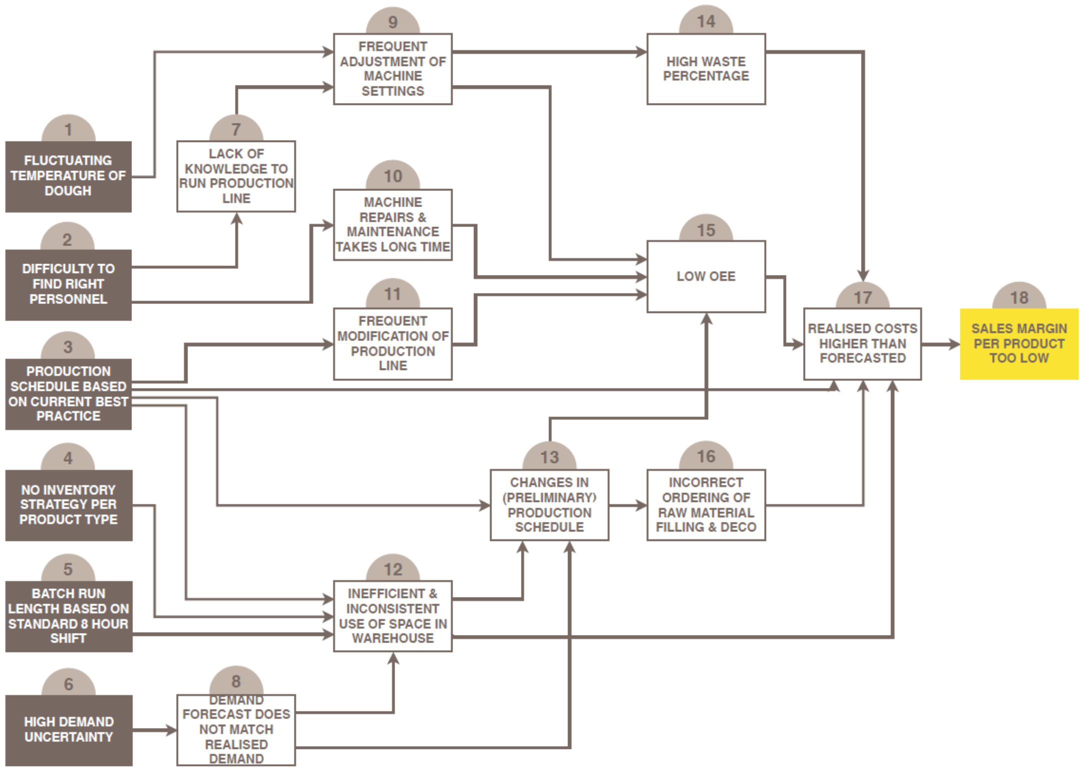

Figure 1.2: Problem bundle

In Figure 1.2, a number of possible core problems is coloured in dark brown. Consequences of these problems are coloured in white and the action problem is coloured in yellow.

The action problem defined by the company is that the sales margin is too low. This is caused by costs being higher than forecasted. Roughly, the costs can be divided into direct raw material costs, direct labour costs, manufacturing overhead costs and inventory costs. We investigate seven core problems that cause this. In this section, we further explain every possible core problem together with its consequences.

- **Fluctuating temperature of the dough (1).** Temperature is a very important factor when producing products from dough. Dough behaves differently with different temperatures. These temperature fluctuations are unavoidable due to factors such as outside temperature, slight fluctuations in the addition of ice in the mixing process, changes in procurement of raw materials or ingredients etcetera. The fluctuating temperature has an influence on the rising of the dough. When dough temperature fluctuates a lot, machines have to be adjusted often. This causes downtime on the line which results in a low Overall Equipment Effectiveness (OEE) rate (15). Next to this, it leads to material waste (14), because dough that does not meet the quality standards cannot be used in the products. Both aspects result in higher manufacturing overhead, direct labour and raw material costs than forecasted.

- **Difficulty to find the right personnel (2).** FrozenBakery has a difficulty in finding the operating and technical service personnel. As a result of the strong economic climate, the permanent workforce is changing often. The leads to a lack of proper knowledge of how to operate the production line (7) and the shortage of technical service personnel results in malfunctioning or defective machines that are off for a long time (10). This leads to a low OEE rate (15) and waste of material (14) as well. Both aspects result in higher manufacturing overhead, direct labour and raw material costs than forecasted.

- **Production schedule is made manually and mainly focussed on actualities of today (3).** Currently, the production is planned according to the best practices and intuition of the production planner at FrozenBakery. Products are scheduled based on demand forecast, incoming orders and current stock level. For planning, the concept of a rolling horizon planning is used. This means that every week, a new week is added to the schedule and the production schedule for the first week is frozen. Based on the preliminary schedule and the forecast, raw materials are purchased and temporary personnel is hired. Currently, the schedule is made manually by the planner and the process is mainly driven by actualities of today, more than focussing on achieving efficient schedules over the entire planning horizon. This obstructs the achievement of economic efficiencies by combining today's orders with future orders. This leads to an overall frequent need for modification and switching of machines (11) and it leads to a frequent need for last-minute changes in the production schedule (13). This results in a low OEE rate (15), because it can lead to high setup times, absence of raw material, or a shortage of personnel. The frequent need for last-minute changes is also caused by uncertainty in demand and production output which we further explain in core problem (6). Furthermore, the needed time for setups in production is not properly taken into account in the schedule. Currently, rough estimations for setup times are made without taking into account the actual needed time for preparing the machines for the corresponding recipes. Finally, in the manual process of scheduling, the impact of a specific schedule on inventory is not a main focus. This leads to products that spend longer in the warehouse than necessary and take up space while this could be used for fast-moving or more profitable products instead. So, the manual planning that is mainly based on today's activities also causes an inconsistent and inefficient use of the space in the warehouse (12).

- **No inventory strategy per product type (4).** FrozenBakery does not have a strategy for determining ideal stock levels for products in order to cope with uncertainty in demand and production output and to prevent excessive stock levels. Currently, the dwell time (time spent in the frozen warehouse) varies from 48 hours to 48 days. This puts a high pressure on the utilisation of the warehouse (12). External storage has to be hired as a result of a full warehouse. This results in high inventory costs (17). On the other hand, last-minute changes often have to be made in the production schedule, because actual demand does not match the forecasted demand (8) and causes the product to be out of stock if no changes in the schedule are made.

- **Batch run lengths are based on standard minimum 8 hour shift (5).** A batch run length is a production batch or lotsize expressed in time. The reason to express this in time is because at FrozenBakery, homogeneous products are mass produced on a flow line. Therefore, the unit time is a more useful factor for them than the unit of production quantity to specify the batch size. The operating and software system at FrozenBakery is based on working orders of 8 hours, which is equal to one shift.

Since the headquarters in Europe and other production locations are focussed on this batch run and work order length, this is used in Overijssel as well. In general, the higher the batch run length, the higher the uptime rate and therefore OEE rate, because no time is lost with setups and other switch related aspects. However, this also has a downside. It leads to less flexibility in production and warehousing. Producing in minimal lengths of 8 hours leads to inefficient use of the storage space in the frozen warehouse (12), because products that are sold less often or in smaller quantities take up a lot of space that could have been used for fast moving or more profitable products instead. Sometimes external warehousing space needs to be used to be able to store the production quantities. This is expensive and therefore FrozenBakery aims to avoid this as much as possible. Holding on to a minimum 8 hour run length therefore in the end leads to high inventory costs for several products (17).

- **High demand uncertainty (6).** Customer demand is highly uncertain. This has a big effect on the products kept in inventory and therefore on the production planning. If actual demand is higher than forecasted, products may run out of stock sooner than expected. This leads to need for last-minute changes in the production schedule (13), because FrozenBakery aims for achieving a customer service level of 99.5%. On the other hand, if actual demand is lower than forecasted, products are left in inventory and raw material may become obsolete. This leads to high raw material costs (17) and to the occupation of valuable space in the warehouse which causes inventory costs to be high (17).

According to Heerkens and Van Winden (2012), a problem can only be a core problem if it is easy to influence and if it has a large impact. Therefore, based on the possible core problems above, we select the problems that are easy to influence and have a large impact.

'Fluctuation of temperature of the dough' is a factor that is hard to influence, therefore we cannot choose it as core problem. Next to this, we also see 'Difficulty to find the right personnel' as hard to influence in our field of expertise. Therefore, this problem is not chosen as core problem as well. Furthermore, 'High demand uncertainty' is a consequence of the needs in the market and the demands from the branch that FrozenBakery operates in. This is considered hard to influence, but we do have to take the uncertainty factor into account in this thesis because it has an effect on the production planning process in general. Therefore, we consider *uncertainty in demand'* as possible core problem. Next to this, three possible core problems are left: '*Production schedule is made manually and mainly focussed on actualities of today*', there is 'N*o inventory strategy per product type'* and *'Batch run lengths are based on a standard minimum 8 hour shift'*. These three problems are all part of the supply chain process. Scheduling and lotsizing are part of the production planning on operational level and inventory strategies have to do with aggregate planning. The three problems are highly interrelated, because of the automated flow process at FrozenBakery. Therefore, we conclude that we see the main core problem as a combination of the following four problems: *High uncertainty in demand, production schedules are made manually and mainly focus on actualities of today, no inventory strategy per product type exists, and batch run lengths are based on a standard minimum 8 hour shift*.

1.4 The research objective

The goal is to gain insight into structural improvement areas in the production planning process of FrozenBakery by means of developing a method to plan the production in an efficient way. We aim to combine two relevant aspects of the supply chain process at FrozenBakery: production and finished product inventory. This research includes looking for ways to better cope with uncertainty in the process by inventory strategies and includes looking for ways to improve lotsizing and scheduling of production. Based on this, we present a planning model that is able to create feasible production schedules. The objective of this model is to minimise total costs, while optimising capacity utilisation and maintaining a desired customer service level of 99.5%. We aim to gain insight in areas which can lead to reductions in total costs. In this thesis, the most important costs include inventory holding costs, setup costs, and production costs.

The main research question of this thesis can therefore be formulated as:

'How can the production planning process of FrozenBakery be structurally improved in order to save total associated costs, while maintaining a service level of 99.5%?'

1.5 Research questions and research approach

We formulate a number of research sub questions in order to answer the main research question. The different research sub questions make up for different chapters in this thesis.

Research question 1*: How is the production and the planning process currently organised?*

- How is the current order-delivery process organised?
- How does the demand forecast relate to the realised demand?
- How are production quantities currently determined?
- How is sequencing of production runs currently executed?
- How is inventory control currently taken into account in the production planning process?

Chapter 2 covers research question 1. We investigate and describe the current situation. We collect information and data that is needed to describe the current situation by means of interviewing personnel of different departments, such as production, sales, supply chain, logistics, procurement and planning. Next to this, helping and shadowing in the production helps to gain a clear insight into how the process from the customer's order to delivery works at FrozenBakery. We use historical data to describe the current situation as well, such as demand information and inventory levels over time of the production.

Research question 2*: What is currently known in literature about inventory strategies and about methods for efficient scheduling and lotsizing in a homogeneous mass production environment under uncertain circumstances?*

- What is currently known in literature on dealing with uncertainty in demand and supply?
- What is currently known in literature on strategies for keeping inventory?
- What is currently known in literature on determination of lotsizes, production sequence and timing of production?

Chapter 3 answers the second research question. It includes an extensive literature overview about methods for planning and scheduling, lotsizing, simultaneous methods for scheduling and lotsizing and strategies for inventory policies under uncertain demand.

Research question 3*: What method or methods can we best use to gain insight into structural improvements in the production planning process?*

- What requirements and assumptions do we take into account in our method?
- What lotsizing and scheduling method is suitable for representing the production situation at FrozenBakery?
- What inventory control policy is suitable for FrozenBakery?
- What planning factors do we change in order to test for improvements in the production planning process?
- How can we integrate the inventory, lotsizing and scheduling strategies into one general planning method?

In Chapter 4, we compare methods for lotsizing and scheduling that exist in literature and discuss the suitability for our purpose. Furthermore, we formulate requirements and assumptions that have to be met in our method. Based on this comparison, we make a decision on what lotsizing and scheduling method is most suitable for this research. We do not only base this on the model output, but we also base our decision on the efficiency of using the corresponding method in order to allow for testing of different planning factors. In Chapter 5, we further detail and extend our lotsizing and scheduling method to be able to test different scenarios that we use for finding out what planning factors have an impact on the total costs. Next to this, we present an inventory control policy that we implement in the lotsizing and scheduling method, in order to combine production and inventory goals.

Research question 4: *What is the impact of various planning factors on total costs and how does the quality of the production planning under various circumstances compare to the current planning method?*

- What key performance indicators do we include in our performance assessment?
- What is the impact of batch production on our key performance indicators?
- What is the impact of production capacity utilisation our key performance indicators?
- What is the impact of including inventory control parameters on our key performance indicators?
- What effect does the method for sequence determination have on setup costs?

In Chapter 6, we test the impact of various planning factors on the total costs and on the production planning output and we compare this output to the realised production planning by means of historical data of 2019.

1.6 Scope

This research focusses solely on the production plant in Overijssel, because the motivation for this research to improve the planning process is specifically relevant at this location. Next to this, within the planning and control process, we focus on lotsizing and scheduling of production and on inventory control for finished products. We do not take into account planning of raw materials, because of time limitations. The reason for choosing to focus on the inventory for finished products, is because this inventory is in direct relation with the production. Everything that is produced according to the production planning, ends in the finished product warehouse. The finished product warehouse is dealing with high dwell times due to goals in production. We therefore ought it more relevant to include this instead of inventory of raw materials. Next to this, we focus our research on the planning of production on Line 1, Line 2 and Line 3, which are the main production lines of FrozenBakery. There is one additional small rework/packaging line which we do not include in our research, because other planning rules apply to this line, which are independent of the production on the other three lines.

2. CURRENT SITUATION

This chapter describes the current situation at FrozenBakery. The chapter starts with an introduction about FrozenBakery in Section 2.1. We describe the history of FrozenBakery as well in short. Thereafter, Section 2.2 continues with a description of the processes at FrozenBakery, organised according to the order-delivery process. Within this section, we analyse the current working methods and flows in the company. Section 2.3 focusses on problems that we identify and on research directions. Section 2.4 covers the conclusions of this chapter.

2.1 Introduction

This section encompasses a short history about FrozenBakery, because the history is of importance in the description of the current business processes. Accordingly, it describes the relation FrozenBakery has with its other production locations.

2.1.1 History of FrozenBakery

FrozenBakery founded in the late 1980's in Europe, when the owner started the company to satisfy the needs of customers and professionals in the bakery and food-service sectors. FrozenBakery was growing fast since then and took over more and more bakery plants in countries in Europe. In 2015, FrozenBakery constructed a production plant in Overijssel, the Netherlands. Within three years, three production lines were realised and plans for more lines are already present. Working methods from the headquarters in Europe were applied to the production and surrounding processes at these Dutch plants. Until today, this is still reflected in instructions and systems being written in foreign languages. Since 2019, FrozenBakery Overijssel is operating independently from FrozenBakery International and has its own budget responsibility. This has led to a feeling of independence and to the aim of adapting working methods to the Dutch culture, language and technology standards. It has also led to the aim of reflecting the vision of FrozenBakery, being traditional in an innovative way to guarantee the best products and service more and more in the practices on operational and tactical level as well. FrozenBakery is therefore currently working on building an original, outstanding product portfolio, while improving current processes to be able to respond to the needs of the market for flexibility, fast and reliable delivery and high quality products.

2.1.2 Product structure

The products sold by FrozenBakery vary in both recipe and packaging. A customer may require a special type of packaging for a standard recipe product. Therefore, the products in stock are called stock keeping units (SKUs). This means that for one product recipe, multiple SKUs exist and the product structure is therefore diverging. This is relevant to know when planning production, because switching between two SKUs with the same recipe requires no setup time, while switching between two recipes does.

2.2 Order-delivery process

In this section, we address the current order-delivery process of FrozenBakery. This order-delivery process holds in general for all products. For each part of the process, we describe and explain the current working methods. Figure 2.1 illustrates the order-delivery process of FrozenBakery. Section 2.2.1 addresses the customer ordering and demand process. This includes the process of forecasting and actual customer orders that arrive at FrozenBakery. In Section 2.2.2, we discuss the production planning process. In this section, we describe the different inputs that are used when planning production and we describe the current preliminary and final production schedule processes at FrozenBakery. In Section 2.2.3, we describe the purchasing process of raw materials and the relation with the production planning process. In Section 2.2.4, we handle the long-term, medium-term and short-term capacity planning process. Section 2.2.5 focusses on the production system of FrozenBakery. In this section, we describe the material flow and the system in general. In Section 2.2.6, we focus on the storage process of finished products in the frozen warehouse.

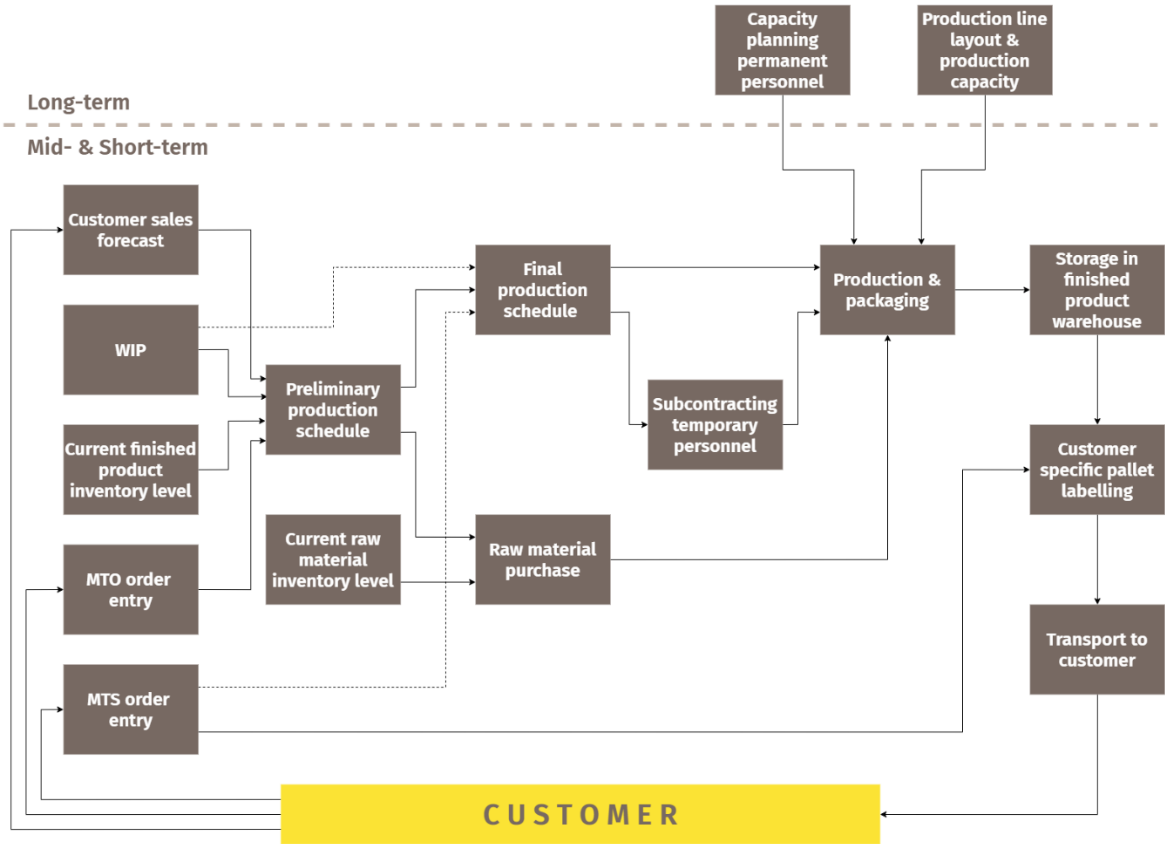

Figure 2.1: Order-delivery process at FrozenBakery

2.2.1 Demand and ordering process

FrozenBakery typically serves (large) retailers. Most of the products are delivered based on make-to-stock (MTS) delivery strategy (Van Donk, & Van Doorne, 2016). For MTS products, the production and planning process is forecast-driven. This makes the customer sales forecasts a very important input for planning of the production. Figure 2.1 and Figure 2.2 show that for this strategy, the product is pushed through the operating system based on customer forecasts until the finished product is stored in the warehouse. When such a customer orders a product, the product is retrieved from the warehouse, labelled with the correct information and transported to the customer. Next to this, some customers are served based on make-to-order (MTO). Usually, these products include a special packaging or a seasonal or temporary recipe. These products and ingredients are only purchased and produced when a customer orders this product.

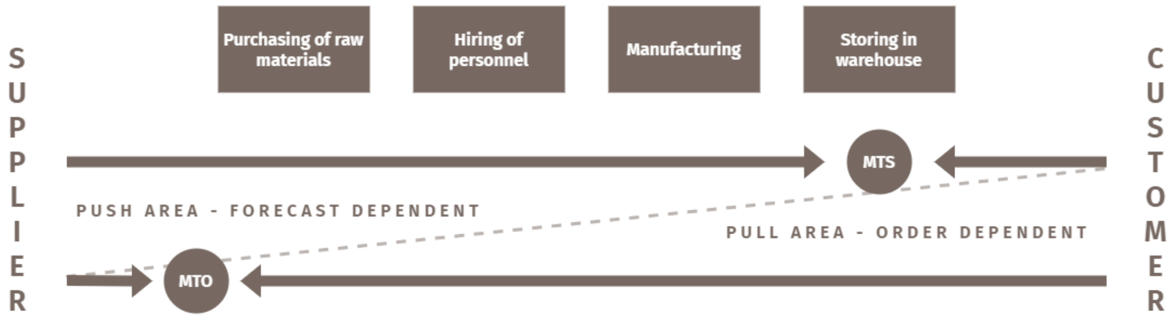

Figure 2.2: Customer order decoupling point per delivery strategy (Akillioglu, Maffei, Neves, & Ferreira, 2012)

Customer forecasts
Usually, a customer sends demand forecasts on a monthly or weekly basis to FrozenBakery. Based on this forecast, the production is planned. However, often forecasts turn out to be higher or lower than expected. This is mainly caused by the branch and industry that FrozenBakery is in. The end consumer is highly unpredictable in his or her buying behaviour and therefore FrozenBakery's customers are as well. We consider uncertainty in demand to be the difference between forecasted and realised demand.

In order to limit the extent to which this uncertainty manifests itself, FrozenBakery uses an advanced program (Slim4) to predict demand. Figure 2.3 shows an example of a forecast for one SKU. In this program, the forecasts that the customer sends are combined with historical data, trendlines and planned events to provide for reasonable forecasts. The graph in Figure 2.3 shows the expected forecast for the current and next month and in case of planned events, the expected forecast for that corresponding month is added as well. Events are temporary promotions that are requested by the customer. General forecasts are coloured in yellow and events are coloured in orange in the example. The forecast for the current and upcoming month is used as an input for making the production schedule. On occasion, it happens that special promotions requested by the customer are not registered in this program. Instead, they are requested via e-mail and therefore not included in the forecast.

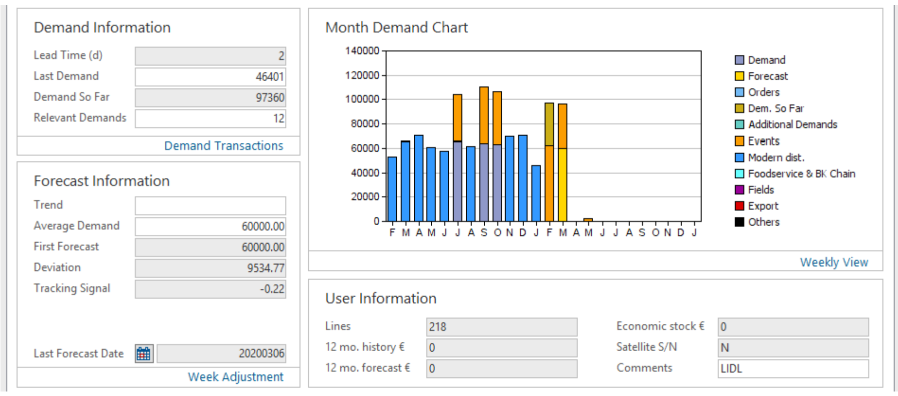

Figure 2.3: Program used for forecasting of demand (Data FrozenBakery 2020)

To exemplify the uncertainty in demand, we show an example of the demand pattern for an average-sales SKU at FrozenBakery in Figure 2.4. The yellow line shows the forecasted weekly demand that is given by the customers on a monthly basis. This information is extracted from the program Slim4. The brown bars show the realised demand for the corresponding weeks. In a number of weeks, the realised demands deviates from the forecasted demand heavily. A possible cause for a high deviation is that promotional event are not registered correctly in the software that keeps track of the forecasts, while possibly FrozenBakery was updated by means of email. Another possible cause of a high deviation is that products are requested all at once for one month instead of on weekly basis.

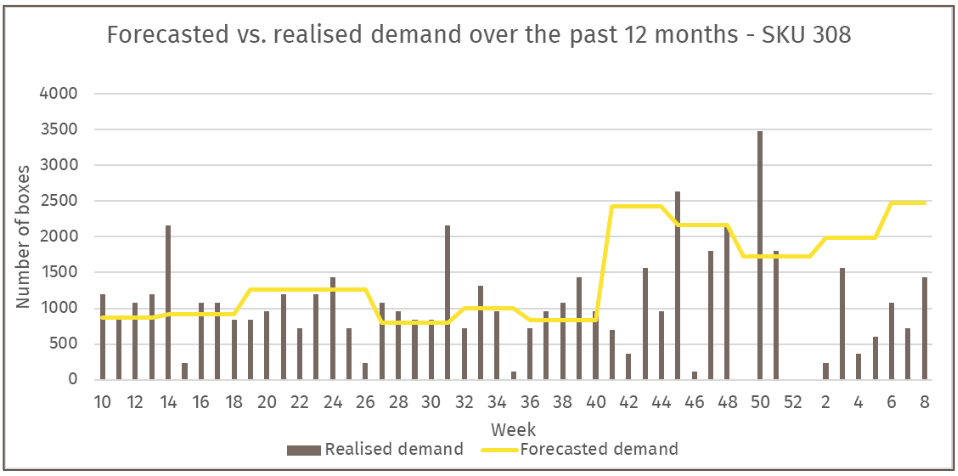

Figure 2.4: Typical demand pattern for an average-sales SKU (Data FrozenBakery 2019-2020)

MTS orders
Parallel to the forecasts that a customer sends to FrozenBakery on a monthly or weekly basis, the actual orders come in on a daily basis. Delivery time is two working days for an MTS order. Based on experience and intuition of the planner, some additional stock is kept on occasion to be able to deliver the customers with a 99.5% service level.

There are a few products that are bought in very large quantities by a few customers. For these customers, FrozenBakery sends the products to the distribution centre (DC) of the customer and is therefore automatically replenished by FrozenBakery. A these DCs, a general stock level around 9 days is hold on to for these customers. The DCs update FrozenBakery every week about remaining actual stock and sales information, so that this can be taking into account in the production planning together with the general forecast for these products.

MTO orders
For MTO orders, the production and purchasing process is initiated only when an order arrives. Delivery time for these specific products or customers is 3 weeks. The majority of this time is needed for the purchasing of raw material. Often, the MTO products only differ from regular MTS products in the packaging type. The process for production, meaning the recipe, usually is the same. The planner is therefore usually able to fit the MTO order in addition to the already planned MTS production in the schedule. There are exceptions, where a customer wants a special decoration or filling. If this is the case, clear agreements have to be made and a delivery time of 3 weeks or even longer, mainly depending on the raw material delivery time, is agreed upon.

2.2.2 Planning process

The planning process consists of two phases: making the preliminary production schedule and freezing the production schedule for the forthcoming week. The main purpose of the preliminary production schedule is to be able to purchase raw materials in time. A period of 3 weeks is set as planning horizon by FrozenBakery, because this is seen a reasonable time to successfully purchase these materials. The current planning method uses a frozen period of 1 week in general. During the week, latest on Wednesday, the production schedule for the forthcoming week is frozen. This frozen period is needed for hiring temporary personnel at the deployment agency that FrozenBakery works with and is for preventing last-minute changes in the production planning.

Preliminary production schedule
A preliminary production schedule is created manually with a rolling horizon planning and a weekly review period. The concept of a rolling horizon planning is used, because forecasts and actual demand only becomes known gradually. Forecasts are updated every month for the next month and the actual demand becomes known only a few weeks (in case of MTO products) to a few days (in case of MTS products) in advance. To clarify the rolling horizon planning concept that FrozenBakery uses, Figure 2.5 provides an illustrative example. The rolling horizon planning consists of a frozen and a free interval. Orders in the frozen interval are not subject to change (anymore) and orders within the free interval can still be rescheduled (Sahin, Narayanan, & Robinson, 2013). In week 9, the planning is reviewed and updated for weeks 10, 11 and 12. On every Wednesday, the production schedule for the next week, week 10 in this example, is made definitive. Week 10 becomes the frozen interval which is coloured red in this case and equals 1 week. Weeks 11 and 12 make up the free interval. For week 11, a the preliminary schedule is reviewed if applicable and is coloured in yellow. For week 12, the planner makes a preliminary production schedule, this is coloured in dark brown. The planner schedules production per week, so the schedule has a cycle length of one week.

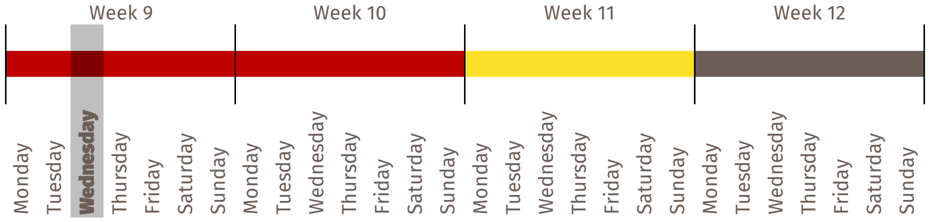

Figure 2.5: Illustration of rolling planning horizon

Inputs for the preliminary production schedule

The entire production planning and scheduling process is carried out manually in Excel. When the planner starts the planning process, three main inputs are used in the Excel file:

1) Sales forecast. Current forecast data is extracted from Slim4. This data comprises the forecasts for the current and for the next month for all MTS products.
2) Current inventory level. From the Enterprise Resource Planning (ERP)-system, AS400, the current stock level per SKU is imported.
3) Actual work orders. The actual work orders containing production orders that are scheduled for the upcoming weeks (in Figure 2.5 this includes weeks 9, 10, and 11) are extracted from the system and imported into Excel as well. This data shows the already planned production.

Creating the production schedule in steps

Subsequently, this information is automatically updated in the main sheet of the Excel file. A part of the main sheet is depicted in Figure 2.6. The first step in preparing the file for scheduling is to sort the current free-stock level from low to high. This sorting gives immediate insight into the SKUs with lowest or even negative free-stock levels. The free-stock level represents the on-hand stock minus all customer orders that are processed in the system. This value does not take into account the planned production quantities. Therefore, this value only serves as an indication for most urgent products to produce. The planner needs to further investigate in the ERP-system AS400 to get correct information about the on-hand stock level, when orders are due, and if and when production is already planned in the next two weeks.

5.5					Current week (selling days) 5.5					WO	WO	WO	WO	WO	WO		Cobertura	Cobertura
sku	Tipy of Prod	FILLED	COATING	Process	Descr.	Current Forecast (bx/Mtl	Weekly Forecast	Daily Forecast	Next Forecast (bx/mt	9	10	11	12	13	14	Free Stock (box)	9	10
15514	DOT	NO	SUCR	F0005A	Dots sucr, (72u)MB	37,193	9,071	1,649	29,811	0	14448	2726	0	0	0	-6667	-4.0	-9.5
11720	BERLINA	YES	SUCR	F0012	Aardbei BallDots (36u) MB	5,862	1,430	260	4,186	0	3408	0	3408	0	0	-1865	-7.2	-12.7
1746	DOT	NO	SUCR	F0005	Donut MitKristallzucker(72u)MB	1,613	393	72	1,606	0	852	0	0	0	0	-660	-9.2	-14.7
13084	DOT	NO	HALF	F0041	Tutti Dots (36u) MB	1,414	345	63	1,405	720	0	1200	0	0	0	-54	-0.9	5.1
62026	DOT	NO	HALF	F0036A	Krokante(36u)MB	0	119	22	0	0	0	0	0	0	0	-26	-1.2	-6.7
~~15519~~	~~DOT~~	~~NO~~	~~SUCR~~	~~F0005~~	~~BEKO Gesuikerde donut (72u)MB~~	259	63	11	144	0	0	0	0	0	0	0	0.0	-5.5

Figure 2.6: Part of the planning Excel file used by FrozenBakery (Data FrozenBakery 2020)

In Figure 2.6, the red cells at the right side of Excel file are used for an estimation of the runout time. The runout time represents the expected number of days until the product is out of stock. This is used by the planner as an estimation of what and how much needs to be produced.

Estimating the production run length

In general, recipes are scheduled for a minimum run length of 8 hours, which equals one shift. This decision stems from the desire for achieving economic quantities, as setups and changeovers sometimes obstruct the efficiency rate of the production line to run smoothly. For some products the minimum run length is set higher. Especially products that contain new recipes often include minimum production run lengths of multiple shifts, because it takes longer to achieve a stable production line that runs correctly. Additionally, a changeover from one recipe to another can play a role in this. If the planner specifically knows that there is a substantial amount of time needed for changing from one recipe to another, this is taken into account in the planning by subtracting the estimated setup time from the total production time of 8 hours prior to the recipe that incurs a setup. In general, changeovers take place at the end of a shift. This is decided by FrozenBakery, because in this way the next shift can start production immediately.

In Figure 2.7, one day of the production schedule for production Line 2 is shown. Each box represents a shift: the left box is the morning shift, the middle box is the afternoon shift and the right box represents the night shift of that day. The afternoon shift has a planned work order duration of 6 hours. This means that the planned production time of this product is 6 hours. After 6 hours, the last dough should be put on the line. The 2 hours that are left are meant for changeover and setup of machines for the next shift. Based on the planned production hours, the theoretical number of boxes that can be produced are estimated. This is referred to as 'Planned boxes'. The number of planned boxes that can be produced per hour are based on the speed of the production line combined with the efficiency rate that FrozenBakery uses for the corresponding line.

WEDNESDAY

04/03/2020

PLANNING	WORK ORDER	856390	SKU	82122
PLANNING	PROCESS	B0694A	UNITS / BOX	96
PLANNING	DESCRIPTION		BOX / PALLET	40
PLANNING	PLANNED BOXES	1.215	HOURS	8
PRODUCTION & PACKAGING	KG / BOX	10	BOX	856737
PRODUCTION & PACKAGING	BAGS / BOX	2		
PRODUCTION & PACKAGING	Total KG/shift	11664	BOX COLOUR	brown
PRODUCTION & PACKAGING	CLIENT		PERSON PRODUCTION	11.3
PRODUCTION & PACKAGING	PALLET	EU - brown	PERSON PACKAGING	1.3
REPORTING	DIF. WASTE		TAI WEIGH	
REPORTING	TIME			
REPORTING	WP			

WORK ORDER	856391	SKU	82122
PROCESS	B0694A	UNITS / BOX	96
DESCRIPTION		BOX / PALLET	40
PLANNED BOXES	911	HOURS	6
KG / BOX	10	BOX	856737
BAGS / BOX	2		
Total KG/shift	8748	BOX COLOUR	brown
CLIENT		PERSON PRODUCTION	11.3
PALLET	EU - brown	PERSON PACKAGING	1.3
DIF. WASTE		TAI WEIGH	
TIME			
WP			

WORK ORDER	856392	SKU	86215
PROCESS	B0758	UNITS / BOX	112
DESCRIPTION		BOX / PALLET	40
PLANNED BOXES	1.018	HOURS	8
KG / BOX	10	BOX	856737
BAGS / BOX	2		
Total KG/shift	10261	BOX COLOUR	brown
CLIENT		PERSON PRODUCTION	13.5
PALLET	CHep - Blue	PERSON PACKAGING	2.5
DIF. WASTE		TAI WEIGH	
TIME			
WP			

Figure 2.7: Production schedule for one day at one production line (Data FrozenBakery 2020)

Sequencing of the production runs

The planner plans products that either need to be replenished to stock or that need to be delivered to the customers, until the shifts for the corresponding weeks are full. After this, the planner prints the draft schedule and starts sequencing. FrozenBakery uses a so-called natural sequence in scheduling the products when this is possible. In general, Line 1 is sequenced from light to dark chocolate recipes, Line 2 is sequenced from natural to line-contaminating recipes and for Line 3, no specific natural order is taken into account. Furthermore, the planner aims to take the following four aspects into account when determining the sequence of production:

1) **Allergens and products that contaminate the production lin**e. This is the most important and restricting sequence factor that needs to be taken into account. Products that contain allergens such as nuts, are always scheduled directly before planned cleaning activities, which usually is at the end of a production week. The same holds for products that heavily contaminate the production lines.
2) **Setup times as result of raw material usage and colour transitions.** The planner attempts to plan the products in the most logical way, for example going from light to dark brown colours or when switching from natural to filled products, because of switching and cleaning of machines.
3) **Speed of the production line**. Scheduling recipes with different line speeds can incur high changeover times if incorrectly planned. Therefore, if applicable this is taken into account in the planning.
4) **Labour costs during night and weekend**. All production lines run during the nights and two of the production lines run in the weekend as well. Labour costs are more expensive during the night and during the weekend. During the weekend, an employee is paid 100% extra, and during the night shifts this is about 30% extra. Therefore, it is more cost efficient to produce labour intensive products in day shifts during the week. This is taken into account when possible in the schedule.

Due to the manual scheduling of the planner, not all aspects are always taken into account properly. Since allergens and line-contaminating products are most important to take into account, these are always considered by the planner. The rest of the aspects are taken into account whenever that is easily possible in the schedule.

Final production schedule

Ideally, no changes are needed in the preliminary production schedule before the schedule for the next week is frozen. However, due to uncertainties in demand, supply and in the production process, changes need to be made in the schedule frequently. This may be due to a rush order from an important customer, poorly estimated risk of stock-outs, poor production output or by poor delivery of raw materials. We analyse the changes in the preliminary production schedules by investigating the revisions of historical production schedules in 2019. We find that in general, revisions to the preliminary schedules are made between 2 and 6 times per production schedule. For Line 1 and Line 3, extreme cases show up to 11 revisions per production schedule. These revisions include changes within the frozen period as well. These changes can result additional raw material costs, labour costs and setup costs. This is because the changes can lead to last-minute orders for raw materials, last-minute hiring of personnel, or because extra recipes have to be squeezed into the schedule and lead to an increase the number of setups.

2.2.3 Purchasing process of raw materials

Most raw materials have a delivery time of around or less than 3 weeks. Therefore, the purchasing of raw materials is based on the preliminary production schedule and this is the reason that the preliminary production schedule has a planning horizon of 3 weeks. Raw materials that have a delivery time of more than 3 weeks are purchased based on sales forecast. This makes it important as well to have a sales forecast that is as reliable as possible. For common raw materials, a safety stock of around a month is hold on to. However, several products cannot be kept in stock for more than a week due to short best-before dates. For the purchasing department, it is relevant to ensure that the actual production matches the planning. This is because purchasing and estimation of order quantities is based on the planning. If the actual production does not match this planning, short lasting raw material may need to be disposed if it is not used in time.

2.2.4 Capacity planning process

Capacity planning is executed based on long-term, medium-term and short-term. We explain this in detail in this section.

Long-term capacity planning
During the development of a new product, it is determined how many products can be produced per time unit, what machines are needed and how many personnel is needed to produce and pack the product. This is referred to as long-term capacity planning at FrozenBakery.

Medium-term capacity planning
A few times per year, the capacity of the three production lines is revised. Since FrozenBakery runs it production based on a shift system, the number of shifts needed per week per production line to match demand is revised every once in a while. This is referred to as medium-term capacity planning.

One shift equals 8 hours and all production lines *can* produce 24 hours for 7 days a week. However, currently not all lines are running at full capacity. In Figure 2.8 we illustrate the weekly shift schedule for the three production lines. A day (24 hours) is divided in three shifts. Each production line has a fixed full cleaning shift every week. We show this cleaning shift in blue in Figure 2.8. Line 1 produces 18 shifts per week, which equals 144 hours. Line 2 produces 13 shifts per week, corresponding to 104 hours. And Line 3 produces on full capacity, which equals 160 hours. The production capacity is reviewed on medium-term basis or whenever sudden major demand changes occur, such as during the Corona pandemic.

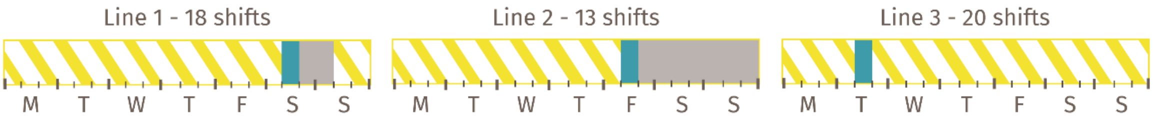

Figure 2.8: Weekly shift schedule per production line

Short-term capacity planning
Finally, the planning of temporary personnel is executed on short-term basis. As stated before, the number of personnel needed for the production of a certain SKU is known from the long-term capacity planning. Based on the medium-term capacity planning, the number of shifts and deployment of permanent personnel is determined. The permanent personnel teams are supplemented with temporary personnel. This is a substantial part of the total employee capacity. Based on the frozen production schedule, extra temporary personnel are hired from temporary employment agencies on a weekly basis.

2.2.5 Production and packaging system

As mentioned before, FrozenBakery currently has 3 production lines. All production lines consist of automated serial flow lines. We show the general material flow for all production lines in Figure 2.9.

Figure 2.9: Material flow from raw material entry until warehouse exit

Material flow
The material flow starts at the raw material entry. There are a number of ways in which raw material is stored at FrozenBakery. Raw material that is used in large volumes, such as flour and powders, are stored in large tanks or silos and are connected to the dough mixing area by means of pipes. Every production line has a mixing area where raw material for the dough is mixed in large buckets that can fit around 100-150 kg of material. A fully automatic system ensures that the right quantity of the right product in the right proportion is mixed in the buckets. This results in dough that has the right temperature to start the forming process. Depending on the recipe of the product, it follows the route through production while undergoing different forming activities. Some products are filled or decorated before continuing to the rising or frying area. Thereafter, the products continue their route to the packaging area. Depending on the packaging type, the products are packed automatically or manually. When packed in bulk, the products are processed by the machine and automatically packed in bags-in-boxes. When packed in trays or blisters (plastic small-sized packaging that can fit 4-6 products), the products are processed manually by the personnel. The speed of the production line mainly determines the number of personnel needed to fill the boxes with products and vice versa. Afterwards, the boxes are packed onto a pallet by a robotic arm and are transported to the frozen warehouse by means of conveyor belts. For a lot of products, a minimum stay of 48 hours in the frozen warehouse is necessary to freeze the products to the right temperature. When a customer order comes in, the products are retrieved from the warehouse and transported to the customer.

Production system layout
The production system can be seen as single-stage. Although the processes in the brown boxes in Figure 2.9 can be seen as different phases of the production process, there are no intermediate buffers or storage opportunities between them. Everything, from raw material tanks until the frozen warehouse, is connected with pipes or conveyor belts. Due to the connection between all phases of the production process, we see the system as one large single-stage system. The throughput time of a product in production depends on the speed of the production line. The speed is determined by a bottleneck resource. For some products, the bottleneck is the restricted capacity of a machine and for some products the bottleneck is the capacity of personnel at the packaging area. The speed of the production line in combination with the number of products that fit on one row on the conveyor belt determines the theoretical output of production.

Setups and changeover of machines
The production lines are built in such a way that modular machines can be removed from and added to the line. This results in a flexible production line that is capable of producing many types of products. However, this also results in required downtime of the line, because of cleaning and changing purposes. In Figure 2.10, we show a picture of one of the many modular machines. This specific machine performs one of the many steps of forming dough into the right shape and thickness.

Figure 2.10: Example of a modular machine on wheels installed on the production line

Typical changeover activities for the setup of a machine include de-assembly of components, cleaning the machine in a special cleaning room, possible changing of components, re-assembly and making sure the settings are correct for the next process. Some machines have a duplicate variant. Processes that need machines with a duplicate variant can switch and setup faster.

The time, effort and required cleaning activities that are needed to prepare the production line for a recipe depends on the current and next recipe that has to be produced. Therefore, the setup costs and time are sequence-dependent.

As mentioned in Section 2.2.2, setup time is taken into account in the production schedule to some extent. However, the times are estimated by the production planner and are not based on data. This results in realised setup times that do not match with the planned setup times. In Figure 2.11, we compare the planned setup times with the realised setup times per month in 2019 for the three production lines together.

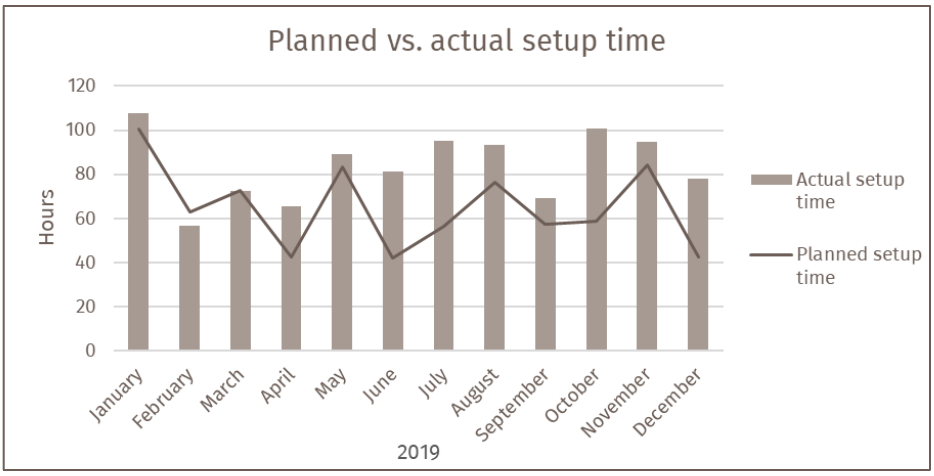

Figure 2.11: Comparison of planned and realised setup times (sum of production lines) over 2019

In 10 out of the 12 months, the realised setup time is higher than the planned setup time. In 5 of the 12 months, the realised setup time is even more than 50% higher than planned for. This indicates that setup times are underestimated and not taken into account in a proper way in the planning.

Production uncertainty

In Section 2.2.1, we analysed the uncertainty in demand. However, there is also an uncertainty in the production process. We can analyse the uncertainty in production by means of the difference in produced and planned boxes. The production planning department includes an efficiency rate of 87%, 90% and 87% respectively for Line 1, Line 2 and Line 3. This rate is included to take into account production errors, unplanned maintenance, absence of personnel etc. Still, we note differences in the planned and produced number of boxes for all three lines. We show this in Figure 2.12.

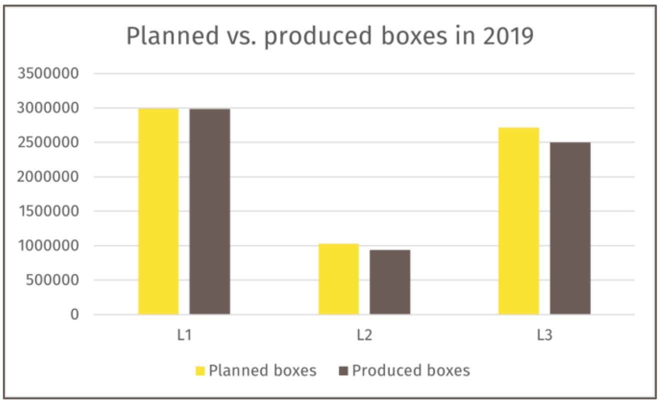

Figure 2.12: Difference between number of produced and planned boxes (Data FrozenBakery over 2019)

For production Line 1, the total produced boxes differences 0.1% from the planned boxes. For Line 2, we note a difference of 8.6% and for Line 3 we note a difference of 8.1%. For all three lines, it holds that the produced boxes are less than what was planned for. This can be caused by actual setup times that were higher than planned for.

2.2.6 Storage in finished product frozen warehouse

The frozen warehouse consists of an automated and a manual warehouse. The automated part of the warehouse has a capacity of 6000 Euro-pallets and the manual warehouse has a capacity of 1000 Euro-pallets. When a stacked pallet enters the warehouse, a number of sensors check whether the pallet is packed according to the quality standards. If so, the pallet is transported to the automated warehouse by means of conveyor belts. If not, the pallet is transported to the manual warehouse. In the manual warehouse, the pallet is repaired or stored, because the automated warehouse allows for only tight, right pallet dimensions. A small part of the automated warehouse spots is occupied by American pallets that take more space. Because of this, a total of 6766 spots in the warehouse is available for storage. We refer to this as the *design capacity*.

A safety threshold also has been set for the warehouse. If the warehouse is 100% utilised and the production is still running, the freshly produced products cannot be stored in the warehouse. When this is the case, additional temporary storage space has to be hired and this is expensive. Therefore, a safety threshold of 24 hours of production is set by FrozenBakery. This corresponds to approximately 400 pallet spots, so the maximum capacity including the safety threshold is 6366 pallets. We refer to this as the *effective capacity* of the warehouse.

Since the warehouse has a limited capacity, it is relevant to keep track of the utilisation rate of the warehouse. We can make a distinction between *utilisation* and *effective utilisation*. *Utilisation* is the percent of design capacity actually filled and *effective utilisation* is the percent of the effective capacity actually filled. The design capacity is the maximal theoretical output of a system in a given period under ideal circumstances, whereas the effective capacity is the capacity that a company *expects* to achieve given the current operating constraints (Heizer & Render, 2008). It is more relevant to use the *effective utilisation*, because this better reflects the real situation in the warehouse than using *utilisation.*

FrozenBakery keeps track of the daily number of pallets that enter, leave and stay in the warehouse. In Figure 2.13 we illustrate the effective utilisation rate of the warehouse. The dark brown line shows the effective utilisation rate over 2019 on a daily basis. The yellow line shows the average effective utilisation rate over 2019. We recall that 100% equals 6366 pallets. Everything that enters the orange zone is in the 'danger zone'. If on that moment a lot of pallets also leave the warehouse due to sales, there is no problem. But if this happens during the night or during a Sunday, there is not enough space to store the pallets that come from production.

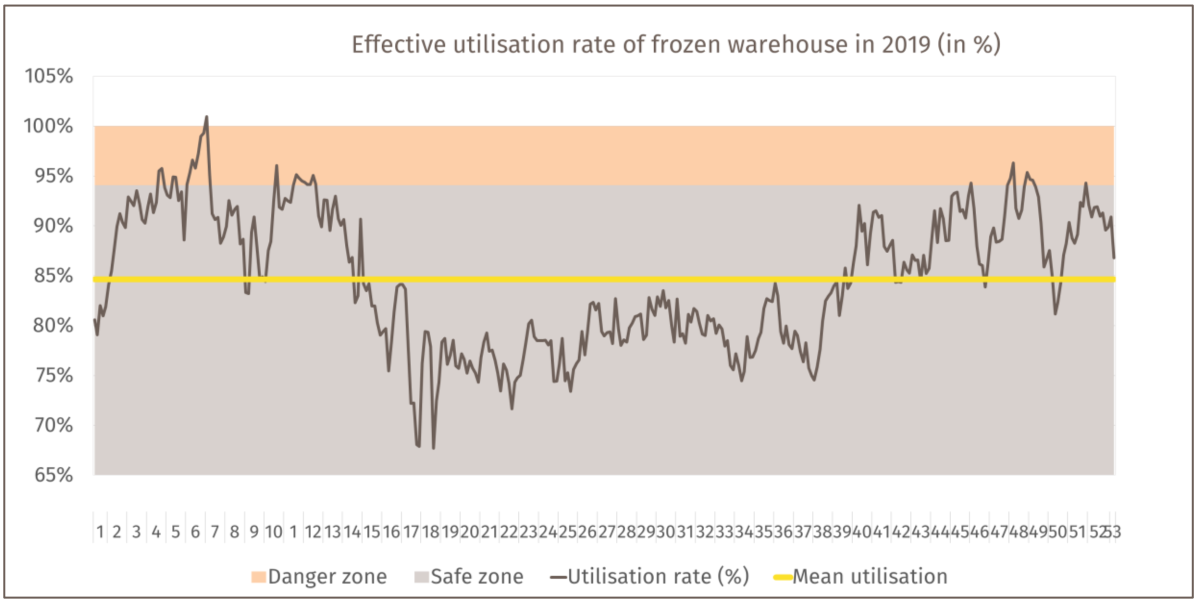

Figure 2.13: Effective utilisation rate of finished goods inventory warehouse in 2019

As mentioned before in the introduction of Chapter 2, additional production lines will be realised in the future. One of these production lines will be installed in the same building as the current production lines. All products made on this line will also have to be stored in the current warehouse. As can be seen in Figure 2.13, currently the effective utilisation rate over 2019 was 85%. This already causes extra costs due to the need of external warehouses and will cause more problems in the future when the output of a fourth production line flows into this warehouse as well. In conclusion, the utilisation rate is high. A high utilisation rate on itself is not a problem when it its balanced enough. However, a high dwell time which is referred to as the time spent in the warehouse, causes more trouble. In the next section, we investigate the average dwell time in the warehouse.

Dwell time warehouse

Products that are produced at the location in Overijssel are allowed to be stored in the warehouse for a maximum of 35 days. Currently, the goal is an average of 25 days in storage. The supply chain department has determined this threshold value, because when storing pallets for more days, the throughput rotation system of the warehouse is disrupted too much. The value of 25 days is based on a basic calculation of the number of pallets that can be produced per day, for the three production lines together. This equals around 500 pallets per day in total. With a design capacity of little below 7000 pallets in the internal warehouse and 800 extra pallet storage capacity at one of the customer's warehouses, the total capacity equals around 7800. By approximation of the supply chain department, 800 pallets are saved for externally produced products (FrozenBakery products that are produced at other locations), so subtracting this number from the total capacity equals out to 7000 pallets again. The number of days before the storage is full is calculated by dividing 7000 pallets by 500 pallets and equals 14 days. If assuming that products leave the warehouse with the same rate as products that enter the warehouse, FrozenBakery can hold on to a dwell time of 28 days and rounded this to 25 days as the goal. Every week, the sales department receives a list from the supply chain department with pallets that are in the warehouse for more than 35 days. For these products, an attempt is made to sell these pallets as soon as possible.

In the ideal case, production quantity and timing follow the same pattern as the demand pattern. In this way, the spots in the warehouse are used in the optimal way. However, there is an uncertainty factor in the process both on the demand and on the production process side. Therefore, the planner at FrozenBakery keeps some safety stock for its products. This is purely based on the experience and intuition of the planner and is not a standard rule that is taken into account.

We calculate the time that an SKU spends in the warehouse by the time between the production date and the delivery date. In Figure 2.14 we show the mean dwell time for MTO and MTS products in the warehouse over 2019.

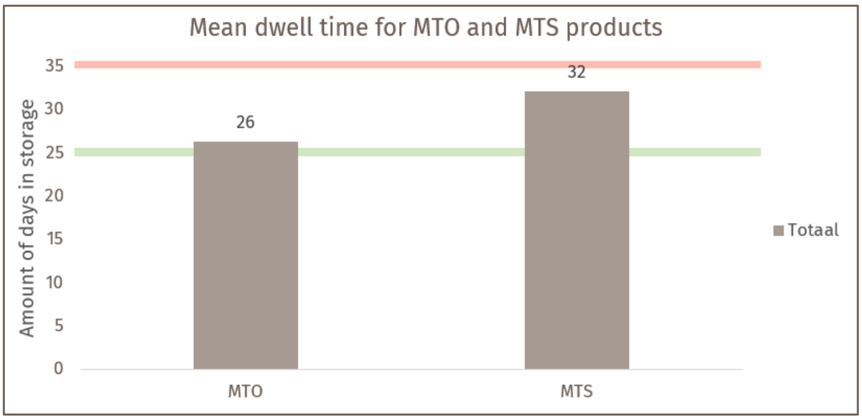

Figure 2.14: Mean dwell time in the frozen warehouse (data from FrozenBakery over 2019)

From Figure 2.14, we find that MTO products spend on average 26 days in the warehouse before being transported to the customer and MTS products spend on average 32 days in the warehouse. On average, this results in an average dwell time of 31 days. This is quite high, because we recall that the goal is to have an average dwell time of 25 days and a maximum of 35 days. We consider it remarkable that MTO products still have an average dwell time of 26 days in the frozen warehouse, as these products are produced only on order and in the quantity ordered.

2.3 Problem identification and research directions

By means of our findings in Chapter 2, we further specify *costs* as associated costs that are influenced by the production schedule. This includes setup and inventory holding costs. Setup costs are incurred when changing over from one recipe to the next recipe. Setup costs are important to FrozenBakery, because during a setup the corresponding production line and personnel are not adding value. Inventory holding costs are important as well because the production schedule determines which and how much products are kept in inventory. In Section 2.3.1, we summarise the main problems that have an impact on these cost factors. In Section 2.3.2, we present initial research directions that can help us solve the main problems. Section 2.3.3 focusses on the goals for our solution directions.

2.3.1 Problem identification

In Chapter 2 we analysed the current situation and working methods at FrozenBakery. We identify the following two main problems that cause the production and inventory costs to be higher than desired:

1. High dwell time and inventory levels. FrozenBakery has an effective utilisation rate of the warehouse of 85% on average and moreover a high dwell time of 31 days on average, while the goal is to achieve a dwell time of 25 days on average. Because of this, external storage space has to be hired regularly. The current inventory levels and thereby the need for external storing space lead to high inventory holding costs. The main cause of this is that FrozenBakery produces in standard batch run lengths of 8 hours. Because of this, for items that are not frequently sold in large quantities, more products are produced than needed for demand during a certain period. The decision for using this standard batch runs of 8 hours stems from the desire to minimise setup time and costs and therefore seems logical. However, currently it does lead to high inventory levels and dwell time in the warehouse and moreover, the need for expensive external warehousing space and therefore inventory holding costs. Currently, there is no specific strategy for holding onto safety stocks, while the uncertainty of demand per SKU highly deviates. This leads to either excessive inventory or stock-outs that have to be replenished last-minute and therefore imply last-minute changes in the schedule. We address this further in the second main problem.

2. Production planning process is executed manually and mainly focusses on actualities of today. The current process of manual planning results in schedules that are created sequentially per week and together form the production schedule for the entire planning horizon. This way of manual planning makes it challenging to consider the best schedule over the entire planning horizon. Also, last-minute changes are made in the production schedule between 2 and 6 times per weekly schedule before it is frozen, and sometimes after it has been frozen as well. Last-minute changes are caused by unforeseen changes in demand or supply, or because orders from other departments often have to be squeezed in because they are seen as urgent and therefore the current planning process is mainly focussed on actualities of today, more than focussing on achieving efficient schedules by the combination of current and future orders. Moreover, there is currently no insight into the effects of these last-minute changes in the production schedule on costs, because cost factors are not included in the planning process. As a result, decisions are based on subjective opinions and can lead to increases in costs. Based on intuition and experience of the planner, some safety stock is hold on to for products. However, this is not documented nor quantified. This leads to either excessive inventory or to stock-outs for an SKU, the latter resulting in last-minute schedule changes. In addition, there is no overview of the products that need to be replenished due to their risk for a stock-out. Instead, current replenishment decisions are based on the absolute comparison of SKU inventory values. Products can therefore turn out to be out-of-stock sooner than expected and impose changes in the schedule as well. In conclusion, the current planning process leads to the need for frequent last-minute changes in the production schedules. The last-minute schedule changes are caused by unforeseen changes in demand and supply, subjective opinions on urgent orders and poor estimation of safety stocks. This can result in costs that are higher than forecasted.

3. Uncertainty in demand and finished product inventory supply. Both from the demand side as well as from the production side, we are dealing with uncertainty. Even though a sophisticated program is used for forecasting demand, we note a major difference between forecasted and realised demand based on data of the past 12 months. Also from the production side, the output is uncertain. The difficulty in finding good technical staff and operators is a major contributor to this. Corrective and preventive maintenance sometimes takes longer than it should and availability of trained operators is limited which has an effect on the efficiency of the production lines. Therefore, we consider the uncertainty from both demand and production side as inevitable. This means that we have to deal with it in the best possible way in the production planning process.

2.3.2 Research directions

In order to address the problems we describe in Section 2.3.1, we search in a number of different research directions. First, we look into inventory theory and inventory policies to better deal with the uncertainty in demand and to avoid stock-outs caused by this uncertainty. We have to take into account that uncertainty is inevitable to a great extent, therefore we focus on reducing the effects of uncertainty on the planning. Second, we look for solutions that are able to plan production by taking into account both production and inventory goals. More specifically, we search in the direction of lotsizing and scheduling techniques to be able to quantify cost factors and generate production schedules by means of data about demand, production and inventory, instead of planning solely based on experience and intuition. Finally, we aim to find solutions that are able to create production schedules on a global level over the entire planning horizon.

2.3.3 Goals for solution directions

The goal of focussing on inventory control and inventory policies is to better balance inventory levels, decrease the dwell time in the warehouse and to better deal with uncertainty to decrease the need for last-minute changes and therefore inefficiencies in the production schedule. The goal of focussing on production scheduling techniques is to help the production planner in his decision making and to help gain insight into the effects of a certain production schedule on associated costs with the ultimate goal of reducing costs that are influenced by the production planning in the future.

2.4 Conclusion

FrozenBakery is a company that has grown fast in the last few years. Running 3 production lines nearly full-time brings a lot of challenges. Producing more nearly two million products per day requires a smart and reliable material flow from start to finish. This requires smart planning that takes into account the restrictions of products, raw material, production and of the warehouse. We analysed the current process and processes that are related to planning at FrozenBakery. FrozenBakery wants to decrease total costs and we specify this further as production and inventory costs that are influenced by the production planning.

The 3 production lines all produce their own set of SKUs. This allows for an individual planning for the three lines. The current production planning process is executed manually by one planner at FrozenBakery. Demand forecasts, inventory information and processed work orders are used for making decisions about what and how much to produce. Decisions about which products to add to the production schedule are made based on comparing absolute free-stock values of SKUs. The products with the lowest values are added to the schedule and are produced in quantities such that 8-hour shifts are filled. The sequence of production is determined by holding onto a standard natural sequence. The production planner plans production based on a rolling horizon method with a planning horizon of 3 weeks and a frozen interval of 1 week.

We identify three main problems that result in costs being higher than desired, influenced by the production planning. Currently, the planner makes weekly production schedules by using standard batch run lengths of 8 hours. Batch run lengths of 8 hours are used due to the desire to minimise overall setup time, as this is seen as a loss of time. However, producing in large batches currently leads to high inventory levels and the need for external storage. The average dwell time in the warehouse is 31 days against the goal of 25 days. Products, especially products with a low sales volume, stay too long in the warehouse because production quantities are higher than needed for demand. This leads to occupation of storage space that could be used for more valuable products with a higher chance of getting sold soon and leads to the risk of getting obsolete and becoming waste in the end. The second main problem is that high setup times are incurred due to the current way of planning. The production planning process is carried out manually in which main focus is on actualities of today, rather than focussing on achieving efficient schedules over the entire planning horizon. Moreover, planning decisions are currently mainly based on subjective opinions rather than on quantified cost factors. This makes it challenging to considering the best possible schedule over the entire planning horizon and can cause production costs due to setups to be higher than desired. Finally, the third problem includes the uncertainty of demand and production output. We consider both types of uncertainties as inevitable and conclude that we have to deal with both in the best way possible in our production planning process. Main part of the production process is based on customer forecasts that highly deviate from actual demand. Based on intuition, the planner keeps inventory for a number of products on occasion, but no strategy for this is used. Since FrozenBakery aims to achieve a service level of 99.5%, this causes last-minute changes in the production schedule often. This causes costs to be higher than desired as well.

In order to solve the main problems, we decide to look in the direction of inventory control and policies and the direction of lotsizing and scheduling techniques. The goal of focussing on these directions is to create a better inventory level balance, decrease the dwell time in the warehouse, better deal with demand uncertainty, and to help gaining insight into possible improvements in the planning process on the associated costs and to reduce these costs in the future by creating better production schedules based on mainly data instead of estimations and intuition.

3. LITERATURE REVIEW

This chapter presents a literature overview about the topics relevant for this research. In Section 3.1, we outline the context in which production planning takes place and what encompasses the production planning and control process from literature point of view. Section 3.2 describes literature about rolling horizon planning procedures and concepts. Section 3.3 covers relevant literature about inventory control and management. In this section, we outline aspects such as policies for inventory control, safety stocks, and different objectives that come along with inventory management. In Section 3.4 we look into methods for lotsizing and scheduling. In particular, we discuss simultaneous lotsizing and scheduling techniques. Section 3.5 continues with another type of scheduling problem, the block planning concept. We finish the chapter with the main conclusions from our literature review in Section 3.6.

3.1 Manufacturing planning and control

Production planning is an activity that considers the best use of production resources in order to satisfy production goals over a certain period named the planning horizon. According to Karimi, Ghomi, and Wilson (2003), this planning typically encompasses three time ranges for decision making: long-term, medium-term and short-term. Much research has been focussing on planning models until now. Hans, Herroelen, Leus, and Wullink (2007) use three broad categories for dividing managerial activities: strategic planning, tactical planning and operational planning. These different categories are concerned with different levels of decisions and objectives, managerial levels, time horizons and planning frequencies as well as different levels of detail and modelling assumptions. This kind of model is called a hierarchical planning and control model. It reflects the increasing information that gradually becomes available as time progresses (Zijm, 2000). Zijm primarily focusses the planning architecture on the interaction between different planning elements. Moreover, the planning architecture integrates material and capacity constraints in the model. Because of the main focus on integration and interaction between different planning elements, we choose the model of Zijm (2000) to further investigate. We look into this model to get a clear idea of what encompasses production planning and control and to learn more about the elements that are related to production planning and control.

3.1.1 Architecture for manufacturing planning and control

In Figure 3.1, a manufacturing planning and control architecture is depicted. This architecture is developed by Zijm (2000) and mainly focusses on the interaction between different planning elements.

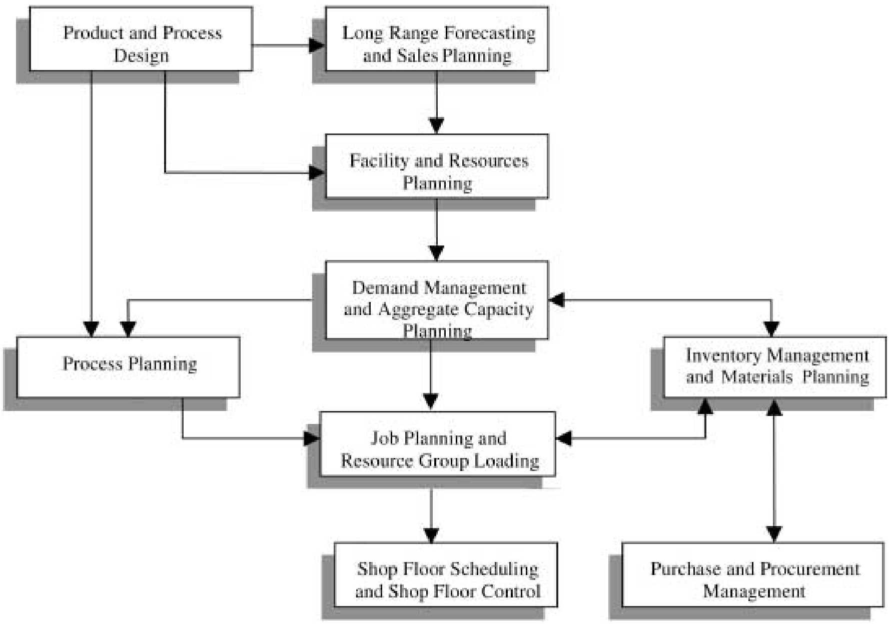

Figure 3.1: A Manufacturing planning and control architecture (Zijm, 2000)

From Figure 3.1, we see that the element 'Demand Management and Aggregate Capacity Planning' is connected by many arrows. It encompasses short term demand forecasting and synchronisation of production requirements with available resources for MTS environments. For MTO environment, this element mainly focusses on requirements, delivery time and price. A clear insight into the relations between the available capacity, workload and lead times is essential in order to determine sound inventory policies and to generate realistic customer order delivery times. The 'Demand Management and Aggregate Capacity Planning' element is an important input for other planning elements, such as 'Inventory Management and Material Planning' and 'Job Planning and Resource Group Loading'. In the research for FrozenBakery, the main focus is on planning elements 'Inventory Management and Materials Planning', 'Job Planning and Resource Group Loading' and 'Shop Floor Scheduling and Shop Floor Control'. Therefore, we discuss these elements in more detail.

Job Planning and Resource Group Loading
The planning element 'Job Planning and Resource Group Loading' occurs after an order is accepted and the macro process is planned. In this planning element, the lotsizes of jobs are determined. Usually, the goal of job planning is to minimise total costs, such as setup, ordering and holding costs for keeping the products in stock. A trade-off should be made between loss of time due to setups and number of parts in inventory. The size of a lot can depend on the availability of raw materials in stock, customer order delivery dates, inventory run-out times and the output of this planning element is internal release and due dates for each separate production job.

Inventory Management and Material Planning
Inventory management plays an essential role at both aggregate and detailed level (Zijm, 2000). The goal is to match internal production capacities with external demand. Three different reasons for the formation of inventory exist: 1) the natural arising of temporary capacity stocks such as for seasonal demand, 2) the use of batch production, and 3) the existence of safety stocks. According to Zijm (2000), inventory management and policies deliver essential input to job planning as well as to purchase and procurement management.

Purchase and Procurement Management and Shop Floor Scheduling
The planning of raw material purchasing receives instructions from the inventory planning and strategy. The allocation of production jobs to time windows depends on the availability of these externally procured materials. Therefore, this is also an important chain element in the entire order-delivery process. Finally, shop floor scheduling contains the detailed scheduling and sequencing of jobs on the workstations. The goal in general is to meet internal due dates and requirements set at the higher order planning level.

The research of Zijm (2000) emphasises the relationship between inventory management and production planning, including lotsizing and scheduling. The research also shows that these elements are highly dependent on the demand and management of demand within the company. The strategy to handle demand, either on a stock-based or order-based manner, is also of importance in the further development of inventory, lotsizing and scheduling techniques.

3.1.2 Push and pull vs. make-to-stock and make-to-order

In manufacturing industry, different kinds of systems can be distinguished, in particular push and pull systems. In a push system, the production order is scheduled and the material is pushed into the production line until it arrives at the finished goods inventory. Usually, the production orders are based on demand forecasts (Benton, 2010). In a pull system, the production process is triggered by a process that comes after production. In this way, production is initiated if it is needed a later process, for example the finished goods inventory. In conclusion, push systems allow for the production or material flow in anticipation of future demand, whereas pull systems the production order release is triggered when an end item is removed from the finished goods inventory.

Make-to-stock (MTS) environments often use push systems for their production (Akillioglu, Maffei, Neves, & Ferreira, 2012). Products are stored at finished goods inventory after passing through all necessary processes. The volume and timing of production is dependent on forecasts. Make-to-order (MTO) environments often use pull systems for their production, because the process is initiated only when a customer order arrives (Akillioglu et al., 2012).

A customer order decoupling point (CODP) represents the strategic point in the value chain of a product where the product is linked to customer order (Akillioglu et al., 2012). The flexibility in choosing the location of the CODP is directly related to the production system capabilities. If product variety is quite high, but the production system is not capable of converting its production from one variant to another in a short time, this forces a company to produce in large batches in order to reduce setup and system down time. The large batches are stored in the warehouse, which is typically an MTS production, because demand is met by finished goods inventory. The challenge in MTS environments is to match and time production and forecasted demand, such that early production is avoided and inventory costs can be kept as low as possible while keeping in mind the target service level.

Soman, Van Donk, and Gaalman (2006) present a conceptual production planning and inventory control framework that combines make-to-order (MTO) and make-to-stock (MTS) production. Their business case focusses on a Dutch food processing company that produces 230 products which differ in recipe, granule and packaging. The material flow at this company is divergent, which means that there are more stock-keeping-units (SKUs) than semi-finished products and more semi-finished products than recipes during production. For many years, a common strategy for such food processing companies was to produce in large batches to keep production costs low and limit the number of setups. However, nowadays wishes and demands of customers change and show an increase in the number of packaging sizes, the number of products as well as the number of products introduced. A result of this is that logistical performance needs to be improved in such companies. It needs to be faster, more reliable and more dependable. This is a trend that we also see at FrozenBakery. It forces a company to operate under a hybrid MTO-MTS strategy. A pure MTO strategy would not be suitable because of the large number of relatively long, costly setups that are required. A pure MTS strategy would not work as well because of unpredictable demand. There is a wish to be flexible and being able to respond to demand and on the other hand there is a wish to restrict setups and to produce efficiently.

3.1.3 Uncertainty in the process

Hans et al. (2007) stress that it is important to notice that all real-life projects are faced with uncertainty. This is caused by the fact that detailed information becomes available only gradually and because of operational uncertainties on the shop floor, for example due to resources that have become unavailable, raw material that arrives late, or activities that turn out to take more or less time (Herroelen & Leus, 2005).

Two different types of approaches can be distinguished when dealing with uncertainty (Hans et al., 2007). The first method is the proactive method and the second method is the reactive method. The proactive method tries to alleviate the consequences of uncertainties prior to the start of the project. In this way, flexibility is allocated in a plan usually by a slack in time or in capacity (Hans et al., 2007). The reactive method approach aims at generating the best possible reaction to a disturbance that cannot be absorbed by the plan without changing it. The reactive method is useful if disturbances cannot be completely foreseen or when they have too much impact to be absorbed by an eventual slack in a plan.

3.2 Rolling horizon planning

A rolling schedule procedure provides a mechanism for dealing with incomplete data. Usually, this method is used in systems where demand only becomes known gradually. Therefore, it is a system that is used in situations with uncertain demand. The alternative to this method is to use a schedule procedure based on a static problem, where it is assumed that demand is known for the entire period. The research of Narayanan and Robinson (2010) encompasses an experimental design for solving a joint replenishment problem in rolling horizon environments.

A system with a rolling horizon solves a series of linked short-term stationary lotsizing problems for which demand is relatively well known. This implies a frozen interval period where planning is fixed and a free interval where lots may be rescheduled (Sahin, Narayanan, & Robinson, 2013). The replanning periodicity is the duration on which the planning is reviewed and updated. Decision variables for a rolling horizon planning system policy include the choice for a lotsizing rule, replanning periodicity, length of the planning horizon and the frozen interval period. In Figure 3.2, an illustration of a rolling planning horizon including the mentioned terminology can be found.

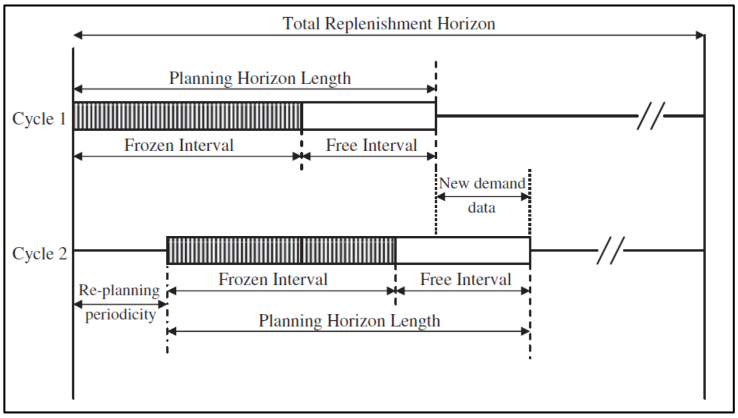

Figure 3.2: Illustration of rolling planning horizon (Narayanan, & Robinson, 2010)

Research about planning in a rolling horizon context primarily focuses on understanding the impact of forecast errors on stockouts and the role of safety stocks. Furthermore, the lotsizing rule and inventory policy have a greater impact on cost than policy parameters such as planning horizon and freezing interval (Sahin et al., 2013). The research of Xie, Zhao, and Lee (2003) contradicts this and shows that three parameters have a significant impact on total costs, schedule instability and service level: the length of planning horizon, freezing proportion which is described as a percentage of the planning horizon and the replanning periodicity, which is described as a percentage of the freezing proportion. A trade-off between total costs, service level and schedule instability has to be made. Xie et al. (2003) conclude that a replanning periodicity that has the same length as the freezing proportion always results in the best performance on all three performance measures.

3.3 Inventory management and control

Inventory is usually held to protect against uncertainties in the process, in demand and supply and to provide for economic efficiencies (Swaminathan & Tayur, 2003). Two distinctions can be made in the management of inventories: uncertainty is managed by means of safety stocks and economic efficiencies are managed through the use of batches. Typically, both types should be considered simultaneously to avoid excessive inventories. Swaminathan and Tayur (2003) describe tactical planning as the setting of key-operating targets such as safety stocks, planned lead times and batch sizes. These key-operating targets serve as guidance as to which day-to-day operations can be executed.

3.3.1 Policies for inventory control

Policies for inventory control depend on a number of parameters. The first important parameter is the type of demand. Demand is assumed to either be independent or dependent (Silver, Pyke, & Thomas, 2016). Independent demand indicates that the demand for item X is not related to the demand for item Y. Dependent demand assumes a relation between demands. Also, demand can either be deterministic or stochastic (Silver et al., 2016). Deterministic demand is assumed to be fully known upfront and stochastic demand represents uncertain demand that is generated by a certain distribution. Deterministic demand is the easiest for optimisation models, but often does not properly represent reality (Silver et al., 2016). The second important parameter is lead time. In purchasing systems, it is the time needed to receive raw material. In a production system, lead time indicates the time needed for waiting, moving, setup, and running until it reaches the finished product warehouse.

Moreover, three fundamental purposes are to be resolved in order to find out what inventory control policy fits a company (Silver et al., 2016):

- How often the inventory status should be determined. The less frequently the inventory status is determined, the longer is the period over which the system must protect against unforeseen variations in demand in order to achieve the desired customer service.
- When a replenishment order should be placed. A trade-off must be made between the costs of ordering somewhat early and therefore carrying extra stock and the costs of providing inadequate customer service.

- How large the replenishment order should be. This issue has an interaction with the previous issue, because the 'when to replenish' may be affected by the replenishment quantity used.

To be able to solve these issues, Silver et al. (2016) suggest four main aspects that managers can use to systematically establish inventory policies: 1) assessing the importance of an item, 2) the review moment, 3) policies for inventory and 4) objectives for costs and service.

1) How important is an item to a company

The first aspect addresses the assessment of the importance of an item. A well-known principle that is often used in inventory management is called the ABC analysis. An ABC analysis helps with focussing on keeping the few critical parts in inventory instead of many trivial ones (Silver et al., 2016). The definition of critical parts is dependent on strategy of the company.

2) Continuous or periodical review

In this aspect, the review interval (R) is specified. This equals the time that elapses between two consecutive moments at which we know the stock level (Silver et al., 2016). In cases with a continuous review, the stock status is always known. However, even though data collection systems are continuously and immediately updated, inventory decisions are often made periodically in reality. When using a continuous review, a replenishment decision can be made any moment in time, this implies that the workload is less predictable. The major advantage of continuous review is that it requires less safety stock than in periodic review, because an order is replenished as soon as it drops below the reorder point. When using periodic review policies, replenishment orders are only places on a review moment (Silver et al., 2016). Advantages of periodic review are that items in a coordinated group can be given the same review interval. Periodic review also allows for a reasonable prediction of the level of workload on the staff involved. Another advantage of periodic review is that it forces a review of the situation.

3) Inventory policies

Four major types of inventory policies can be distinguished. The four most well-known inventory systems are: (s,Q) systems, (s,S) systems, (R,S) systems and (R,s,S) systems. The first two assume a continuous review period and the last two policies assume a periodic review. Currently, FrozenBakery uses periodic review and the systems and processes are based on this. The major reason why FrozenBakery uses periodic review is to batch the production of SKUs with the same recipes together. This decreases the total setup time needed, therefore we decide to look into periodic reviews for FrozenBakery, instead of continuous review. The advantage of continuous review to requiring less safety stock than in periodic review does not outperform the former reason why FrozenBakery uses periodic review.

(R,S) System | Periodic-review, Order-Up-to-Level

Every R units of time, the exact number of items is ordered to raise the inventory position to the level S. The inventory position is calculated as follows:

$$Inventory\ position = On\ hand\ stock + On\ order - Backorders - Committed$$

Where: 'On hand stock' means the stock that currently is in inventory, 'On order' means stock which has been ordered but not yet received by the stocking point and 'Committed' is stock that cannot be used for other purposes in the short run and 'Backorders' are eventual orders that could not be satisfied in the previous period. The (R,S) system offers a regular opportunity to adjust the order-up-to-level S. This is desirable if the demand pattern is changing with time. The main disadvantage of a method like this is that replenishment quantities vary. Also, according to this system, every R units of time, a replenishment order is placed, no matter what the current inventory position is. The next inventory system does take into account whether a reorder is needed yet or not, i.e. whether the inventory position is below the threshold to order again.

(R,s,S) System | Periodic review, reorder-point, Order-Up-to-Level

This system is a combination of the (R,S) and (s,S) system. Every R units of time the inventory position is checked. If it is at or below the reorder point s, a sufficient number of products are ordered to raise it to the order-up-to-level S. If the inventory position is higher than threshold s, nothing is done until at least the next review instant.

4) Objectives for costs and service
When demand is probabilistic instead of deterministic, there is a chance of not being able to satisfy demand directly out of stock or high costs are incurred because of excessive inventory. Safety stocks ss provide a buffer against demand that is higher than expected during the effective replenishment lead time. The safety stock is defined as the average level of the net stock (Net stock = on-hand inventory − backorders) before a replenishment arrives. If backorders are allowed, a negative safety stock is possible since the net stock can be negative as well.

Calculation methods for safety stocks
Different methods are available to determine the safety stock. The first method is to determine this through the use of a 'Simple-minded approach' (Silver et al., 2016). In this approach, a common safety factor or common time supply is assigned as safety stock to each item. The second approach is based on minimising costs. This involves specifying a way of costing a shortage and then minimising the total cost. This approach trades off costs to find the lowest cost policy (for example the trade-off between holding inventory and the cost of using a more expensive transportation method instead of the regular method to be able to meet demand). The third method is to base the safety stock on customer service. The service level becomes a constraint in establishing the safety stock of an item. The last method is to determine the safety stock based on aggregate consideration. The idea behind this method is to establish individual the safety stock using a given budget, to provide the best possible aggregate service across a population of items. The individual safety stocks are based on keeping the total investment in stocks as low as possible, while meeting a desired aggregate service level. There is no one best method to use. It highly depends on the competitive environment of a company what is best. Next to this, it depends on the phase of the product life cycle, on customer wishes and especially on the vision of the company in what method fits best. The inventory policy to choose should be based on this.

We decide to focus in more detail on the (R,s,S)-policy, because the current inventory system at FrozenBakery seems most suitable for this policy. Currently, the planner at FrozenBakery bases the replenishment of products on the free stock level. Furthermore, the planning is updated weekly so a review period of 1 week is hold on to. We note that FrozenBakery uses the rolling horizon planning concept, because demand only becomes available gradually. Furthermore, no reorder points or safety stocks are currently determined by the planning department. Instead, based on intuition the planner keeps extra inventory for certain products. Also, FrozenBakery does not use SKU-specific order-up-to-levels, but do keep track of the average dwell time in the warehouse in order to prevent excessive inventories and dwell times.

3.3.2 (R,s,S) policy and safety stocks

Reorder point s
Maintaining an adequate service level is an important factor for FrozenBakery. The probability of a stockout (probability of a stockout = 1-service level) can be compensated by keeping safety stocks. Therefore, we include safety stocks in the formula that we use for calculation reorder points s (Heizer & Render, 2008):

$$Reorder\ point\ s = d\ x\ L + ss$$

Where d represents the daily demand, L represents the lead time in days and ss represents the safety stock.

Review period R
The review period R is a decision variable as well in inventory policy literature. Since we are dealing with the parameters of a rolling horizon planning, we refer to Section 3.2 for literature about the review period R.

Order-up-to-level S
For systems that solely focus on optimising inventory, the order-up-to-level S can be determined. Order-up-to-levels can be used to prevent excessive inventory and can be used by the procurement department as guidelines for an efficient inventory control. For inventory of finished goods in production systems, the order (or production) quantity is also dependent on factors in the production phase. Therefore, the order-up-to-level S may not be used as only measure to determine the order (production) quantity.

Silver, Naderaldin and Bischak (2009) present a method to determine reorder points and order-up-to-levels in a periodic review with the goal to achieve desired service levels and desired average time between replenishments. In this review, the order-up-to-level S is calculated by means of the following formula (Silver, Naderaldin, & Bischak, 2009):

$$Order\ up\ to\ level\ S: \frac{S}{\mu} = \frac{s}{\mu} + n - E(\tau)$$

Where:

S	Order-up-to-level
s	reorder point
μ	average demand in a unit time interval
n	desired average number of review intervals between consecutive replenishments
$E(\tau)$	average value of τ, where τ is a random variable representing the time from when inventory position hits reorder point s until the next review instant

Safety stocks SS

Different methods exist for calculation the safety stock level (we refer to Section 3.3.1). For FrozenBakery, an important focus point is to realise a high service level. Therefore, we focus on the safety stock method that bases its calculation for safety stock level on the service level. Furthermore, the research of Schmidt, Hartmann, & Nyhuis (2012) focusses the calculation of safety stocks also on the forecasted error of the demand. This is relevant for FrozenBakery, because the production planning is based on customer forecasts, while inventory mutates with actual demand. We therefore consider it more relevant to use a safety stock calculation method that focusses on the forecast error, instead of using a safety stock method that focusses on deviation of mean demand. We illustrate this in Figure 3.3. The bars represent fictitious actual demand, the blue line represents forecasted demand and the orange line represents the mean demand during that period. Since the production process is pushed by means of forecasts and actual demand is subtracted from inventory, the safety stocks should provide protection against deviation between forecast and actual demand.

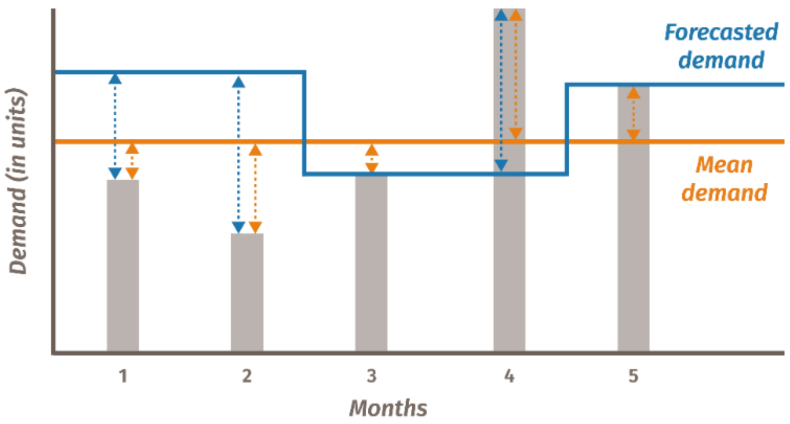

Figure 3.3: Illustration of comparing the actual demand with mean and forecasted demand

We therefore use the following formulation for calculating the safety stock (Schmidt, Hartmann, & Nyhuis, 2012):

$$Safety\ stock\ level = SF(SL) * \sigma_F * \sqrt{TRP}$$

Where:

$SF(SL)$	Safety factor depending on the service level
σ_F	Standard deviation of forecast error for demand during the replenishment time (TRP)
TRP	the replenishment time in number of days

Schmidt et al. (2012) perform a simulation study to assess the performance of different types of safety stock calculations. Of the 9 methods tested, the method that uses the forecast error method is one of the most suitable methods in situations where there is a low to medium variance of demand and a medium to high variance of replenishment time.

3.4 Combinatorial lotsizing and scheduling problems

Many different types of lotsizing and scheduling models have been developed in the field of Operations Research until now. In industrial situations where sequence-dependent setup times are predominant, the capacity available for production depends on both the sequence and the size of the lots. In such a situation, lotsizing and scheduling have to be applied simultaneously in a single step of planning (Meyr, 2000). Since setups at FrozenBakery are sequence-dependent as well, we further investigate simultaneous lotsizing and scheduling problems.

Copil, Wörbelauer, Meyr, and Tempelmeier (2017) conducted an extensive research into different kinds of simultaneous lotsizing and scheduling models. They describe five basic models for simultaneous lotsizing and scheduling: 1) general lotsizing and scheduling problem (GLSP), 2) capacitated lotsizing problem with sequence-dependent setups (CLSD), 3) discrete lotsizing and scheduling problem (DLSP), 5) continuous setup lotsizing problem (CSLP), and 6) proportional lotsizing and scheduling problem (PLSP) (Copil et al., 2017). The main difference between the models is the number of different lots in a period. In GLSP, the number of lots is unlimited. In CLSD, the number of different lots in a period is equal to K products. The size of K is to be predefined. In PLSP, at most 2 lots can be scheduled in a period because it can handle a maximum of 1 changeover per period. In CSLP, this is at most 1 lot and 1 changeover in a period. The DLSP model also handles 1 product per period and is also distinguished from the rest, because of its all-or-nothing rule. This rule states that either a product is produced or is not produced at all in a period. Another main difference between the different basic models is that GLSP and CLSD are based on macro-periods and are also called large-bucket models, and the other models (CSLP, DLSP, and PLSP) are based on micro-periods and are also called small-bucket models.

At FrozenBakery, major cleaning activities are executed every week, therefore the production planning cycle is equal to one week. In one week, FrozenBakery produces more than two different types of products. When switching from one product to the next, changeovers are necessary. Therefore, a small-bucket model is not suitable for our company situation. Next to this, we especially focus on a lotsizing and scheduling method that is able to cover multiple weeks to be able to gain a global optimum. Covering multiple weeks in the planning horizon means that the model determines the optimal timing of a production run of a product over multiple weeks within the planning horizon. Therefore, we decide to focus on large-bucket models only. We further investigate the GLSP and CLSD methods.

3.4.1 General lotsizing and scheduling problem with sequence-dependent setup times - GLSPST

General lotsizing and scheduling problem with sequence-dependent setup times (GLSPST) is a model for simultaneous lotsizing and scheduling of several products on a single, capacitated production line when sequence-dependent setup times are present (Meyr, 2000). In this model, products are scheduled over a finite planning horizon consisting of macro-periods with a given length. A macro-period t is divided into a fixed number of non-overlapping micro-periods with variable length. According to Meyr (2000), the number of micro-periods in one macro-period needs to be fixed in advance to allow for mixed integer programming (MIP). But what differentiates the GLSP in general from other models like DLSP and PLSP is that the number of products per (macro-)period is not restrictive. The length of a micro-period is a decision variable, expressed by the quantity produced in this period. Minimum production quantities or lotsizes can be set in this model. The objective of the GLSPST is to minimise holding and sequence-dependent setup costs over the finite planning horizon. The model is subject to capacity restrictions, maximum lengths of changeovers, minimum lotsizes and setup states of a period.

3.4.2 Capacitated lotsizing problem with sequence-dependent setups – CLSD

Much research has been conducted about the capacitated lotsizing problem with sequence-dependent setups (CLSD). Almada-Lobo, Klabjan, Carravilla, and Oliveira (2007) describe the lotsizing problem as to find production orders or lots in order to satisfy customer demand. Simultaneously with the lotsizes, the sequence of the lots is determined. The main difference between the CLSD model of Almada-Lobo et al. (2007) and the GLSPST model of Meyr (2000) is that the latter subdivides the macro-periods into micro-periods and the former does not.

Subdivision into micro-periods allows for more precise plans, but increases the complexity of the mixed integer linear programming models (Almada-Lobo et al., 2007).

3.4.3 Model formulations GLSPST and CLSD

Both the GLSPST model from the literature of Meyr (2000) and the CLSD model from the literature of Almada-Lobo et al. (2007) use MIP-modelling for model formulation. We present in Table 3.1 the model formulation for GLSPST of Meyr (2000) on the left and the model formulation for CLSD of Almada-Lobo et al. (2007) on the right:

Table 3.1: GSLPST and CLSD model formulations

GLSPST – Meyr (2000)	**CLSD – Almada-Lobo et al. (2007)**
Indices i,j = product 1,…,N t = macro-period 1,…,T with given length s = micro-period 1,…,S *Parameters* S_t = set of micro-periods s belonging to macro-period t K_t = capacity available in macro-period t a_j = capacity consumption needed to produce one unit of product j (time) M_j = minimum lot size of product j (units) h_j = holding costs of product j (per unit per macro-period) s_{ij} = setup costs for a changeover from product i to j st_{ij} = setup time for a changeover from product i to j d_{jt} = demand of product j in macro-period t (units) I_{jo} = initial inventory of product j at beginning of planning horizon (units) Y_{jo} = equals 1 if machine is setup for product j at beginning of planning horizon (otherwise 0) *Decision variables* I_{jt} ≥ 0 : inventory of product j at end of period t (units) X_{js} ≥ 0 : quantity of product j produced in micro-period s (units) $Y_{js} \in \{0,1\}$: setup state, Y_{js} = 1 if machine is setup for product j in micro-period s (otherwise 0) z_{ijs} ≥ 0 : takes on 1 if changeover from product i to j takes place at beginning of micro-period s (otherwise 0) *Objective function* $\min \sum_j \sum_t h_j I_{jt} + \sum_i \sum_j \sum_s s_{ij} z_{ijs}$ (1) *Subject to* $I_{jt} = I_{j,t-1} + \sum_{s \in S_t} x_{js} - d_{jt} \ \forall j,t$, (2) $\sum_j \sum_{s \in S_t} a_j X_{js} + \sum_i \sum_j \sum_{s \in S_t} st_{ij} z_{ijs} \leq K_t \ \forall t,$ (3) $X_{js} \leq \frac{K_t}{a_j} Y_{js} \ \forall s,j,$ (4) $X_{js} \geq M_j (Y_{js} - Y_{j,s-1}) \ \forall s,j,$ (5) $\sum_j Y_{js} = 1 \ \forall s,$ (6) $z_{ijs} \geq Y_{i,s-1} + Y_{js} - 1 \ \forall i,j,s.$ (7)	*Indices* i,j = product 1,…,N t = period 1,…,T *Parameters* d_{it} = demand of product i in period t s_{ij} = setup time incurred when setup occurs from product i to product j c_{ij} = setup cost incurred when setup occurs from product i to product j h_i = cost of carrying one unit of inventory of product i from one period to another p_i = processing time of one unit of product i C_t = machine capacity available in period t M_{it} = upper bound on production quantity of product i in period t *Decision variables* X_{it} = quantity of product i produced in period t I_{it} = inventory level of product i at end of period t V_{it} = auxiliary variable that assigns product i in period t $T_{ijt} \in \{0,1\}$: 1 if setup occurs from product i to j in period t (otherwise 0) $\alpha_{it} \in \{0,1\}$: 1 if machine is setup for product i at beginning of period t (otherwise 0) *Objective function* $\min \sum_i \sum_t h_i I_{it} + \sum_i \sum_j \sum_t c_{ij} T_{ijt}$ (1) *Subject to* $I_{it} = I_{i,t-1} + X_{it} - d_{it} \ ,\forall i,t$, (2) $\sum_i p_i X_{it} + \sum_i \sum_j s_{ij} T_{ijt} \leq C_t \ ,\forall t$, (3) $X_{it} \leq M_{it} (\sum_j T_{ijt} + \alpha_{it}) \ \forall i,t$, (4) $\sum_i \alpha_{it} = 1 \ \forall t$ (5) $\alpha_{it} + \sum_j T_{jit} = \alpha_{i,t+1} + \sum_j T_{ijt} \ \forall i,t$, (6) $V_{it} + N \cdot T_{ijt} - (N-1) - N \cdot \alpha_{it} \leq V_{jt} \ \forall i,t,j \backslash \{i\}$, (7) $T_{iit} = 0 \ \forall i,t$, (8) $I_{i0} = 0 \ \forall i$, (9) $(X_{it}, I_{it}) \geq 0 , (T_{ijt} \alpha_{it}) \in \{0,1\}, V_{it} \in \mathbb{R}, X_{it} \in \mathrm{i}$ (10)

From these model formulations, we can conclude some commonalities and some minor differences between the models. The main commonalities between the models are that they both assume a capacitated production system, both models focus on minimisation of sequence-dependent setup and holding costs and both models include an upper bound to the production quantity of product i. This makes both models suitable for the situation at FrozenBakery. The main difference between the models is the way in which the sequence is determined. The GLSPST model uses variable micro-periods for generating the sequence of production, i.e. a product that is scheduled in micro-period one is produced first. The number of micro-periods is predefined to allow for MIP (Meyr, 2000). The CLSD model uses an auxiliary variable (V_{it}) in combination with additional constraints to ensure the optimal sequence.

3.5 Block planning

Next to these models, we investigate a block planning concept developed by Günther, Grunow, and Neuhaus (2006). The sequence of production orders and simultaneous the sequence of products within a block are predefined. The sizes of the production orders and corresponding processing times are decision variables. Block planning is especially suitable for companies with different variants of products, high output rates and fixed product routings between capital-intensive equipment (Günther et al., 2006).

Block planning is introduced in order to reduce the complexity of the scheduling problem that arises in many processing industries (Günther et al., 2006). Throughout the planning horizon, the production of blocks is repeated in a cyclical fashion, for example a weekly cycle of production orders. The size of the individual production order may vary from block to block. Binary variables are used to indicate whether a production run for a particular product is scheduled or not. This type of planning also aims at minimising inventory holding and setup costs while satisfying the given customer demands.

3.5.1 Model formulations for block planning

Günther et al. (2006) have developed a model for solving block planning by means of a mixed integer linear programming (MILP) model formulation. Günther et al. (2006) stress that they differentiate themselves from previous literature, because they focus on continuous time representation which decreases the problem size. We formulate the block planning model as follows in Table 3.2:

Table 3.2: Block planning model formulations

Block Planning – Günther et al. (2006)	
Indices i = sequence of production orders over all blocks i=1,..I k = product types t = macro-periods 1,..,T i(k,t) = production order in which product k is produced in period (block) t *Parameters* B setup time before starting a block d_{kt} demand of product k in period t h_k costs for holding one unit of product k in inventory L length of a period M sufficiently large number s_i setup costs for production order i σ_i fixed setup/cleaning time of production order i τ_i variable processing time per unit of production order i	*Decision variables* X_i=1 if production order i is produced (0 otherwise) Y_i size of production order i TS_i start-off time of production order i P_{kt} stock of product k at end of period t δ_i duration of production order i *Objective function* $\min \sum_i (s_i * X_i) + \sum_k \sum_t h_k * P_{kt}$ (1) *Subject to* $Y_i \leq M \cdot X_i \quad ,\forall\, i$ (2) $\delta_i = \sigma_i \cdot X_i + \tau_i \cdot Y_i \quad ,\forall\, i$ (3) $TS_i \geq TS_{i-1} + \delta_{i-1} \quad ,\forall\, i = 2,..I$ (4) $TS_{t \cdot K} + \delta_{t \cdot K} \leq L \cdot t - B \quad ,\forall\, t$ (5) $P_{kt} = P_{k,t-1} + Y_{i(k,t)} - d_{kt} \quad ,\forall\, k,t$ (6) $X_i \in \{0,1\}, Y_i,\ TS_i, P_{kt},\ \delta_i \geq 0$ (7)

As can be seen from the model formulations, the MILP model of Günther et al. (2006) also uses micro-periods, which they call production orders for assigning products and lotsizes within a macro-period. Next to this, it is important to note that the model described above uses setup or cleaning times depending on the production order i (in which product k is produced), so sequence-dependent setup times and costs are not included in this model.

3.5.2 Determining the sequence of production – Traveling Salesman Problem

As mentioned in the beginning of Section 3.5, block planning assumes a predefined sequence of production. Determining the predefined sequence can be done in many ways. One of these ways is to maintain a fixed sequence. This can be decided upon by a company, either due to product characteristics or to keep it the scheduling process manageable. An alternative is to determine the production sequence by a mathematical optimisation model. Determining the production sequence for a certain number of recipes or products (e.g. a week) is very similar to the well-known Traveling Salesman Problem (TSP) in which the salesperson does not have to return to its depot. TSP can be described as a problem in which a salesperson wishes to visit exactly once all m cities by taking the least costly possible route (Hoffman, Padberg, & Rinaldi, 2013). In Table 3.3, we formulate the basic TSP as follows:

Table 3.3: Traveling Salesman Problem model formulations

Traveling Salesman Problem – Hoffman et al. (2013)	
Indices	*Objective function*
i,j = city i,j = 1,..m	$\min \sum_j \sum_i c_{ij} x_{ij}$ (1)
Parameters	*Subject to*
c_{ij} cost for traveling from i to j	$\sum_j x_{ij} = 1 \ , \forall\, i$ (2)
	$\sum_i x_{ij} = 1 \ , \forall\, j$ (3)
Decision variables	$\sum_{i \in K} \sum_{j \in K} x_{ij} \leq \lvert K \rvert - 1 \quad , \forall\, K \in \{1, \dots, M\}$ (4)
x_{ij}=1 if tour i to j is in the tour (0 otherwise)	

3.6 Conclusions

Chapter 3 provides existing literature that is relevant for our research about production planning and inventory control in general, the integration between those two and on uncertainty in the planning process. We learn from the manufacturing planning and control architecture of Zijm (2000) that mutual connections between different planning elements exist and that changes in one of the elements also imply changes in other elements. It is however exactly these connections that can enable us to make improvements in the overall planning process. Furthermore, we describe differences between make-to-stock and make-to-order production environments and we combine this with developments in the market. Recent research of Soman et al. (2006) learns us that, because of rising needs in the market for flexibility, an increase in product and packaging variety, reliability and rapid response, there is a need for switching from a solely MTS environment to a hybrid MTO-MTS environment to be able to meet these market demands. This requires a smart control and planning system that is able to produce in both ways.

Next to this, different methods to deal with uncertainty exist in literature. The reactive method aims at generating the best possible reaction to a disturbance that cannot be completely foreseen and that cannot be absorbed by the plan without changing it. A widely used method for dealing with uncertainty and with information that only becomes known gradually, is the concept of rolling horizon planning. This concept solves a series of linked short-term stationary problems for which demand is relatively well known. The planning includes a frozen interval period where the schedule is fixed and it includes a free interval period where changes in the schedule can still be made.

Moreover, different inventory policies are available in literature. We look deeper into literature about the (R,s,S) inventory policy, because this policy matches best with the situation at FrozenBakery. We need to take into account safety stocks to deal with uncertainty, while still being able to achieve the service level goals. A relevant calculation method for safety stocks is to use forecasted error of demand, because deviations exist between the forecasted and realised demand. Order-up-to-levels can serve as an upper bound for the order (production) quantity in production to prevent excessive inventory as a result of production goals that force a minimum number of setups.

Many scheduling and lotsizing methods exist. We find that the basic difference between block planning method and simultaneous lotsizing and scheduling methods is that block planning assumes a predefined production sequence and simultaneous lotsizing and scheduling methods include the production sequence as decision variable in the MILP model. Moreover, we find that within the simultaneous lotsizing and scheduling methods, large-bucket and small-bucket models exist. We conclude that large-bucket models are more suitable for the situation at FrozenBakery, because large-bucket models allow for the scheduling of more than 2 types of products per production cycle. We compare the GLSPST and CLSD large-bucket models and conclude that even though the method for determining the sequence is different, the models in general do the same. The GLSPST method uses micro-periods for determining the sequence and the CLSD uses auxiliary variables for determining the sequence of production. Using micro-periods allows for more precise production plans, but can also increase the complexity of the mixed integer linear programming models.

4. SOLUTION DESIGN – PHASE I

In this chapter, we aim to find an answer on the question '*What method or methods can we best use to gain insight into structural improvements in the production planning process*?'. This chapter addresses the first phase of our solution design and focusses on the development of two production planning methods. Subsequently, we compare the quality of the methods to each other and we choose the method that fits our purpose best. Recall that the purpose of this research is to gain insight into factors that structurally improve the production planning process in order to save costs, while meeting a service level of 99.5%. We cover the second phase of our solution design in Chapter 5. Chapter 5 focusses on detailing and extending the production planning method that we choose in this chapter and focusses on methods for inventory control.

Section 4.1 elaborates on the solution direction that we focus on in our solution design. Section 4.2 describes the requirements that we set and assumptions that we make in our solution. Section 4.3 discusses different solution alternatives for lotsizing and scheduling methods. In Section 4.4, we denote the mathematical model formulations for the models that we work out in detail. We test the performance of these models and decide which model we choose to further develop in detail in Section 4.5. Section 4.6 covers the conclusions of this chapter.

4.1 Solution direction

Recall from our literature review in Chapter 3 that many methods exist for lotsizing and scheduling of production. We decide to use a method that uses mathematical optimisation modelling, because it can be used to find an optimal production schedule in order to minimise total associated costs. Such methods determine optimal production quantities, run lengths, optionally sequences and thereby schedules. We use this planning model as a means to investigate the impact of structural changes in FrozenBakery's planning factors. Based on the main problems identified in Chapter 2, we consider a number of planning factors that are relevant for gaining insight in improvements in production and warehouse departments at FrozenBakery. The first main problem identified in Chapter 2 is that FrozenBakery has high inventory levels. One of the possible causes for this is that FrozenBakery produces in standard 8-hour batches. The first planning factor we consider is therefore *batch production*. The second planning factor is *capacity utilisation*. FrozenBakery uses a shift system and this results in a fixed weekly capacity per production line. We want to gain insight into the number of hours actually needed for production, therefore we include this planning factor as well. The third planning factor that we consider stems from another main problem that we identified in Chapter 2: uncertainty in demand. To be able to properly respond to this uncertainty, an inventory policy can be used. We therefore focus on the development of an inventory policy in Chapter 5 and want to test the usage of the corresponding *inventory control parameters* in the production planning phase. The fourth planning factor is the *sequence of production*. Currently, the sequence is determined by the planning department based on experience and intuition as well and is based on a standardised natural sequence in general. We want to test whether sequencing based on setup time data improves the production planning. Finally, we want to gain insight into differences between the current way of planning and planning based on an optimisation model.

In conclusion, the planning factors include: *batch production*, *utilisation of production capacity*, *inventory control parameters* and *sequence of production*. We create different scenarios in which we test the impact of every factor. To be able to do this, we develop a mathematical optimisation model that is able to construct a production schedule for a given planning horizon based on minimisation of costs.

4.2 Requirements and assumptions

In order to develop a mathematical model that fits with the situation at FrozenBakery, we need to set up requirements and assumptions. From conversations with operational departments at FrozenBakery and based on the production and warehouse systems, we include the following requirements in our model and we make the following assumptions:

4.2.1 Requirements

- All forecasted demand has to be fulfilled on time
- Setups occur on recipe level at the end of a production run
- Setup times are sequence-dependent

- Multiple SKUs can belong to a single recipe
- Production capacity set for a certain line and week cannot be exceeded
- Inventory levels are measured at the end of a week

4.2.2 Assumptions

- Product units are based on boxes rather than individual products
- Forecasted demand is known
- Processing times and setup times are known
- A recipe is produced at most once per week
- Enough raw material and personnel is available to run production according to planning

4.3 Solution alternatives for a lotsizing and scheduling model

In our literature review, we describe different methods that can be used for lotsizing and scheduling of production. The most important difference between the methods described is whether or not the *sequence* of production a variable in the model or not. The block planning method is a method that assumes a predefined production sequence and determines production quantities and timing of production. Simultaneous lotsizing and scheduling methods determine the sequence, timing, and quantities for production.

4.3.1 Block planning and simultaneous lotsizing and scheduling methods

The method for block planning (BP) assumes that the order in which products are made is predefined, based on product characteristics or significant cleaning and setup times between products. Next to BP, simultaneous lotsizing and scheduling methods (SLSM) are available. We discuss two SLSM methods in our literature review: GLSPST and CLSD. The main difference between these two is that GLSPST works with micro-periods in which products are assigned to in order to generate the sequence of production and CLSD does this by means of an auxiliary variable. Working with micro-periods allows for more precise planning, but also increases the complexity of the mathematical model (Almada-Lobo et al., 2007).

The main difference between SLSM and BP is that in SLSM the sequence of production is a decision variable in the mathematical model and in BP the sequence of production is an input parameter that is determined beforehand. Another difference between both methods is the complexity of the mathematical model. SLSM contains a decision variable that determines the production sequence. This specific type of sub-problem is comparable to the traveling salesman problem, which is known to be NP-hard to solve and therefore SLSM is as well (Almada-Lobo et al., 2007). NP-hard means non-deterministic polynomial-time hardness. BP does not include this decision variable, which makes the model less complex and therefore likely easier to solve. Günther et al. (2006) show that their MILP formulation for BP can be solved within 0.25 seconds of central-processing-unit (CPU) time for a problem instance of 26 products and 6 periods, which corresponds to 780 variables and 786 constraints. At FrozenBakery, the production planning comprises 3 periods and Line 1 produces around 26 different recipes, Line 2 produces 20 different recipes and Line 3 produces around 61 different recipes. This means that the problem instances are comparable to the instance of Günther et al. (2006). The GLSPST method of Meyr (2000) and the CLSD method of Almada-Lobo et al. (2007) are solved to optimality for small instances, but need heuristics for very large problem instances.

It is relevant to know to what extent the sequence of production is fixed at FrozenBakery if we want to find out what model is best suitable. At FrozenBakery, two of the three production lines follow a so-called natural sequence because of specific cleaning times. The products at Line 1 are mainly produced in the order from light to dark chocolate. On production Line 2, where mostly savoury products are produced, the products are produced in the sequence from clean to contaminating. The sequence of production Line 3 does not follow a specific standardised sequence. Furthermore, recipes that contain allergens are scheduled at the end of a production cycle. This current way of sequencing is based on estimations and experience of the planning department and is not quantified by data. Next to this, the standardised sequence is not future-proof, because it does for example not give a clear idea on what sequence to use in case non-savoury products are to be produced on Line 2 as well. In conclusion, current decisions for sequencing are mainly based on preventing excessive cleaning and setup times. Therefore, we decide to include decision-making for the production sequence in a mathematical model that minimises on sequence-dependent setup costs, amongst others.

In order to find out the preferred method for FrozenBakery, we consider two criteria: 1) the extent to which the problem can be modelled properly (reality should be reflected in the right way) and 2) the time it takes for solving the problem to optimality. As far as we learned from literature, all methods described above are suitable for modelling the real production situation in a proper way if some extensions are included. We also learned that BP is capable of solving realistic problem instances within a second. BP would therefore be the preferred method to use when looking at the time that it takes to solve the problem to optimality. However, we have to keep in mind that we decompose the overall problem in two parts when using BP: determining the optimal predefined sequence in a separate model and determining the timing of production and production quantities in the BP model. So the preference for the BP model only holds if the solution that we find after solving the decomposed problem performs well enough compared to solving the problem simultaneously by means of our SLSM model. We therefore decide to test the quality of the BP method against the quality of the SLSM method. In this comparison, we not only focus on the solution value, but also on the time that it takes to find this solution. Since we have limited time available in this research and want to test multiple different scenarios with the production planning model, we need to find the right method that is able to do so within the available time. From this comparison, we analyse whether BP is capable of creating solutions that are acceptable compared to the efficiency of finding this solution. In order to do so, we need to make the following decisions:

1) What method do we use for our SLSM method?
2) What method do we use for determining the predefined production sequence?

1) SLSM - Simultaneous lotsizing and scheduling method

As mentioned in Section 3.4.2, the main difference between GLSPST and CLSD is that GLSPST uses micro-periods to determine the production sequence and CLSD does not use micro-periods. Instead, CLSD uses auxiliary variables and a number of constraints that determine the sequence. Making use of micro-periods allows for more precise production plans but has the disadvantage of increasing the complexity of the mathematical model (Almada-Lobo et al., 2007). Therefore, we need to determine whether we need micro-periods for determining the production sequence or not. In the current situation at FrozenBakery, a production shift of 8 hours consists of production time and, if applicable, setup time at the end of the shift to prepare for the next recipe. If the recipe stays the same, no setup is needed and the shift is fully filled with production time. We illustrate this in a fictive example in Figure 4.1. In order to determine the lotsize, we need to know whether there is a setup from the corresponding recipe to the next recipe at the end of the shift or not. This needs to be stored in 'production order i' index for the model to know that the production time and setup time from the current to the next recipe have a total duration of any predefined length (in the current situation this equals 8 hours). In the GLSPST model of Meyr (2000), this index is used as well. So, one recipe is assigned to a production order i in a specific week. The number of production orders per macro-period needs to be predefined in order to allow for MIP programming (Meyr, 2000). The index for production order i has a size of $i = 1, \dots, K \cdot T$ with K as the number of recipes that can be produced in a week and T the number of periods within the planning horizon.

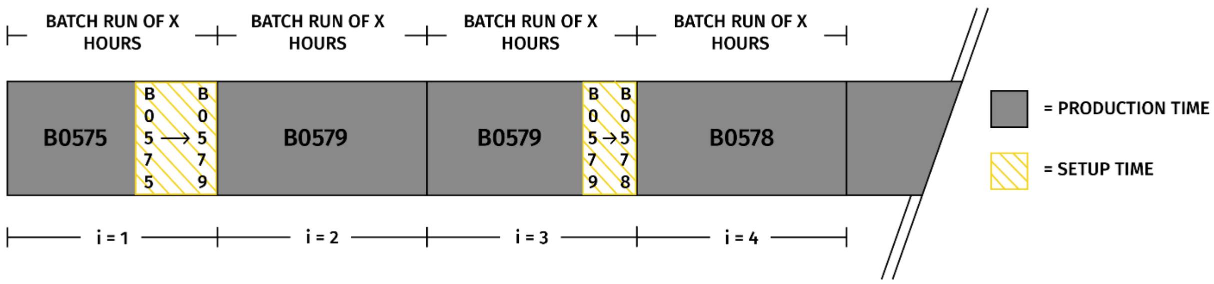

Figure 4.1: Fictive example for the need for a production order i

Because we need to use a production order i for storing the combination of setup and production time, we conclude that the GLSPST model of Meyr (2000) is most suitable to use as the basis for our mathematical SLSM production planning model. This method allows us to test different scenarios regarding the restriction of batch run lengths and we note that this method also allows us to not restrict the duration of production to any standard length (such as the 8 hours in the example in Figure 4.1).

2) BP – Block Planning with predefined Sequence Determination

The second method that we test is the BP concept with an additional method to determine the production sequence beforehand (from now on we refer to the sequence determination method as SD). As mentioned in Section 4.3.1, FrozenBakery uses some basic rules for determining the sequence per production line. The core of these decisions lies in the prevention of excessive cleaning and setup times, therefore we can make use of the sequence-dependency of setup times to quantify and find out whether the current way of working is the best way compared to what a mathematical model would propose. To be able to predefine the production sequence, we decide to develop a separate mathematical model that can be used before solving the block planning model. This model can be used to find the optimal sequence of production while minimising on sequence-dependent setup times.

This optimisation problem for our SD model is comparable to the asymmetric traveling salesman problem without return (TSP), in which each city has to be visited once, no subtours may exist and the salesman does not have to return to its first city or depot (Hoffman, Padberg, & Rinaldi, 2013). Whereas the TSP output consists of a route of m cities with the objective to minimise the total distance of the route, our SD model needs an output that consists of a recipe sequence with the objective to minimise the total setup time of the corresponding sequence. To do this, we can combine the theory on TSP with various constraints and variables from one of the models described in our literature review in Chapter 3: the GLSPST model and the CLSD model.

Since we only need to determine the sequence of production in this separate mathematical model, we do not need micro-periods. Therefore, we decide to use the constraints and variables from the CLSD model as the basis for our Sequence Determination model.

4.3.2 Two production planning methods

In conclusion, we develop two main production planning methods:

1) **SLSM** - a method that is able to simultaneously determine production quantities, timing of production and the production sequence within a planning horizon by means of an MILP model based on the GLSPST model of Meyr (2000) and
2) **BP** – a method that decomposes our problem into two sub problems: a method that first determines a predefined production sequence by means of a basic TSP-based MILP model and then schedules and determines production quantities and timing of production within a planning horizon by means of a MILP model based on the Block Planning model of Günther et al. (2006).

Subsequently, we test the quality of the solution methods based on the solution values that it is able to find and the time that it takes to solve the problem to optimality. Based on this comparison, we decide what method is best suitable in this research for creating solutions that are acceptable compared to the efficiency of finding this solution.

4.4 SLSM & BP model formulations

For testing the quality of both methods, we do not need to develop detailed models yet. The goal of this test is to find out whether it is acceptable to hold on to a predefined sequence before lotsizing and scheduling products or whether it is more efficient to use a model that simultaneously determines the sequence and lotsize of products. Since setup times occur on product recipe level, we develop both our SLSM and BP models on recipe level. This means that production quantities for SKUs with the same recipe are summed and costs associated with SKUs are averaged.

4.4.1 Formulation of costs

Both methods that we use are aims at minimisation of total costs. The costs are a representation of the number of products kept in inventory at the end of a period and the time needed for setups in production. Currently, these costs are not defined at FrozenBakery and therefore we define them in cooperation with the financial department.

Inventory holding costs
A widely used method in practice for defining the inventory holding costs consist of dividing it into three parts: cost of capital, cost of storage and handling and cost of risk (Durlinger & Paul, 2012). Together with the financial department, we determine the inventory holding costs using this method, because it covers the aspects that are relevant for storage at FrozenBakery. For the calculation of the inventory holding costs, we use data of 2019. Moreover, we extend this method to be able to make a distinction between 'high risk' and 'low risk' products. This allows the model to make better decisions to produce products that have a 'low risk' of not being sold in case of overcapacity. A 'high risk' product has a relatively 'high risk' of spending more days in the warehouse than the goal of max. 35 days. We make a distinction between MTO and MTS products and we make a sub classification for MTS products: MTS products that are sold often in large volumes and products that do not. The top 10 high sales volume products are classified as 'low risk', the other MTS products are classified 'high risk'. For MTO products holds that there is a 'low risk', since the production quantities equal demand and therefore the risk of spending longer in the warehouse than the goal of max. 35 days is low.

Risk | Cost of risk
Products that are classified 'low risk' do not include risk costs. Products that are classified 'high risk' include two types of risk costs, risk costs of not selling before the 35-day threshold and the risk of not selling the product at all. The risk costs of not selling before the 35-days threshold equal € 0.97 per pallet per week and the risk costs of not selling a product at all equal € 0.71 per pallet per week. This is based on costs in 2019 of products that were disposed from the warehouse due to obsoleteness.

Space | Cost of internal warehousing & handling
The cost of storing and handling a pallet in the internal warehouse is calculated by taking all costs that are associated with the internal warehouse (costs of energy, insurance, warehousing personnel) over 2019. These costs are divided by the number of pallets that can be stored at an average dwell time of 25 days in a year and result in € 3.38 per pallet per week.

Interest | Cost of capital
We define the cost of capital as the interest value per pallet. We use the total inventory value of 2019 and use an interest rate of 5%, as this is given to us by FrozenBakery. We calculate this cost factor by dividing the total interest value by the number of pallets that can be stored at an average dwell time of 25 days in a year. This equals € 0.50 per pallet per week.

We summarise the total inventory holding costs for internal and external storage and for low and high risk products in Table 4.1.

Table 4.1: Inventory holding costs per pallet per week

	Low risk products	High risk products
Inventory holding costs per pallet per week	€ 3.88	€ 5.56

Recall from Section 4.2 that we use the unit 'boxes' for product units in our mathematical model. Therefore we further calculate the holding costs per box per week by dividing the inventory holding costs per pallet per week by the number of boxes per pallet for every SKU. For example, for SKU 31740 it holds that 60 boxes fit on 1 pallet. This results in inventory holding costs per box per week of € 0.09 (€ 5.56 / 60 = € 0.09).

Setup costs
We base our calculation for setup costs on actual costs that exist still while the production line stands still at that moment. These costs include utilities, direct labour costs, maintenance and indirect costs at FrozenBakery and to get a result of the setup costs per hour, we divide the total of these costs in 2019 by total production hours in 2019. We show the hourly setup costs per production line in Table 4.2.

Table 4.2: Setup costs per hour per production line

	Line 1	Line 2	Line 3
Setup costs per hour	€ 1,010	€ 805	€ 1,085

Subsequently, we calculate the setup costs from a recipe to another by multiplying the needed setup time in hours between the corresponding recipes with the hourly setup cost rate for the corresponding production line.

4.4.2 Adaptations to the models from literature

For our BP model, we need an important adaptation compared to the model of Günther et al. (2006). Instead of using standardised setup times and costs per production order, we use sequence-dependent setup times and costs.

4.4.3 SLSM and BP Model formulations

First, we denote the model formulations for our SLSM model and the BP model. Thereafter, we denote the model formulations for our Sequence Determination (SD) model. All product units are in boxes and all time dependent parameters are in hours. We formulate both models in Table 4.3.

Table 4.3: SLSM and BP model formulations

SLSM model		**BP model**	
Sets		**Sets**	
k, m	Recipe with k, m = 1,..., K	k	Recipe with k = 1,..., K
t	Macro-period (weeks) with t = 0,..., T. Period t = 0 equals the week before the first planning week	t	Macro-period (weeks) with t = 0,..., T Period t = 0 equals the week before the first planning week
i	Production order over all macro-periods i = 1,..., I with $I = K \cdot T$	i, j	Production order over all macro-periods i = 1,..., I with $I = K \cdot T$
T_i, I_t	Subset of periods t in production order i and Subset of production orders i in period t	T_i, I_t , K_i	Subset of periods t in production order i , Subset of recipe k in production order i and Subset of production orders i in period t
		I_{kt}	Subset that denotes recipe k and period t in production order i
Parameters		**Parameters**	
d_{kt}	Demand of recipe k in period t	d_{kt}	Demand of recipe k in period t
hc_k	Inventory holding costs for recipe k	hc_k	Inventory holding costs for recipe k
sc_{km}	Setup costs for changing over from recipe k to m	sc_{ij}	Setup costs for changing over from production order i to j
st_{km}	Setup time for changing over from recipe k to m	st_{ij}	Setup time for changing over from production order i to j
C_t	Production capacity in period t	C_t	Production capacity in period t
p_k	Processing time for producing one unit of recipe k	p_k	Processing time for producing one unit of recipe k
I_{k0}	Initial inventory level of recipe k at the end of period t=0	I_{k0}	Initial inventory level of recipe k at the end of period t=0
$BigM$	Sufficiently large number	$BigM$	Sufficiently large number
Variables		**Variables**	
Y_{ki}	Binary variable that denotes whether recipe k is in production order i (1) or not (0)	Y_i	Binary variable that denotes whether production is planned in production order i (1) or not (0)
Q_{ki}	Production quantity of recipe k in production order i	Q_i	Production quantity in production order i
I_{kt}	Inventory level of recipe k at the end of period t	I_{kt}	Inventory level of recipe k at the end of period t
CH_{kmi}	Binary variable that determines whether a changeover occurs from recipe k to m in production order i	CH_{tij}	Binary variable that determines whether a changeover occurs from production order i to j in period t

S_i	Start-off time of production order i		S_i	Start-off time of production order i	
D_i	Duration of production order i		D_i	Duration of production order i	
Objective			**Objective**		
	$\min \sum_k \sum_t hc_k \cdot I_{kt} + \sum_k \sum_m \sum_i sc_{km} \cdot CH_{kmi}$			$\min \sum_k \sum_t hc_k \cdot I_{kt} + \sum_t \sum_i \sum_j sc_{ij} \cdot CH_{tij}$	
Subject to			**Subject to**		
1)	$I_{kt} = I_{k,t-1} + \sum_{i \in I_t} Q_{ki} - d_{kt}$	$\forall\, k, t > 0$	1)	$I_{kt} = I_{k,t-1} + Q_i - d_{kt}$	$\forall\, k, t > 0, i \in I_{kt}$
2)	$D_i = \sum_k Q_{ki} \cdot p_k + \sum_k \sum_m st_{km} \cdot CH_{kmi}$	$\forall\, i$	2)	$D_i = p_k \cdot Q_i + \sum_j st_{ij} \cdot CH_{tij}$	$\forall\, i, k \in K_i, t \in T_i$
3)	$Q_{ki} \leq BigM \cdot Y_{ki}$	$\forall\, k, i$	3)	$Q_i \leq BigM \cdot Y_i$	$\forall i$
4)	$CH_{kmi} \geq Y_{ki} + Y_{m,i+1} - 1$	$\forall\, k, m, i$	4)	$CH_{tij} \geq Y_i + Y_j - 1 - \sum_{h=i+1}^{j-1} Y_h$	$\forall\, t > 0,\ i, j \in I_t,\ j > i$
5)	$S_i \geq \sum_{w=1}^{t-1} C_w$	$\forall\, t,\ i \in I_t$	5)	$S_i \geq \sum_{w=1}^{t-1} C_w$	$\forall\, t, i \in I_t$
6)	$S_i \geq S_{i-1} + D_{i-1}$	$\forall\, i$	6)	$S_i \geq S_{i-1} + D_{i-1}$	$\forall\, i$
7)	$S_i + D_i \leq \sum_t C_t$	$\forall\, i,\ t \in T_i$	7)	$S_i + D_i \leq \sum_t C_t$	$\forall\, i, t \in T_i$
8)	$\sum_k Y_{ki} = 1$	$\forall\, i$	8)	-	
9)	$Y_{ki}, CH_{kmi} \in \{0,1\}$, $Q_{ki}, I_{kt}, S_i, D_i \geq 0$	$\forall\, i, k, m, t$	9)	$Y_i, CH_{tij} \in \{0,1\}$, $Q_i, I_{kt}, S_i, D_i \geq 0$	$\forall\, i, j, k, t$

Constraints 1) assure the inventory balance. Constraints 2) calculate the duration of a production order i. Constraints 3) assure that the binary variable Y_{ki} is set to 1 if production of recipe k is planned in production order i, and otherwise to 0. Constraints 4) and 8) together assign a recipe k to production order i in our SLSM model. Constraints 8) make sure that exactly one recipe k is assigned to every production order i and constraints 4) determine whether a changeover occurs between recipe k and m in production order i. In an optimal solution, the production orders are filled with recipes that need production in the corresponding period t. Constraints 5) and 6) make sure that the start-off time of a production order i is at least equal to the end time of the previous order and is at least equal the start-off time of the corresponding week. Constraints 7) assure that the production capacity of the corresponding week is not exceeded. Constraints 9) form the basic domain constraints for every variable in the mathematical model.

We illustrate the difference between SLSM and BP models in determining the changeover variable in Figure 4.2 with a fictive example: a schedule has to be made for 1 week for a production line with 5 recipes, so $i = 1, .., I$ with $I = K \cdot T = 5$. So in the SLSM model, we have 5 production orders that need to be filled with a recipe k. In the BP model, we also have 5 production orders, but these have already been filled in with the recipes by means of the Sequence Determination model (which we elaborate on in Section 4.4.4). Let us assume that the inventory balance constraints force recipes B0574, B0571 and B0572 to be produced in the corresponding week. The output of the BP model includes a changeover from B0574 and B0571 and a changeover between B0571 and B0572. The output of the SLSM model shows that B0574 is assigned to production order $i = 1$ etc. and therefore indicates the same changeovers as the BP model.

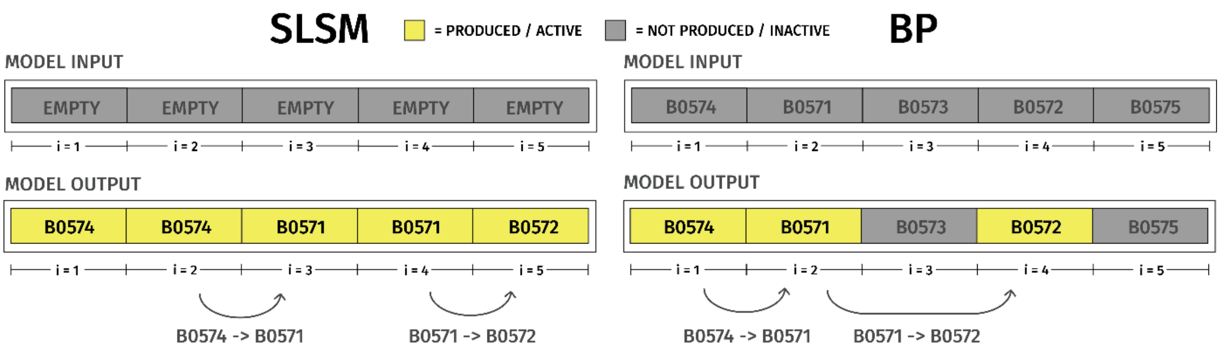

Figure 4.2: Difference in changeover variable determination

4.4.4 SD model

We use the Sequence Determination (SD) model for predefining the production sequence for a set of recipes k. For this we use standard TSP model formulations in which no returns are included. The output of the model is the sequence of recipes in a given planning horizon for a predefined set of recipes. For the detailed formulations, we refer to Appendix 8.2.

4.4.5 Rolling horizon planning parameters

Recall from Chapter 2 that FrozenBakery uses the rolling planning horizon concept to cope with uncertainty. Our literature review also shows us that this concept is suitable when demand only becomes known gradually. The closer the demand forecast is to today, the more accurate it is. Currently, FrozenBakery uses a planning horizon of 3 weeks, a frozen period of 1 week and a review period of 1 week. So for example at the beginning of week 1, week 2, week 3 and week 4 are planned. These parameters are chosen by FrozenBakery, because it gives a preliminary idea of what raw material is needed in the next weeks and the frozen period of 1 week is needed to make a planning for the temporary personnel and to prevent an overload of last-minute changes in the schedule. Due to time limitations, we decide not to test scenarios with different parameters for rolling planning horizon. We expect that changing these parameters is not as relevant for gaining insight as testing other planning factors that we want to test (see Section 4.1).

4.5 Performance of the models

The goal of the first phase of our solution design is to find out if it is more efficient to use a mathematical model that determines the production sequence on the one hand and the production quantities and timing of production on the other hand simultaneously or to decompose this problem into two parts. In the latter, we decompose the problem into two sub problems: determining the sequence of production in one model and determining the production quantities and timing of production in another. By efficient, we mean that it allows us to gain insight into factors that improve our planning process structurally by means of scenario testing within a considerable amount of time. We make this decision based on two criteria:

1) The solution values that the optimisation model is able to find,
2) The time that it takes to solve the problem to optimality

For all three production lines at FrozenBakery, we test the performance of both models for a dataset of 3 weeks in 2019, because this is the length of a planning horizon. In Table 4.4, we summarise the outcomes of the models.

Table 4.4: Performance of SLSM and BP models

	Line 1		Line 2		Line 3	
Performance indicators	**SLSM**	**BP**	**SLSM**	**BP**	**SLSM**	**BP**
# Constraints	37448	8702	1875	1557	74534	13580
# Variables	40331	10064	1995	1743	79131	15888
Solving time (seconds)	28800	2.2	28800	0.06	28800	14
Best lower bound solution (€)	€ 24,954	€ 34,925	€ 2,557	€ 3,705	€ 11,628	€ 23,690
Gap (%)	25.3%	0%	31.0%	0%	49.5%	0%
Best feasible solution (€)	€ 33,425	€ 34,925	€ 3,705	€ 3,705	€ 23,008	€ 23,690
Deviation solution values	4.5%		0%		2.9%	

The first criterium on which we base our decision, is the extent to which the models are able to find a solution value. Both models are able to find a solution for every production line. After the solving time has been passed, the solution values of both models for Line 1 show a deviation of 4.5% in favour of the SLSM model. Solving both models for Line 2 results in solution values that are exactly the same. The solution values for Line 3 show a deviation of 3.9% in favour of the SLSM model. However, the SLSM model has not found an optimal solution within the respective solving time for any of the production lines. The BP model however did find optimal solutions for all three production lines within a very short time. The biggest dataset is solved within 14 seconds.

Therefore, we either consider a fast model that finds a good solution, or a model that needs a long running time for a solution that might be a little better. In our choice, we have to take into account that we want to detail and extend the model further in Phase II (Chapter 5) to make it more suitable for the practical situation at FrozenBakery and to be able to run the scenarios (recall this from Section 4.1). In addition, we have to take into account that there is limited time available to test these scenarios in this research. Therefore, we make the decision to being able to test all relevant scenarios and accept that the solution might deviate a little bit from the optimum due to decomposition of the problem, or we have to make the decision to further develop the model with long runtimes and accept that we cannot test all scenarios.

In order to better understand the behaviour of the models, we compare the output production quantities per recipe of both models. We compare the production quantities for production Line 3 (the line that contains most recipes) in Figure 4.3. From this comparison, we can conclude that the minor differences in the solution value are caused by differences in the *timing* of production. By this we mean that in some cases, for example for recipe F0036, we note that the BP model decides to produce all boxes in week 37 and the SLSM model produces half of the total number of boxes in week 37 and the other half in week 38. This can be caused by differences in the sequence of production, but overall we find that this does not have big consequences for the quality of the planning since deviation of solution values is only 2.9%. Differences in the sequence of production do not directly cause big changes in the production plan, because a considerable number of recipe-combinations share the same setup time. For example, in the SLSM model recipe F0307 changes over to F0320 which takes 45 minutes and in the BP model this recipe changes over to F0077 which also takes 45 minutes. Furthermore, we find that the summed production quantities per recipe are exactly the same in the output of both models.

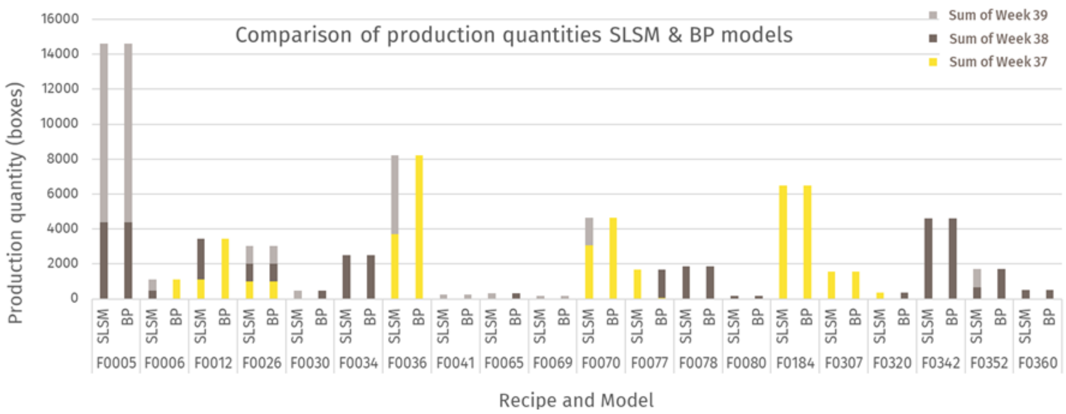

Figure 4.3: Comparison of production quantity outputs SLSM and BP models

From our comparison, we conclude that the summed production quantities that form the output of the production planning model are the same for both the SLSM and BP model, even though the sequence of production may differ. We do find differences in the timing of production for some recipes, which can be caused by the differences in setup time and costs as a consequence of the sequence of production. However, overall the differences are minimal because setup times and costs between recipes are not unique for every recipe combination and can therefore be the same even though the sequence is different. The solution values that both models are able to find are deviating only 2.9%. Finally, when we compare the time that it takes to find a solution, we find that it takes between 1.8 and 8 hours to find an integer solution that is not yet the optimum for the SLSM model and it takes between 0.06 and 14 seconds to find the optimal solution for our BP model.

In conclusion, a planning method that determines the sequence and lotsizes simultaneously (SLSM) performs a little better in terms of best feasible solution values, but the time that it takes to find this solution equals 8 hours compared to about 10 seconds for the model that determines the sequence and lotsizes separately (BP). Recall that the main goal of conducting this research is to gain insight in possibilities for structural improvements in the planning process. Therefore, we conclude that for this research it is more relevant to continue with the BP model. In this way, we use our limited time for testing all scenarios that we see as relevant for gaining more insight in the planning process and the best combination between production and inventory goals. Finally, the scenarios that we want to test allows us to gain insight in improvements of the planning process, without the necessary need to use expensive optimisation software in the future to achieve these improvements. This is an extra motivation to continue with a model that allows us to test the scenarios, because optimisation software is considered as a high investment and forces training and knowledge of the software to be able to work with it efficiently.

4.6 Conclusions

In this chapter, we explored different methods for lotsizing and scheduling of products that we found in literature. The goal of this chapter was to gain insight in the differences in quality of planning by means of a method that determines the sequence and lotsizes simultaneously and a method that decomposes this problem into two subproblems: determining the production sequence in one model and determining the production quantities and timing of production in another model. First, we made a decision on what simultaneous lotsizing and scheduling method is best for using as starting point for our model. Since we need to know whether a setup needs to take place in a certain production run, we need to make use of micro-periods. Therefore, we decide to use the GLSPST model of Meyr (2000) as starting point for our simultaneous lotsizing and scheduling model. Furthermore, we use standard TSP literature and sequence determination formulations from CLSD for our SD model and we use the block planning concept of Günther et al. (2006) as a starting point for our BP model and we adapt this model to allow for sequence-dependent setup times and costs. We analyse the performance of both the SLSM and BP models and this allows us to answer the first part of our research question for this chapter: '*What method or methods can we best use to gain insight into structural improvements in the production planning process?'*. We conclude from our performance comparison that the BP model is more suitable to continue with for this research than the SLSM model. Even though the SLSM outperforms the BP model a little in terms of finding the best feasible solution (between 0-4.5% in our comparison), the SLSM needs 8 hours for finding this solution compared to around 10 seconds for the BP model. By continuing with further developing the BP model, we are able to test the scenarios that we see as relevant for gaining more insight into possibilities for structural improvements in the production planning process of FrozenBakery.

5. SOLUTION DESIGN – PHASE II

This chapter focusses on extending our mathematical BP planning model to be able to gain insight in planning factors that can improve the production planning process in order to save costs. We create scenarios that allow us to change one planning factor at a time. In Section 5.1, we describe the need for model extensions in order to test different scenarios. In Section 5.2 we compare solution alternatives for our finished products inventory control policy. Section 5.3 focusses on developing an inventory policy that can be used in our BP model. Section 5.4 focusses on the detailed and extended model formulations of our BP model. Section 5.5 describes the scenarios that we create. Section 5.6 comprises the conclusions of this chapter.

5.1 Model extensions for scenario testing

In our model comparison in Chapter 4, the main focus was on determining the production sequence simultaneously or separately in a mathematical model. Since sequencing happens on recipe level, we accepted to plan production quantities on recipe level as well. However, the inventory system at FrozenBakery is based on SKUs rather than recipes. Therefore, we need to further detail our model to be able to determine production quantities on SKU level. Also, we extend our BP model to allow for scenario testing. Recall that we create scenarios based on the planning factors *batch production, capacity usage, inventory parameter usage* and *production sequence*. We aim to answer the following sub questions regarding gaining insight in structural improvement of the production planning process:

1) What is the impact of batch production on inventory and setup costs within the planning horizon?
    a. What are the effects of using standard batch run lengths of 8 hours?
    b. What are the effects of using standard batch run lengths of 4 hours?
    c. What are the effects of using free batch run lengths?
2) What is the impact of production capacity utilisation on inventory and setup costs within the planning horizon?
    a. What are the effects of utilising all production capacity available within the planning horizon?
    b. What are the effects of only utilising production capacity needed to fulfil forecasted demand?
3) What is the impact of including inventory control parameters in the production planning model compared to the current situation?
4) What effect does the method for sequence determination have on setup costs?

To be able to answer the first question, we extend the model with restrictions that make sure that the duration of a production order is a multiple of either 4 or 8 hours. For our second question, we need to add a restriction that forces the total time used for production to be equal to the capacity of the corresponding production weeks. To gain insight in the differences between fully utilising capacity and only using needed capacity, we also need an additional variable that calculates the idle time left at the end of the week in case capacity is not fully utilised. The third question involves developing an inventory control policy that fits FrozenBakery and involves adding the inventory parameters that result from our policy into our mathematical planning model. To be able to answer the fourth question, we determine the predefined fixed sequence and we need our SD model for determining the optimal production sequence.

5.2 Solution alternatives for finished products inventory control

There are multiple policies available that can be used to gain better control over inventory. Primarily, it is important to emphasise that we focus only on the finished products inventory. The inbound pallets at the finished product frozen warehouse result from production output. Therefore, we consider the definition for order quantity used in literature to be the same as production quantity in our research. The outbound pallets in the warehouse are determined by actual customer orders. Recall from Chapter 3 that we decide to only look into periodic review inventory policies, because the main advantage of a continuous review to require less safety stock does not outperform the main advantage of the opportunity for batching in periodic review in the case of FrozenBakery.

Recall from Chapter 3 that two periodic review policies are widely used: (R,S) policy and (R,s,S) policy. In general, the (R,S) policy is suitable when products are supplied by one or a few suppliers and for which a company pays fixed costs per order, no matter the products that are ordered. The (R,s,S) policy on the other hand is generally suitable when there is a restriction in the number of different types of products that are ordered, for example when variable ordering costs need to be paid depending on the products ordered. In this case, it is more cost-friendly to only order the products that are expected to be needed soon. Variable ordering costs can be referred to as the setup costs that are product or sequence dependent. Therefore, we conclude that the more different types of products (and recipes) are produced, the higher the setup costs. This is what we want to minimise in our planning model, therefore we conclude that the (R,s,S) policy is more suitable for the inventory control in the finished product warehouse than the (R,S) policy.

Note that an inventory policy holds only for MTS products. MTO products are produced when they are ordered by a customer and are produced in the quantities that they are ordered. Our main goal with respect to inventory control is to provide protection against uncertainties in demand and production output and to decrease the dwell time in the warehouse. The (R,s,S) policy allows to do this by setting SKU-specific safety stocks, reorder points and order-up-to-levels. The SKU-specific reorder points provide protection against uncertainty and make sure that a replenishment order for production is placed at the right moment. Moreover, order-up-to-levels can be used to limit the number of products to order or produce.

5.3 Setting inventory policy parameters

The (R,s,S) policy consists out of the following parameters: review period R, reorder point s_u and order-up-to-level OUL_u. Recall from Chapter 3 that in situations with uncertainty, a safety stock is included in the reorder point. Moreover, the order-up-to-level OUL_u in the original (R,s,S) policy is used for determining the quantity to order. However, we determine the 'order' or production quantity by means of our mathematical planning model. But we can influence the production quantity by including inventory policy parameters in our model, to put an emphasis on inventory goals while determining the production planning. We therefore use the theory of (R,s,S) policy for setting minimum and maximum inventory levels per SKU. We base the maximum inventory level on the goal of FrozenBakery to decrease the dwell time in the finished product warehouse, this goal is set by FrozenBakery to a maximum of 35 days. In this way, we limit the production quantity while planning. Furthermore, we base the minimum inventory level on the reorder point from the (R,s,S) inventory policy. Comparing the reorder point to the expected inventory position has to make sure that we do not run into a stock-out for an MTS-SKU. To clarify: when the inventory position at the end of a week is expected to drop below the minimum inventory level, we need to schedule the corresponding SKU for production. We illustrate the different parameters in Figure 5.1. The first week within the planning horizon is frozen, so we know at the beginning of week 1 if and how much we produce of certain SKU in that week. We use the mathematical model to make a production schedule for the remaining weeks in the planning horizon. The model needs to schedule an SKU for production in one week, if the inventory position is expected to drop below the minimum inventory level at the end of this week. In our illustration in Figure 5.1, we want the model to schedule this illustrated SKU at latest in week 3, because the inventory position is expected to drop below the reorder point I_u^{MIN}.

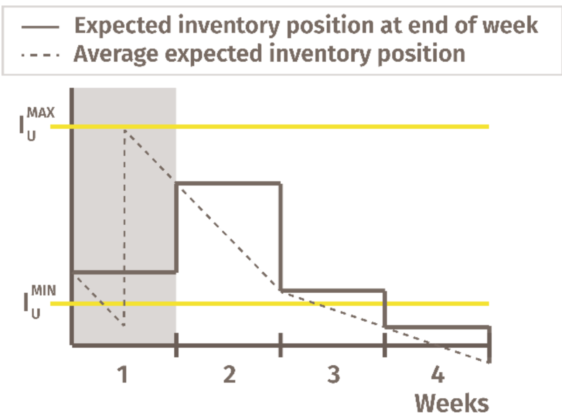

Figure 5.1: Example of (R,s,S) inventory policy parameters and inventory over time

The inventory level corresponds to the actual number of units in inventory on a certain moment in time, we refer to this as the on-hand stock. Next to the on-hand stock, products are possibly planned for production or are committed. Committed items can be seen as products that are reserved for expected demand. To be able to determine the required number of units in stock to be able to meet demand, we need the number of units *available* for demand in a certain period. This can be calculated by means of the inventory position. We adapt the formulation for the inventory position from Chapter 3 (Silver et al., 2016) into the following formulation:

$$Inventory\ position\ IP_u = on - hand\ stock + on\ order - committed$$

5.3.1 Minimum inventory level

The reorder point of an SKU serves as the minimum inventory level that is input to our mathematical model. In this research, the reorder point serves as threshold value that instructs the model to produce again. The reorder point is calculated by taking the forecasted demand that has to be replenished from inventory during the replenishment time and by the safety stock.

Safety stock
The safety stock of an SKU can be calculated in different ways, based on what a company values most. We decide to use the formulation of safety stocks by means of the forecast error, because FrozenBakery faces a discrepancy between the customer forecast that is input to the production planning and the actual demand that is extracted from the finished product warehouse. Furthermore, we need to include the desired service level in the safety stock calculation, because this is important for FrozenBakery as well. For an extensive explanation, we refer to Section 3.3.2. The safety stock calculation for an SKU u based on forecast error is calculated in the following way (Schmidt, Hartmann, & Nyhuis, 2012):

$$Safety\ stock\ level\ ss_u = SF(SL) * \sigma_u^F * \sqrt{TRP}$$

Where:
σ_u^F Standard deviation of the forecast error for the demand during the replenishment time of SKU u
$SF(SL)$ Safety factor for the desired service level
TRP Replenishment time before the order reaches inventory

Schmidt et al. (2012) emphasise that the standard deviation of the prognosis error (σ_F) is calculated via historical data from the mean squared deviation of the forecasted demand from the actual. This method is independent of a specific statistical distribution of the demand.

Reorder point
The reorder point can be calculated by determining the expected demand during the time that it takes to replenish the inventory plus the safety stock. Therefore, we formulate the reorder point calculation as follows:

$$Reorder\ point\ s_u = d_u^{AVG} \cdot TRP + ss$$

Where:
d_u^{AVG} Average weekly (forecasted) demand for SKU u
TRP Replenishment time before the order reaches inventory
ss Safety stock

The time it takes to replenish (TRP) at FrozenBakery depends on the production cycle of a production line. If a product is demanded in a certain week, it depends on the production sequence whether it is scheduled at the beginning or at the end of the week. Therefore, on average it takes 0.5 week before a replenishment order reaches inventory. Furthermore, we recall that FrozenBakery holds on to a desired service level of 99.5%.

In conclusion, we calculate the minimum inventory level as follows for every SKU u:

$$Minimum\ inventory\ level\ I_u^{MIN} = 0.5 \cdot d_u^{AVG} + SF(99.5\%) * \sigma_u^F * \sqrt{0.5}$$

5.3.2 Maximum inventory level

We use a mathematical model to determine the production quantity, however we do want to limit the production quantity by means of inventory goals. We therefore decide to apply the goal of maximum 35 days (5 weeks) storage for our maximum inventory level per SKU. In this way, the maximum inventory level serves as an upper bound for the production quantity in the model. We calculate this as follows:

$$Maximum\ inventory\ level\ I_u^{MAX} = 5 \cdot d_u^{AVG}$$

5.3.3 Periodic updating of inventory control parameters

In order to use the inventory control parameters in our mathematical model, we need to know how often it is necessary to update the values that we use for these parameters. Due to, amongst others seasonality, the deviation between forecasted and realised demand can differ per period. Currently, FrozenBakery receives sales forecasts monthly, therefore we analyse the safety stocks and reorder points from March until December of 2019 for every month. Depending on the difference between the monthly values, we determine the review period in which is it acceptable to use the same safety stocks and values for reorder points.

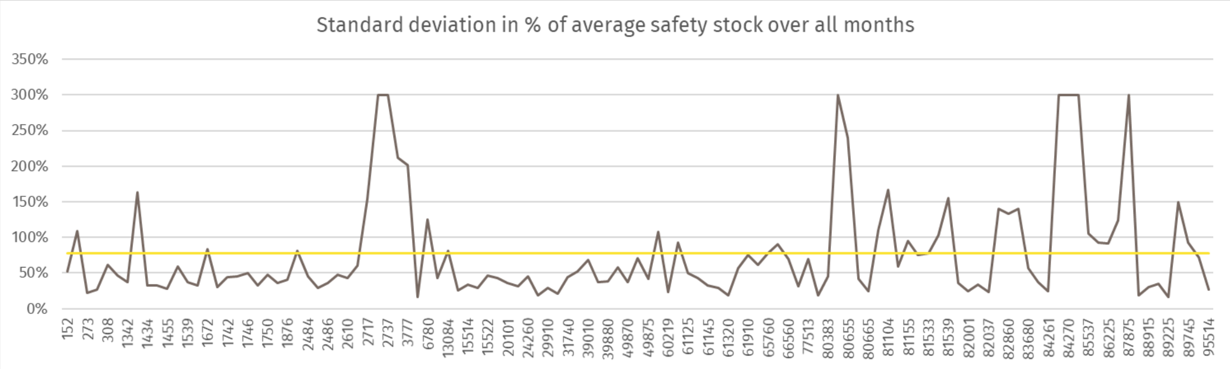

Figure 5.2: Analysis of safety stock deviation

In Figure 5.2, we compare the standard deviation of the monthly safety stocks per SKU. We can conclude from this analysis that the standard deviation in percentage of the average safety stock over all measured months together (March until December 2019) is on average 77%. So, the safety stocks highly differ per month and therefore we decide to update the safety stocks monthly. Furthermore, we decide to take the average of the safety stocks of the preceding three months. So every month, we update the safety stock information per SKU and use the average of the past three months. In this way, we expect it gives a proper indication of the uncertainty in demand. For our reorder point calculation, it holds that we also update the values monthly. To keep our working methods efficient and consistent, we therefore decide to update the maximum inventory level value monthly as well.

5.4 Formulations of extended BP model

In order to be able to test the scenarios described in Section 5.1, we extend and further detail our BP model. The first difference compared to the BP model described in Section 4.4 is that we determine production quantities and inventory levels on SKU level instead of recipe level. Note that setups still occur on recipe level. Furthermore, we add two cost factors that allow for a more realistic production planning.

Penalty costs

First, we need penalty costs for an SKU in case of under capacity. When capacity is not sufficient to fill the production needs, there are products that cannot be produced. Since the objective of the model is to minimise total costs, we have to determine by means of costs which products are more important to produce than others. We do this by classifying the SKUs based on some characteristics and assigning weights to these characteristics. In this way, every SKU gets a penalty cost based on its weight factors per characteristic. Subsequently, this weight factor is multiplied by a basic penalty cost value. Note that penalty costs are imaginary costs to be able to select the right products to include and exclude from the planning in case of under capacity in a certain period of time. The basic value for the penalty cost needs to be very high, because we want to prevent penalty costs if possible. Therefore, we use € 100,000 as basic value. The characteristics of every SKU on which we base the penalty costs are as follows:

1) **Possibility to produce on another line – Weight factor 1000**
Every SKU has a preference production line, but some of them can be produced on another line as well. This holds for a number of SKUs that are produced on Line 1 and Line 3. In case of under capacity on a certain line, we want the model to select *these* products to not include in the production plan because these products can possibly be produced on another production line in that period. In this way, demand can be fulfilled properly. Therefore, SKUs that do not have the possibility to be produced on another production line must receive a higher penalty cost than SKUs that do have this possibility. We do this by assigning a high weight of factor 1000 to the basic penalty cost.
2) **MTO/MTS – Weight factor 2**
In case the previous characteristic is not applicable for a certain SKUs, we still want the model to select the right products to include and exclude from the production plan in case of under capacity. We consider MTO products more important to produce than MTS products, because demand for MTO products do not deviate from actual orders. Therefore, we give MTO products priority in the production planning. We do this by assigning a weight of factor 2 to the penalty costs for MTO products.
3) **MTS High/Low sales volume – Weight factor 2**
Finally, the third characteristic only holds for MTS products. In case of under capacity, we prefer products with a high sales volume to be produced over MTS products with a low sales volume. The first reason for this is that MTS products with a high sales volume have a higher chance to be sold than products with a low sales volume. The second reason for this is that it is easier to reschedule MTS products with a low sales volume that are excluded from the production plan, in case the forecasted demand is actually ordered by a customer.

This results in the following costs per classified SKU which we summarise in Table 5.1:

Table 5.1: Classification of SKU for penalty cost determination

Classification SKU	Cost determination	Penalty costs
MTO – 1 Line	€100,000 * weight 2 * weight 1000	€ 200,000,000
MTO – Possibility another line	€100,000 * weight 2	€ 200,000
MTS – 1 Line – High sales volume	€100,000 * weight 2 * weight 1000	€ 200,000,000
MTS – 1 Line – Low sales volume	€100,000 * weight 1000	€ 100,000,000
MTS – Possibility another line – High sales volume	€100,000 * weight 2	€ 200,000
MTS – Possibility another line – Low sales volume	€100,000	€ 100,000

Idle costs

Idle costs comprise the last cost factor in our model. We include this cost, because we want to prevent that idle time occurs between production orders in the same week. With the use of idle costs, we make sure that the next production order starts directly after completing the previous production order in a week. The idle costs are imaginary costs as well and are set to € 100,000. This could be any value, but since the model minimises on total costs and we want to be able to quickly analyse whether idle costs are incurred, we set this value to € 100,000.

Recall from Chapter 4 that the production sequence is input to the BP model. The sequence of recipes in a week is predefined and SKUs that share the same recipe are bundled in production order i. No setup time is required between changing over from one SKU to another if they share the same recipe. We show the formulations for the extended BP model in Table 5.2. Next to this, we note that we further extend the model for scenario testing. For our planning factor *batch production,* we use an integer decision variable M_i for determining the number of batch runs that are planned by the model for a production order i. For example, if a scenario uses a standard batch run length of 8 hours and the forecasted demand of an SKU forces the model to produce an SKU in production order i for 16 hours, this decision variable M_i becomes 2 (16 hours / 8 hours = 2).

Table 5.2: Extended BP model formulations

Extended BP model		
Sets		
u	SKU with u = 1,…,U	
k	Recipe with k = 1,…,K	
t	Macro-period (weeks) with t=0,…,T. Period t =0 equals the week before the first planning week	
i,j	Production order over all macro-periods i = 1,…, I with $I = K \cdot T$	
T_i, U_i I_t	Subset of periods t in production order i , Subset of SKU u in production order i and Subset of production orders i in period t	
I_{ut}	Subset that denotes SKU u and period t in production order i	
Parameters		
d_{ut}	Demand of SKU u in period t	
hc_u	Inventory holding costs for keeping SKU u in internal warehouse	
pc_u	Penalty costs for SKU u	
ic_i	Idle costs for production order i	
sc_{tij}	Setup costs for changing over from production order i to j in period t	
st_{tij}	Setup time for changing over from production order i to j in period t	
C_t	Production capacity in period t	
p_u	Processing time for producing one unit of SKU u	
I_{u0}	Initial inventory level of SKU u at the end of period t =0	
I_u^{MIN}	Minimal inventory level of SKU u	
I_u^{MAX}	Maximal inventory level of SKU u	
BRL	Standard batch run length	
$BigM$	Sufficiently large number	
Variables		
Y_i	Binary variable that denotes whether production is planned in production order i (1) or not (0)	
Q_{ui}	Production quantity in production order i	
P_{ui}	Penalty products in production order i	
I_{ut}	Inventory level of SKU u at the end of period t	
CH_{tij}	Binary variable that determines whether a changeover occurs from production order i to j in period t	
S_i	Start-off time of production order i	
D_i	Duration of production order i	
M_i	Integer multiplier for batch run length in production order i	
TB_{it}	Idle time before production order i in period t	
Objective		
$$\min \sum_u \sum_t hc_u \cdot I_{ut} + \sum_t \sum_i \sum_j sc_{tij} \cdot CH_{tij} + \sum_i \sum_t ic_i \cdot TB_{it} + \sum_u \sum_i pc_u \cdot P_{ui}$$		
Subject to		
17)	$I_{ut} = I_{u,t-1} + \sum_{i \in I_{ut}} Q_{ui} + \sum_{i \in I_{ut}} P_{ui} - d_{ut}$	$\forall\, t > 0, u$
18)	$\sum_{u \in U_i} Q_{ui} \le BigM \cdot Y_i$	$\forall\, i$
19)	$CH_{tij} \ge Y_i + Y_j - 1 - \sum_{h=i+1}^{j-1} Y_h$	$\forall\, t > 0, i \in I_t, j > i \in I_t$
20A)	$D_i = \sum_{u \in U_i} p_u \cdot Q_{ui} + \sum_j st_{tij} \cdot CH_{tij}$	$\forall\, i, t \in T_i$
20B)	$D_i = M_i \cdot BRL$	$\forall\, i$
20C)	$\sum_{u \in U_i} p_u \cdot Q_{ui} = D_i - \sum_j st_{tij} \cdot CH_{tij}$	$\forall\, i, t \in T_i$
21)	$S_i \ge \sum_{w=1}^{t-1} C_w$	$\forall\, t, i \in I_t$
22)	$S_i \ge S_{i-1} + D_{i-1}$	$\forall\, i$
23)	$S_i + D_i \le \sum_t C_t$	$\forall\, i, t \in T_i$
24)	$\sum_{i \in I_t} D_i = C_t$	$\forall\, t$
25)	$I_u^{MIN} \le I_{ut} \le I_u^{MAX}$	$\forall\, u, t > 0$
26)	$Y_i, CH_{tij} \in \{0,1\}, Q_{ui}, P_{ui}, I_{ut}, S_i, D_i, TB_{it} \ge 0, \; M_i \in \mathbb{Z}$	$\forall\, i, j, u, t$

Constraints 17) assure the inventory balance of an SKU u in period t. In case of under capacity, this equation makes sure that penalty products are determined. Constraints 18), 19), and 20A) are the same as described in Section 4.4, the only difference is that in this model, the production quantities are based on SKU level. In case of testing scenarios that include 4- or 8-hour batches, we replace constraints 20A) by 20B) and 20C). Constraints 20B) make sure that the duration of a production order i is a multiple of the standard batch run length that is set to either 4 or 8 hours. Recall that this duration includes production and eventual setup time. The production quantities are determined by constraints 20C). Constraints 21), 22), and 23) are exactly the same as constraints 5), 6) and 7) of Section 4.4. By constraints 25), we make sure our inventory control parameters are included in the model. Finally, we use additional constraints to allow for our scenario testing. Constraints 24) assure that capacity is fully utilised. We use these constraints for testing the effects on inventory and total setup time when fully utilising the production capacity compared to only use production capacity that is needed to fill demand.

5.5 Scenario testing

In order to be able to gain insight in the impact of different planning factors on the quality of the production planning, warehouse situation and costs, we create a number of scenarios in which one factor changes per scenario. We repeat the planning factors to be: *batch production, capacity usage, inventory policy parameter usage* and *production sequence.* Since running the model is very time-intensive, we only run scenarios that are expected to give us valuable insights. From initial test runs, we find that we cannot make every combination for our planning factors. We cannot force the model to use both production and inventory restrictions such as using 8-hour batch runs and restricting on maximum inventory level. This leads to errors for SKUs with a relatively low demand during the planning horizon, because producing for 8 hours exceeds the maximum inventory level. We therefore create scenarios that restrict only on either production (batch run length) or inventory (maximum) restrictions. This results in running 9 scenarios with different planning factor settings, which we show in Table 5.3. We want to only change one planning factor at a time to be able to properly test the scenario outcomes to the current situation and to properly analyse the impact of every planning factor on the total costs. Therefore, we use the fixed production sequence that FrozenBakery currently uses for predefining the production sequence in our scenarios. We test the impact of the production sequence on setup time and costs afterwards by comparing the setup time when using optimal sequences that we determine through our SD model and the setup time that is output to our model in which we use the fixed sequence (FS) currently used by FrozenBakery.

Table 5.3: Scenario set-up and abbreviations

	FULL CAPACITY (FC)	**NEEDED CAPACITY (NC)**	**NEEDED CAPACITY (NC)**
	FREE INVENTORY (FI)	**FREE INVENTORY (FI)**	**MIN (MINI) & MINMAX INVENTORY LEVELS (MMI)**
8-HOUR BATCHES (8B)	8B_FCFI_FS	8B_NCFI_FS	8B_NCMINI_FS
4-HOUR BATCHES (4B)	4B_FCFI_FS	4B_NCFI_FS	4B_NCMINI_FS
FREE BATCHES (FB)		FB_NCFI_FS	FB_NCMINI_FS
FREE BATCHES (FB)			FB_NCMMI_FS

5.6 Conclusions

In Chapters 4 and 5, we aim to find an answer on the research question: '*What method or methods can we best use to gain insight into structural improvements in the production planning process?*'. The goal of this method is to serve as a means to explore possibilities for structural improvements in the planning process. In Chapter 4, we concluded that the method that suits best for lotsizing and scheduling is the BP model. In Chapter 5, we further develop this method by detailing and by extending the formulations in order to allow for scenario testing. Furthermore, we develop an inventory control policy that we can use in our mathematical planning model in order to combine production and inventory goals in the production planning process. We decide to use the (R,s,S)-policy and adapt it to be able to use it in our planning model. We use reorder points that include safety stocks as minimum inventory levels to prevent stock-outs and the need for last-minute changes in the schedule and we use maximum inventory levels to be able to achieve the goal of decreasing the dwell time in the warehouse. In conclusion, we use the extended mathematical BP model for testing the impact that batch production, production capacity utilisation, the inclusion of inventory control parameters in the planning process and production sequence have on total associated costs and on the service level.

6. ANALYSIS OF SCENARIOS

In this chapter, we analyse the results of the model run for the different scenarios. Section 6.1 provides explanation about the setup of the model. Section 6.2 discusses the scenarios and the key performance indicators that we use for evaluating the different scenarios. Section 6.3 discusses an initial performance analysis of the results and Section 6.4 provides an analysis about the impact of the different planning factors on our key performance indicators. Section 6.5 compares the results of our scenarios to the current situation. Section 6.6 discusses limitations of the results and Section 6.7 comprises the conclusions of this chapter.

6.1 Model setup

Before we start running our mathematical optimisation model, we have to setup the model correctly. In Section 6.1.1, we describe the data sets that we use. In Section 6.1.2 we discuss the input data that we use to generate the production schedules. Section 6.1.3 discusses the computation time of our model.

6.1.1 Data sets

We use historical data of 2019 that is made available to us by FrozenBakery. We decide to use historical data, because this enables us to analyse the production planning that is used in 2019 and compare this to the outcome of the scenario runs. Another reason to use historical data is that in this way we can properly mimic the planning situation at FrozenBakery. By this we mean that the planner schedules production by means of demand forecasts, while the finished product inventory mutates with realised demand. As discussed in Chapter 2, the forecasted and actual demand deviate at FrozenBakery. By using historical data, we can use both the demand forecasts for planning and realistic data for mutation of the inventory with data of 2019. This enables us to test whether the use of inventory policy parameters in the planning process leads to improvements. We have demand and inventory data available from week 23 until week 52 of 2019. Therefore, we create production schedules with the help of our mathematical optimisation model for weeks 23-49 of 2019, which equals half a year of schedules.

We use our mathematical optimisation model to create a production schedule for a planning horizon of 3 weeks, 1 week ahead. For example, in the beginning of week 23, we create the production schedule for weeks 24, 25, and 26. Since FrozenBakery uses a frozen period of 1 week and uses a review period of 1 week, we freeze the production plan for week 24. After the review period passes, so in the beginning of week 24, we create the production schedule for weeks 25-27 and freeze week 25. In this way, we create a production plan for every first week based on the minimisation of total costs for the entire planning horizon. We repeat from Section 2.2.2 that we solve the planning for the entire planning horizon, because in the actual situation at FrozenBakery the preliminary production schedules are used for purchasing of raw material and personnel planning.

6.1.2 Input data

To be able to create production schedules in a situation as realistic as possible, we use the following input data:

- **Demand** - We use monthly demand forecasts of 2019 for MTS products and divide this by the number of weeks to get weekly demand forecasts. This is what FrozenBakery currently does as well. We use realised demand for MTO products and for mutating the inventory at the end of every week. We add to this the assumption that when weekly realised demand in number of boxes for MTS products is more than the monthly forecasted demand in number of boxes, FrozenBakery was aware of this during that time so in this case we use the realised demand. This is an assumption that we consider acceptable, because this often includes temporary promotions for which FrozenBakery is always notified by the customer in time.

- **Inventory holding costs | Setup costs | Penalty costs | Idle costs –** We use costs per unit per time unit that we developed in Section 4.4.1 and 5.4.

- **Setup time –** Setup time data was made available to us by FrozenBakery. This data represents the setup time incurred when changing over from one recipe to another. This data is estimated by assessing a number of recipe characteristics, such as type of dough and topping. Per change in characteristic, setup times are determined. So, the setup time from one recipe to another is the time needed to change the characteristic that takes most time. In this way, we create matrices for changeovers from all recipes to all other recipes per production line. Table 6.1 shows an example of these parameters. Changing from recipe F0050 to F0352 in this example leads to a change in the coating (35 minutes) and the topping (20 minutes). Taking the maximum value for this means that this setup takes 35 minutes (0.58 hours).

Table 6.1: Setup time parameters Line 1

Recipes	Traces	Dough	Coating	Topping	Stamper	Packaging
F0050	No	Dot dough	White sole	Sugar strands	Dot	Granel
F0352	No	Dot dough	Plain	No	Dot	Granel
F0189	No	Dot dough	Black sole	Hazelnut	Mini	Granel

- **Production capacity** – As discussed in Section 2.2.4, every production line uses an employee shift system that in general determines the weekly capacity. Production Line 1 produces 18 shifts per week (144 hours), Line 2 produces 13 shifts per week (104 hours) in 2019 and Line 3 produces 15 shifts per week (120 hours) in weeks 23-43 of 2019 and changed this to 20 shifts per week (160 hours) from week 44 on in 2019.

- **Processing time** – During a product introduction, the processing times per product are set as the number of boxes that can be produced per hour. We use this data for our processing time per SKU. We multiply the number of boxes that can be produced per hour by the efficiency rate per production line that is used currently in the planning process as well. As mentioned in Section 2.2.5, this equals 87%, 90%, and 87% for Line 1, Line 2 and Line 3 respectively.

- **Initial inventory level** – The first week for which we plan production is week 24. Therefore we use data that is given to us by FrozenBakery for the initial inventory level at the end of week 23. The delivery time for MTS products is 2 working days, therefore the expected inventory level at the end of the week can be estimated well on Wednesdays (when the planning has to be frozen). For the remainder of the weeks, the initial inventory level which is input for the model is calculated as follows:

  $$Initial\ inventory\ level\ end\ of\ week\ t = inventory\ level_{t-1} + planned\ production_t - realised\ demand_t$$

  Note that the inventory level is different for every scenario, because the inventory level is dependent on the production quantities which is output to our model and this can differ per scenario.

- **Inventory policy parameters** – Note that we only calculate inventory parameters for MTS products. We use the minimum inventory level formulations that we developed in Section 5.3.1. For every week that we generate the planning, we determine the safety stocks by taking the average of the needed safety stocks of the past 3 months. As discussed in Section 5.3.3, the safety stocks are updated every month. For the maximum inventory levels, we use the formulation developed in Section 5.3.2, so we take the weekly forecasted demand and multiply this by 5 weeks in order to get the maximum inventory levels.

6.1.3 Computation time

Per production line, a set of SKUs is input for the model. We use the set of SKUs for which the corresponding production line is the preference line. This results in 69 SKUs (25 recipes) for Line 1, 28 SKUs (20 recipes) for Line 2 and 92 SKUs (57 recipes) for Line 3. Since Line 3 has the most SKUs and recipes, we expect our mathematical model needs most time for solving for Line 3. We can conclude from some first test runs that the model is able to find the optimal solution for Line 1 within 10 seconds in general, for Line 2 within 1 second and for Line 3 it is more challenging to find a solution within 1 hour. Due to time limitations, we investigate whether it is possible to restrict the computation time for Line 3, while still being able to find an acceptable solution.

After an analysis of the Math Program Inspector of AIMMS for a number of runs, we find that the solution that AIMMS finds within 400-500 seconds often already equals the optimal solution. We illustrate this in Figure 6.1. In this figure, we find the evolution of the solutions that AIMMS finds after time passes. We can also see from

Figure 6.1, the solution that AIMMS finds in the first 10 seconds quickly approaches the solution value that finally equals the optimal solution. After the first 10 seconds, the solution is improving only slightly. The solution that AIMMS has found after 429 seconds in this example is the same as the optimal solution after assessing all possible combinations within the search area. At 429 seconds, the gap is 5.17%. We note that the gap can be formulated as the difference between the best lower bound solution found and the best integer solution found, divided by the best integer solution found.

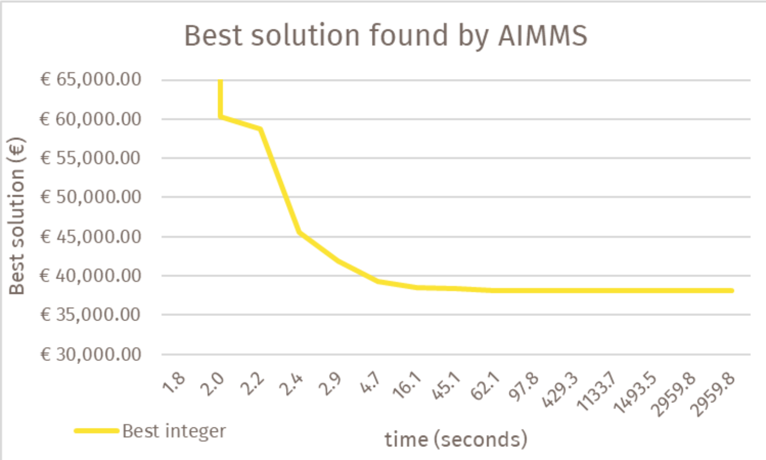

Figure 6.1: Evolution of best integer solutions after time passes (data from AIMMS Math Program Inspector)

This analysis shows that a near optimal solution can be found rather quickly, in this example within 429 seconds. To avoid running the model unnecessarily long, we decide to restrict the computation time of the model for Line 3. Running 9 scenarios for 26 times takes some time and due to the limited time we have available, we decide to run the model for Line 3 for 600 seconds per planning horizon per scenario. We expect that this gives us acceptable solutions with an acceptable average gap of 5%. In Section 6.6, we reflect on this in the limitations of our results.

6.1.4 Additional model restriction

During some initial test runs, we find that an additional restriction is needed to generate realistic production schedules. For the scenarios that have to meet a certain capacity (8B_FCFI_FS and 4B_FCFI_FS), we notice that the model fills up this capacity by scheduling SKUs with the lowest inventory holding costs even if no demand is expected during the planning horizon. We note that we on purpose force the model to use full capacity in these scenarios (8B_FCFI_FS and 4B_FCFI_FS). We therefore decide to add an additional restriction to the model that assures that products are only allowed to be added to the production schedule if demand is expected within the planning horizon. Moreover, we restrict the production of MTO products to the number of products that is needed to fulfil demand, rounded to the nearest 8-hour or 4-hour batch sizes, because we do not want to produce more MTO products than needed for demand. We do this by restricting the inventory level. If no demand is expected during the planning horizon, the inventory level at the end of every week in the planning horizon has to equal the initial inventory that was input to the model. We refer to Appendix B for the exact procedure.

6.2 Scenario setup and KPIs

In this section, we discuss the results of the scenarios that we developed. We assess every scenario on a number of KPIs that are important for FrozenBakery and compare them to the current situation. In Section 6.2.1 we summarise our scenario setup for clarity in this chapter. In Section 6.2.2, we discuss the key performance indicators (KPIs) that we use in this research.

6.2.1 Scenario setup

We repeat from Section 5.5 that we develop 9 scenarios for testing the impact of different planning factors on our KPIs. The planning factors for which we test different instances are *standard batch run length, capacity* *usage* and *inventory policy parameter usage*. We summarise the 9 scenarios in Figure 6.2. Figure 6.2 also shows the meaning of the scenario abbreviations. The addition of FS to every scenario means fixed predefined sequence.

SCENARIOS	STD. BATCH RUN LENGTH			CAPACITY		INVENTORY		
8B-FCFI-FS	**8-HOUR**	4-HOUR	FREE	**FULL**	NEEDED	**FREE**	MIN.	MINMAX.
4B-FCFI-FS	8-HOUR	**4-HOUR**	FREE	**FULL**	NEEDED	**FREE**	MIN.	MINMAX.
8B-NCFI-FS	**8-HOUR**	4-HOUR	FREE	FULL	**NEEDED**	**FREE**	MIN.	MINMAX.
4B-NCFI-FS	8-HOUR	**4-HOUR**	FREE	FULL	**NEEDED**	**FREE**	MIN.	MINMAX.
FB-NCFI-FS	8-HOUR	4-HOUR	**FREE**	FULL	**NEEDED**	**FREE**	MIN.	MINMAX.
8B-NCMINI-FS	**8-HOUR**	4-HOUR	FREE	FULL	**NEEDED**	FREE	**MIN.**	MINMAX.
4B-NCMINI-FS	8-HOUR	**4-HOUR**	FREE	FULL	**NEEDED**	FREE	**MIN.**	MINMAX.
FB-NCMINI-FS	8-HOUR	4-HOUR	**FREE**	FULL	**NEEDED**	FREE	**MIN.**	MINMAX.
FB-NCMMI-FS	8-HOUR	4-HOUR	**FREE**	FULL	**NEEDED**	FREE	MIN.	**MINMAX.**

Figure 6.2: Scenario abbreviations

6.2.2 KPIs

To be able to assess the impact of the planning factors, we set up a number of KPIs. In every scenario, one of the planning factors changes. In this way, we can assess its impact.

Inventory level | Inventory holding costs

The first KPI follows logically from our mathematical model: inventory holding costs. Our mathematical planning model optimises the production planning on the total costs, which consist out of inventory holding costs, setup costs, penalty costs and idle costs. Therefore, inventory holding costs are the first KPI that we include in our assessment. We refer to Section 4.4.1 for a detailed formulation of the inventory holding costs.

Setup time | Setup costs

The second KPI also follows logically from our mathematical model. The weekly setup costs occur when changing over from one recipe to another and is dependent on the corresponding recipes. We refer to Section 4.4.1 for a detailed formulation of the setup costs.

Production time | Production costs

Furthermore, we have developed a number of scenarios that use the needed weekly capacity. Therefore, the outcomes of the different scenarios may lead to different capacity requirements compared to the current situation. Used capacity consists of setup time and production time. We already assess the setup costs in the previous KPI, so we express the production costs as well in a KPI. We define the production costs by looking into the variable conversion costs: direct labour costs and costs for utilities, as these costs are dependent on the hours that production is running. The costs are different per production line, because the number of production employees needed per line differs. We gather this data through the financial department of FrozenBakery and calculate the production costs by dividing the total direct labour and utility costs over 2019 with the total produced hours in 2019 and this results in the following production costs per production line: € 675 per hour for Line 1, € 355 per hour for Line 2 and € 785 per hour for Line 3.

Shortages | Service level

The final KPI that we include is *customer service level*. Shortages occur as a consequence of the uncertainty in demand. The extent to which every scenario is capable of reacting to the deviation between forecasted and actual demand differs per scenario and is therefore of interest in the assessment of the results. FrozenBakery has a desired service level of 99.5% and therefore will try to prevent any shortages. In case shortages occur as a result of uncertainty in demand, FrozenBakery tries to prevent the shortage by changing the planning, even though the planning is frozen. This happens in the current situation as well. We calculate the service level based on the number of boxes short in a certain week as a percentage of the total number of boxes sold in the corresponding week. The formula that we use is as follows (Silver et al., 2016):

$$Service\ level\ (\%) = \left(1 - \frac{Shortages\ (boxes)}{Actual\ demand\ (boxes)}\right) * 100\%$$

6.3 Initial performance analysis

Before assessing the impact of different planning factors on the production planning and inventory in the warehouse, we do an initial analysis of the performance of the scenarios. In this way, we aim to gain insight in the capability of every scenario to create feasible and realistic production schedules. In Appendix C, our detailed initial performance analysis of the Full Capacity (FC) scenarios can be found. We conclude from this analysis that the FC scenarios are not able to create proper schedules. The FC scenarios are forced to use all available weekly capacity and we find that all NC scenarios do not always need all available capacity. We find that for FC scenarios, production is filled with SKUs with the cheapest hourly inventory costs (inventory holding costs per box multiplied by the number of boxes that can be produced per hour). This leads to an increasing inventory level and to unrealistic production schedules that would never be executed at FrozenBakery. We therefore conclude that using a mathematical model that creates schedules based on minimisation of costs in combination with the restriction to always use all available capacity, is not a proper combination and does not lead to proper schedules. We therefore decide to not further investigate the FC scenarios.

6.4 Analysis of planning factors

We further investigate the planning factors *batch production* and *inventory policy parameter usage* for all Needed Capacity (NC) scenarios. Later on, we assess the impact of *production sequence* on the setup time by comparing the results of the scenarios in which we use a predefined production sequence and the optimal sequence. We analyse the set of outcomes per scenario from the perspective of each planning factor.

6.4.1 Batch production

The first planning factor includes 3 different settings: standard batch run length of 8 hour, 4 hours and free batch run length, which means that there is no restriction on the length of a batch run. A batch run corresponds to the production of a recipe. In the current situation, in general standard batch runs of 8 hours are hold on to. By analysing our results, we aim to gain insight in the impact of changing to a standard batch run length of 4 hours and in the impact of completely relaxing this restriction by accepting any batch run length. We analyse the results of our mathematical optimisation model for the first planning factor based on our 4 KPIs.

Inventory and setup costs

First, we compare the results of the scenarios that use free inventory levels (FI) and minimum inventory levels (MINI) for the first two KPIs: *inventory holding costs* and *setup costs*. We combine these KPIs in one cost overview in Figure 6.3, because both cost factors are used by our mathematical optimisation model for creating the production schedules. We conclude from Figure 6.3 that in both type of scenarios (NCFI and NCMINI) the costs decrease when using standard batch run lengths of 4 hours and free batch run lengths compared to using a standard batch run length of 8 hours. We find that our scenarios that include 4-hour batch run length show the lowest inventory holding and setup costs. We also notice a shift between the inventory-setup-cost-ratio between 8-hour batches and free batches. When producing in batch run lengths of 8 hours, the inventory holding costs make up for 71% of the total (inventory holding and setup) costs. In case of free batches, this is only 47%. In Table 6.2, we summarise the average weekly inventory holding and setup costs per batch production setting. We find that changing from 8-hour to a standard batch run length of 4 hours leads to a decrease in weekly inventory holding and setup costs of 10%. Compared to 8-hour batches, the scenarios that use free batch run lengths lead to a decrease of 4%.

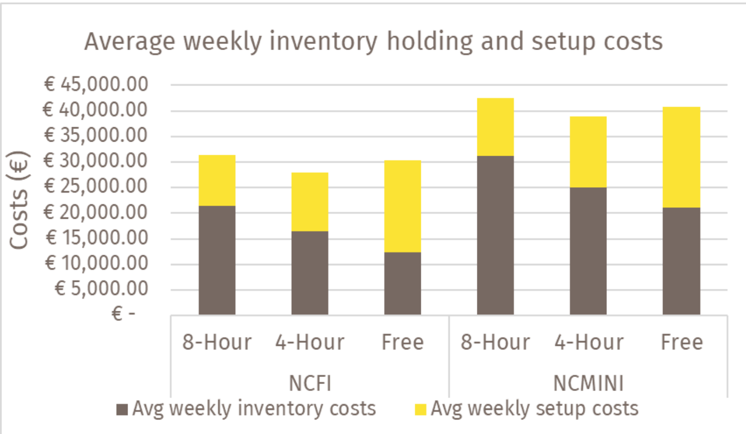

Figure 6.3: Average weekly inventory holding and setup costs per scenario

Table 6.2: Average weekly inventory holding and setup costs per batch production setting

Average weekly costs (of NCFI and NCMINI scenarios)	8-Hour	4-Hour	Free
Average inventory costs % change w.r.t. standard 8-hour batch run length	€ 26,326	€ 20,815 -21%	€ 16,745 -36%
Average setup costs % change w.r.t. standard 8-hour batch run length	€ 10,655	€ 12,588 +18%	€ 18,800 +76%
Average combined inventory and setup costs % change w.r.t. standard 8-hour batch run length	**€ 36,981**	**€ 33,403** **-10%**	**€ 35,546** **-4%**

In conclusion, changing from a standard batch run length of 8 hours to 4 hours leads to decrease in costs of €3,578 in weekly inventory holding and setup costs. This corresponds to savings of €186,056 on yearly basis. Using free batch run lengths saves €74,620 in inventory holding and setup costs on yearly basis. Overall, we find that decreasing the batch run length results in a decrease in inventory holding costs. This means that decreasing the batch run length also has a positive impact on the dwell time of the warehouse. Especially for products that have a unique recipe and products with a low sales volume, lowering the batch run length results in a decrease of the dwell time in the warehouse.

Production costs

Next to this, we analyse the results for our third KPI: *capacity usage and production costs.* A small part of the total weekly production capacity is used for setups, the rest is used for production. In Figure 6.4, we show the total average weekly used capacity divided in production and setup time for the NCFI and NCMINI scenarios and in Table 6.3 we summarise the average weekly production costs per batch production setting. We find a small decrease in production costs for both 4-hour and free batches compared to 8-hour batches. Using a standard batch run length of 4 hours leads to a decrease in production costs of 5%. This corresponds to a decrease of around 5 hours for Line 1 and 8 hours for Line 3 in weekly capacity. Line 2 does not show a significant difference. For free batch production, this saves 9% compared to using 8-hour batches. This corresponds to a decrease of around 9 hours for Line 1, 1 hour for Line 2 and 12 hours for Line 3 in weekly used production time.

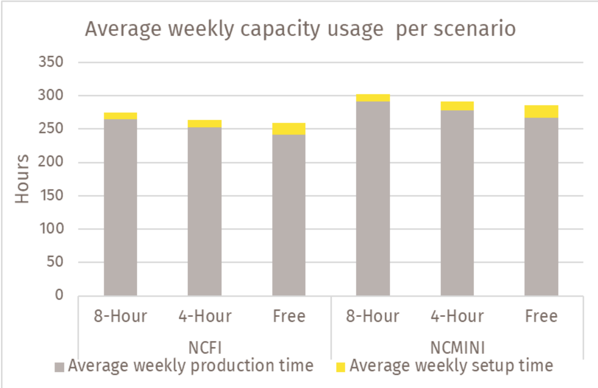

Figure 6.4: Average weekly used setup and production time

Table 6.3: Average weekly production costs per batch production setting

Average weekly costs (of NCFI and NCMINI scenarios)	8-Hour	4-Hour	Free
Average production costs % change w.r.t. standard 8-hour batch run length	**€ 176,085**	**€ 166,664** **-5%**	**€ 159,441** **-9%**

In conclusion, using standard batch run lengths of 4 hours compared to using standard batch run lengths of 8 hours saves €9,421 in production costs weekly, this corresponds to €489,892 on yearly basis. For using free batch run lengths, this results in savings of €16,644 in production costs weekly, which corresponds to €865,488 on yearly basis.

Service level

Finally, we assess the fourth KPI *service level.* FrozenBakery aims to achieve a customer service level of 99.5%. This means that if actual demand in a certain week arrives but cannot be fulfilled from inventory, FrozenBakery changes the production planning to be able to deliver the products. An overview of the service level and shortages per scenario is depicted in Table 6.4. For both type of scenarios, we note an increase in customer service level when changing from 8-hour to 4-hour batches of 0.1%, however this change is so small that it is almost neglectable. Furthermore, the customer service level decreases by 1.1% when comparing the NCFI scenarios of 8-hour and free batches. Overall, we conclude that the setting for batch production in 8-hours or

4-hours do not have a big impact on the shortages or service level. In case of the NCFI scenarios, free batches lead to more shortages, so producing in batches makes up for shortages to a certain extent.

Table 6.4: Average customer service level per batch production setting and scenario type

Customer service level	**NCFI**			**NCMINI**		
	8-Hour	**4-Hour**	**Free**	**8-Hour**	**4-Hour**	**Free**
Customer service level % change w.r.t. standard 8-hour batch run length	**97.2%**	**97.3%** **+0.1%**	**96.1%** **-1.1%**	**99.7%**	**99.8%** **+0.1%**	**99.6%** **-0.1%**
Shortages in number of boxes % change w.r.t. standard 8-hour batch run length	**4,086**	**4,079** **-0.2%**	**5,604** **+37%**	**394**	**364** **-7.6%**	**668** **+69.5%**

6.4.2 Inventory control policy parameters

The other planning factors for which we aim to assess the impact on our KPIs is *inventory control policy parameter usage.* In 3 out of 7 scenarios, our mathematical optimisation model only schedules products that have an expected demand for that week and have an insufficient number of products in stock. Furthermore, 3 of the scenarios use minimum inventory levels for MTS products and 1 scenario uses minimum and maximum inventory levels for MTS products.

Inventory and setup costs

For a visual representation of the comparison between NCFI and NCMINI scenarios for inventory holding and setup costs, we refer back to Figure 6.3. We find that for all three batch production settings (8-hour, 4-hour and free batches) the inventory and setup costs are higher for the NCMINI scenarios compared to the NCFI scenarios. We emphasise that for the NCFI scenarios only products are scheduled for which demand is expected and no additional inventory is kept. In Table 6.5, we summarise the average inventory holding and setup costs for both NCFI and NCMINI scenarios. We can conclude from Table 6.5 that inventory holding costs increase on average by 54% for the NCMINI scenarios with respect to the NCFI scenarios. Moreover, the setup costs increase on average by 14% in this comparison. This leads to a combined inventory holding and setup cost increase of 36% weekly. This corresponds to weekly inventory holding and setup costs of €10,851.

Table 6.5: Average weekly inventory holding and setup costs per inventory policy setting

Average weekly costs (of 8B, 4B and FB scenarios)	**NCFI**	**NCMINI**
Average inventory costs % change w.r.t. NCFI	€ 16,773	€ 25,819 +54%
Average setup costs % change w.r.t. NCFI	€ 13,112	€ 14,917 +14%
Average combined inventory and setup costs % change w.r.t. NCFI	**€ 29,885**	**€ 40,736** **+36%**

Production costs

The second KPI that we assess is the average weekly production time and costs of both the NCFI and NCMINI scenarios. In Figure 6.4, we present a visual representation of the weekly capacity usage in divided in production and setup time for these scenarios. From Table 6.6, we find that the average weekly production costs increase by 11% when using minimum inventory levels over using free inventory levels.

Table 6.6: Average weekly production costs per inventory policy setting

Average weekly costs (of 8B, 4B, FB scenarios)	**NCFI**	**NCMINI**
Average production costs % change w.r.t. NCFI	**€ 159,000**	**€ 175,793** **+11%**

Service level

Our final KPI for which we assess the impact of both free inventory levels and minimum inventory levels is the *customer service level*. We note big differences in the service levels of the NCFI and NCMINI scenarios. In Figure 6.5, we show the customer service level per production line per scenario and summarise relevant values in Table 6.7. We find that the service levels for the NCFI scenarios all underperform in terms of service level, because the service level is lower than 99.5%. On the other hand, we find that all three scenarios that use minimum inventory levels have acceptable customer service levels above 99.5%. Currently, FrozenBakery prevents shortages by adjusting the production planning if sudden changes in demand occur. This means that for our NCFI scenarios, this has to be done as well in order to deliver 99.5% of demand in time. Adjusting the initial production schedule can lead to a non-optimal planning and this leads to higher inventory holding, setup and capacity costs. We need to take this into account in the assessment of the NCFI scenarios.

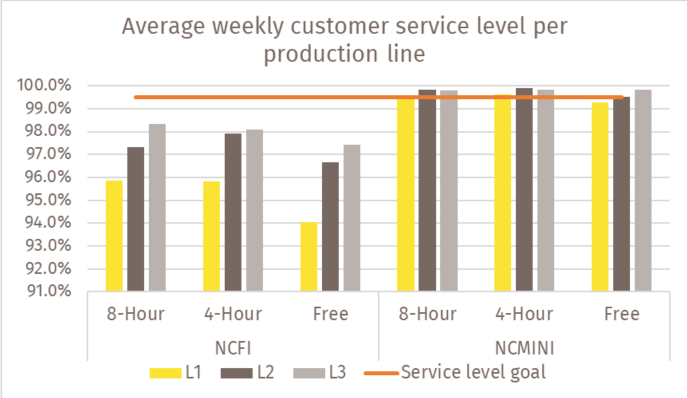

Figure 6.5: Average weekly customer service level per production line

Table 6.7: Customer service level per inventory policy setting and batch production setting

Customer service level	8-Hour		4-Hour		Free	
	NCFI	**NCMINI**	**NCFI**	**NCMINI**	**NCFI**	**NCMINI**
Customer service level % change w.r.t. NCFI	**97.2%**	**99.7%** **+3%**	**97.3%**	**99.8%** **+3%**	**96.1%**	**99.6%** **+4%**
Shortages in number of boxes % change w.r.t. NCFI	**4,086**	**394** **-90.3%**	**4,079**	**364** **-91.1%**	**5,604**	**668** **-88.1%**

Minimum and maximum inventory levels

The final comparison that we make is between minimum inventory levels (MINI) and minimum and maximum inventory levels (MMI). We compare this for the free batch run length settings.

Table 6.8: Minimum and maximum inventory level impact per KPI

Average weekly costs	NCMINI	NCMMI
Average inventory costs % change w.r.t. NCMINI	**€ 21,126**	**€ 19,499** **-8%**
Average setup costs % change w.r.t. NCMINI	**€ 19,700**	**€ 22,163** **+13%**
Average production costs % change w.r.t. NCMINI	**€ 167,721**	**€ 168,070** **+0.2%**
Customer service level % change w.r.t. NCMINI	**99.6%**	**99.0%** **-0.6%**

We can conclude from Table 6.8, that taking into account maximum inventory levels does lead to a decrease in inventory holding costs of 8% compared to only taking into account minimum inventory levels. On the other hand, it leads to an increase in weekly setup costs of 13%. This results in a combined inventory holding and setup cost increase of 2% compared to the scenario that uses minimum inventory levels only. This equals to €836 in weekly inventory holding and setup costs. Production costs increase by 0.2%, so the total costs that include inventory holding, setup and production costs increase by €61,620 or 0.5% in yearly costs. Finally, we note a decrease in customer service level of 0.6% when using minimum and maximum inventory levels. Since we use both minimum and maximum inventory levels in the NCMMI scenario, we investigate why this scenario results in lower service levels than the expected value of 99.5% on which the minimum service levels are based. We analyse the production schedules of the NCMINI and NCMMI scenarios and find that the model keeps the inventory level per SKU lower for the NCMMI scenarios and therefore the model tends to produce SKUs more often and in smaller quantities. For SKUs in which the actual demand highly deviates from the forecasted demand, this strategy (producing more often in smaller quantities in order to keep inventory low) can be the cause for more shortages and therefore a lower service level. Another possible cause for the average service level of 99.0% for the NCMMI scenario is that we run the model only for 26 weeks and that shortages weigh relatively heavy in the average value for the service level. If we would take the average over 1 or 2 years, the service level might meet in the desired value of 99.5%.

6.4.3 Production sequence

Our scenarios base the sequence of production on the general fixed sequence that FrozenBakery holds on to currently. We refer to Section 2.2.2 for a detailed explanation. Following the same sequence pattern every week eases the planning of production, because this is a variable that is fixed and therefore does not have to be considered. However, we are interested whether using this weekly standard sequence pattern is performing well. Therefore, we compare the fixed sequence to the optimal weekly sequence by sequencing the recipes for a number of weeks with the help of our SD model (see Appendix A for the model formulations). We decide to work out the sequence comparison for scenario 4B-NCMINI, because our earlier analysis shows that this is a promising scenario.

In Figure 6.6, we show the differences in using the fixed predefined sequence (FS) and using the optimal sequence (OS) according to our setup time matrices. Due to time limitations, we compare the first 6 weeks instead of all 26 weeks. We use the first 6 weeks, because the specific setup times for these weeks have the same average as the average setup time of the 26 weeks which make them representative to use.

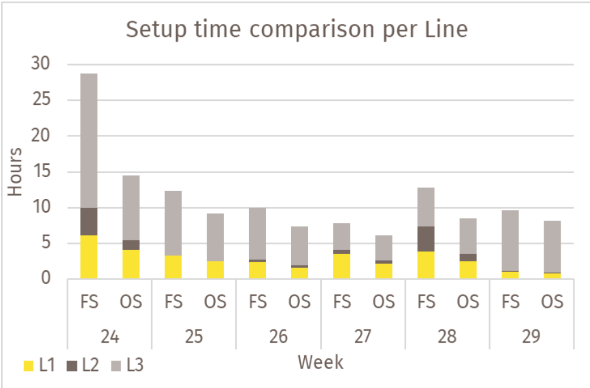

Figure 6.6: Setup time comparison fixed - optimal sequence per week per Line

For all three production lines, the optimal sequence performs better than the predefined fixed sequence. We find that the sequence for week 24 for Line 3 shows a high difference of 9.75 hours, this is because the schedule made with the fixed sequence includes a recipe that contains allergens is scheduled on the position before the last in the week and therefore needs high cleaning times. In the optimal sequence this specific recipe is scheduled last and therefore saves setup time. We realise that this is a rare situation and may give a too optimistic average for the savings on Line 3. Therefore, in calculating the average savings for Line 3, we do not include this value. Using optimal sequences for Line 3 shows a saving of 16% compared to using a fixed sequence in our planning model. For Line 1, the weekly setup time decreases by 32% on average over these 6 weeks. For Line 2, this equals 23%. This means that by sequencing the weekly schedules with the help of a model that minimises the setup time, more capacity time becomes available for actually producing. This equals 2.95 hours of weekly setup time in total and corresponds to €3,100 weekly on average. This corresponds to savings of €161,200 on yearly basis.

6.5 Comparison with current situation

We compare the realised planning in the second half year of 2019 with the production schedules per scenario created by our mathematical optimisation model to learn what differences occur when planning by hand and when planning by means of an automated mathematical optimisation model. We also want to gain insight in differences in our KPIs between the current situation and the scenario outcomes. First, we compare the KPIs of the scenarios and current situation with each other and afterwards, we look deeper into differences between the production schedules created by the planner at FrozenBakery and by our mathematical model.

In a first initial analysis, we conclude that the savings per scenario on the total associated costs compared to the current situation are between 14 and 30%. We consider this quite high, especially the difference in needed weekly capacity has our attention. We therefore decide to look deeper into our data in order to find out what causes this difference. After a deep analysis, we find that there exists a difference between the number of products that leave the warehouse compared to the number of products that are sold for Line 1 and Line 3. For Line 2, the difference is neglectable (less than 1%). The number of products sold is the data set that we used for our realised demand. The number of products that leave the warehouse is 14% higher than the number of products sold according our data file. This is caused by a number of products that are produced as intermediates and therefore do not exist in the realised demand data, as these products are used in so-called mixboxes. Since they do not exist in the realised demand data, our mathematical optimisation model did not include them in the production planning. Mixboxes are made on a separate rework packaging line, which we did not include in our research. We refer back to Section 1.6 for the scope of our research. Therefore, we consider this a consequence of decisions and assumptions made in the beginning of the research.

However, we consider this deviation of 14% too high to ignore. In making a decision in what to do with this difference, we have to balance the time we have left with the quality and reliability of the results. We emphasise that this difference only affects the comparison between the outcomes in our mathematical optimisation model and the outcomes of the realised planning in 2019. The comparison *between* the scenarios and the conclusions of the impact of planning factors on the inventory and production, described and reflected on in Section 6.4, remains the same, because we used the same data set for every scenario. We consider a number of possibilities to deal with this and we conclude to rerun our model calculations for a number of weeks to gain insight in the impact that this difference has on our KPIs. Rerunning takes a lot of computation time, therefore we limit ourselves to rerun 6 weeks of model calculations for Line 1 and Line 3. The first 6 weeks show an average difference of 14% in the number of products that leave the warehouse and the number of products that are sold. This makes it a representable set dataset to run again.

After running the model again for Line 1 and Line 3, we analyse the absolute differences in the outcomes of every KPI and every scenario and use this to re-calculate the outcomes of every KPI and scenario for the rest of the weeks. This gives the following results per scenario per KPI in Table 6.9. The results in red show values that perform worse than the current situation and the green results show values that perform better than the current situation.

Table 6.9: Results of scenarios compared to current situation per KPI

Average weekly costs per scenario (average over 26 weeks)					
	Inventory holding costs	Setup costs	Production costs	Service level	Total weekly costs
Current situation	**€ 21,225**	**€ 17,066**	**€ 221,648**	**99.5%**	**€ 259,939**
8B-NCFI-FS	€ 22,214 +5%	€ 10,788 -37%	€ 188,474 -15%	97.3%	**€ 221,476 -15%**
4B-NCFI-FS	€ 16,614 -22%	€ 11,799 -31%	€ 171,615 -23%	97.0%	**€ 200,476 -23%**
FB-NCFI-FS	€ 12,853 -39%	€ 18,028 +6%	€ 166,876 -25%	95.3%	**€ 197,757 -24%**
8B-NCMINI-FS	€ 30,536 +44%	€ 12,604 -26%	€ 191,536 -14%	99.7%	**€ 234,675 -10%**
4B-NCMINI-FS	€ 24,942 +18%	€ 15,838 -7%	€ 190,861 -14%	99.8%	**€ 231,641 -11%**
FB-NCMINI-FS	€ 20,882 -2%	€ 20,184 +18%	€ 180,463 -19%	99.5%	**€ 221,529 -15%**
FB-NCMMI-FS	€ 19,351 -9%	€ 22,741 +33%	€ 183,315 -17%	99.0%	**€ 225,408 -13%**

We find from the results in Table 6.9 that all NCMINI scenarios are acceptable, because these scenarios meet a service level of 99.5%. For the other scenarios, NCFI and NCMMI, the initial production schedules that are output from our model need to be adjusted in order to achieve the acceptable service level of 99.5%. This may include the need for additional weekly capacity or may include additional setups. The three NCMINI scenarios all lead to savings in costs. We find that compared to the current situation, the combination of using 8-hour batches and minimum inventory levels increases the inventory holding costs by 44%. For 4-hour batches and minimum inventory level this results in an increase in inventory holding costs of 18%. This shows that the combination between keeping inventory as a result of economic efficiencies and as a result of protecting against uncertainty should be carefully considered. At the same time, both 8B-NCMINI and 4B-NCMINI show decreases in setup costs of 26% and 7% respectively.

We find that our mathematical optimisation model is able to produce the needed products in order to fulfil demand with less capacity. Depending on the scenario, this variates between 14% and 25% less production costs. To find out where this difference come from, we compare the realised production schedules with the created production schedules of our model. First, we note that 6 out of the 7 scenarios are able to produce all SKUs on its preferred line where in the realised planning often products are interchanged as a consequence of tight capacity. The scenario that uses 8-hour batches and minimum inventory levels needs capacity on Line 1 in 2 out of the 6 rerun weeks. Second, we find from comparing the production schedules, that our model is able to combine forecasted demand of SKUs over multiple weeks in the planning horizon and also combines multiple SKUs that share the same recipe more often than in the man-made planning. This results in a better timing of production which results in less weekly needed capacity, both because less setups are needed and batches are better combined which leads to less needed production time.

In conclusion, we find that 3 out of the 7 scenarios show acceptable service levels and show cost savings. We find that the combination of using a model to create initial production schedules based on standard batch run lengths of 8 hours, minimum inventory levels and a predefined production sequence leads to weekly total cost savings of €25,264 compared to the current way of planning. This corresponds to €1,313,728 on yearly basis. Using a model to create initial production schedules based on standard batch run lengths of 4 hours, minimum inventory levels and a predefined production sequence leads to weekly total cost savings of €28,298 and corresponds to €1,471,496 on yearly basis compared to the current way of planning. Finally, using a model to create initial production schedules based on free batch run lengths and minimum inventory levels leads to cost savings of €38,410 compared to the current situation and corresponds to yearly cost savings of €1,997,320.

6.6 Limitations of results

The development of our mathematical model also incurs some limitations of the results. We note in Section 6.1.3 that we use a computation time of 600 seconds for the production schedules for Line 3. For some runs, this led to a gap between the best solution found and the best lower bound solution found. In Table 6.10, we summarise the number of runs with nonzero gaps, the average gap out of these nonzero gaps and the maximum gaps. We find that all scenarios have an average gap of less than 5%, and therefore we accept our solutions found. Furthermore, after an analysis we find that all solutions show feasible results. However, it is a limitation of the model that we tolerate minimal gaps for the solutions for Line 3.

Table 6.10: Number of gaps and percentages per scenario for model runs of Line 3

Scenarios	**Number of runs with nonzero gap (out of 26)**	**Average gap (out of nonzero gaps)**	**Maximum gap**
8B-FCFI-FS	6	1.89%	3.33%
4B-FCFI-FS	18	2.11%	5.08%
8B-NCFI-FS	1	3.77%	3.77%
4B-NCFI-FS	18	3.47%	6.70%
FB-NCFI-FS	19	4.86%	10.44%
8B-NCMINI-FS	1	1.49%	1.49%
4B-NCMINI-FS	6	2.73%	5.73%
FB-NCMINI-FS	18	3.49%	7.20%
FB-NCMMI-FS	0	0.00%	0.00%

6.7 Conclusions

In this chapter, we aim to answer the final sub research question in this research: '*What is the impact of various planning factors on total costs and how does the quality of the production planning under various circumstances compare to the current planning method?*'. By running 9 scenarios in which we change one planning factor setting at a time, we gain insight in the impact of every planning factor on our key performance indicators (KPIs): *service level, inventory holding costs, setup costs,* and *production costs.* We also assess the impact of using standard *production sequences* to using optimal sequences on the weekly setup time. Based on an initial performance analysis, we conclude to not further assess the FC scenarios, because these scenarios are not able to create realistic production schedules.

For our first planning factor *batch production*, we find that using standard batch run lengths of 4 hours compared to 8 hours, can lead to yearly cost savings of €675,948. Even though the setup costs increase by 18%, we find savings in inventory holding costs of 21% and savings in production costs of 4%. Furthermore, we find that using free batch run lengths compared to 8 hours can lead to yearly cost savings of €940,108. This is mainly caused by great savings in the needed weekly capacity, as this is not bounded by standard batch run lengths. We do not note large differences in the service level when shifting from 8 hour batches to 4 hours. However, we do note a small decrease in service level when shifting from 8-hour batches to free batches. From this we can conclude that producing in standard batches does compensate for shortages to some extent. Also, lowering the batch run length results in a decrease in the dwell time of the warehouse. This especially holds for products with unique recipes and for products with a low sales volume.

Next to this, we analyse the impact of *inventory policy parameter usage* on our KPIs. We find that using minimum inventory levels is effective in increasing the customer service level to above the desired level of 99.5%. However, this increase in service level comes with a price. It leads to an increase in inventory holding costs of 54%, an increase in setup costs of 14% and to an increase in needed weekly production time of 11% compared to only producing what is expected without keeping any additional inventory (free inventory). Our results also show that in the realised situation in 2019, the planner keeps additional inventory for certain products based on intuition. Therefore, we compare the inventory levels of the scenarios with the inventory levels of the current situation as well. We find that as an effect of using minimum inventory levels in the planning process, the inventory holding costs increase by 44% in case of using standard batch run lengths of 8 hours compared to the current situation. This corresponds to an increase in yearly inventory holding costs of €484,172. Inventory holding costs increase by 18% in case of using standard batch run lengths of 4 hours compared to the current situation, this corresponds to €193,284 in yearly inventory holding costs. The inventory holding costs decrease by 2% when using free batch run lengths in combination with minimum inventory levels. This corresponds to €17,836 in yearly inventory holding costs. We conclude based on this that keeping inventory both as protection against uncertainties and as a result of using batch run lengths should be considered simultaneously. Additionally, we find that using maximum inventory levels in the production planning process lead to a small increase in the total yearly costs of €61,620. Our results show that using maximum inventory levels in the planning process result in a service level of 99.0%, which is below the desired level of 99.5%. We find that this can be caused by the fact that the model aims to keep inventory levels lower for scenarios that use maximum inventory levels and therefore tends to produce SKUs more often in smaller quantities. For SKUs in which actual demand highly deviates from forecasted demand, this can cause more shortages and therefore a lower service level. Another possible cause is that we run the model for a relatively short period of time (26 weeks instead of 1 or 2 years) and therefore shortages weigh relatively heavy in the determination of service level.

Furthermore, we find that using the weekly optimal *production sequence* compared to using a standardised predefined sequence saves on average 2.95 hours in setup time per week for the three production lines together. This corresponds to €3,100 in weekly setup costs and corresponds to €161,200 in yearly setup costs.

Finally, we compare the results of our mathematical optimisation model to the performance of the current situation. We find that all NCMINI scenarios achieve a service level of 99.5%. The other scenarios need last-minute changes to the initial schedules to meet the desired service level. Within the NCMINI scenarios, we find that all three scenarios perform better than the current situation. We find savings between 14% and 19% in needed weekly production time compared to the current situation. Using the BP planning model in combination with using standard batch run lengths of 8 hours, minimum inventory levels and a predefined production sequence leads to cost savings of €1,313,728 yearly. Using the BP planning model in combination with using standard batch run lengths of 8 hours, minimum inventory levels and a predefined production sequence leads to cost savings of €1,471,496 yearly compared to the current situation. Finally, using the BP planning model in combination with using free batch run lengths, minimum inventory levels and a predefined production sequence leads to yearly cost savings of €1,997,320. We find that our BP model achieves this by better combining the timing of production of the SKUs and recipes within the planning horizon.

7. CONCLUSIONS AND RECOMMENDATIONS

In this final chapter, we report our main conclusions and recommendations acquainted in this research. Section 7.1 describes the main conclusions that we draw in this research. Section 7.2 discusses several assumptions and limitations made in this research. Section 7.3 discusses the recommendations on how the production planning process can be structurally improved. In Section 7.4, we do proposals for further research, based on information and findings gathered during this research.

7.1 Conclusions

In this research, we aim to answer the following research question:

'How can the production planning process of FrozenBakery be structurally improved in order to save total associated costs, while maintaining a service level of 99.5%?'

In this section, we summarise the most relevant remarks and findings gained throughout our research.

From our current situation analysis, we identify three main problems that can cause the total costs to be higher than desired. Currently, production schedules are made by using standard batch runs of 8 hours. This stems from the desire to minimise setups in production, as setups are perceived as a loss of time. Producing in large batches causes high inventory levels and therefore dwell time. A product spends on average 31 days in the warehouse on average, while the goal is to maintain an average dwell time of 25 days This is the first problem that we identify. The second problem that we identify is that high setup times are incurred due to the current way of planning. The planning process is executed manually by one person in which main focus is on actualities of today, more than focussing on achieving efficient schedules over the entire planning horizon. This makes it challenging to consider the best possible schedule over the entire planning horizon and can cause production costs due to setups to be higher than desired. The third problem we identify is that FrozenBakery deals with a high uncertainty in demand and in output from production. Main part of the planning process is based on customer forecasts that highly deviate from actual demand. Based on intuition, the planner keeps inventory for a number of products on occasion, but no strategy is used for this. Since FrozenBakery aims to achieve a service level of 99.5%, currently high demand deviations cause last-minute changes in the production schedule often. This also causes production costs to be higher than desired.

Based on our literature review, we find that methods exist for solving lotsizing and scheduling problems. These methods aim to find an optimal trade-off between setups in production on the one hand and keeping inventory on the other hand. Furthermore, we find that inventory control policies can be used for keeping inventory in order to prevent uncertainties in the process. Finally, we learn that two types of inventory exist: the first type of inventory exists as a result of providing for economic efficiencies by the use of batches in production and the second type of inventory exists as a result of protecting against uncertainties in the process.

We use the methods found in literature as input for developing a production planning model based on Mixed Integer Linear Programming (MILP) modelling. In our solution design, we evaluate and compare two methods for creating production schedules: 1) a MILP-based Simultaneous Lotsizing and Scheduling model that determines optimal production sequences, production quantities and timing of production and 2) a MILP-based Block Planning model that determines optimal production quantities and timing of production and assumes a predefined production sequence as input. We use a separate optimisation model, based on Traveling Salesman Problem model formulations, for determining the predefined sequence. We find that the second method, a Block Planning model in combination with a separate sequence determination model, shows results comparable to the first method. Compared to the first method, the second method finds these results much faster. We therefore use the Block Planning model for creating production schedules. Furthermore, we develop an inventory control policy that determines minimum and maximum inventory levels for MTS products in order to protect against uncertainties. We run our Block Planning model for a number of scenarios that include a combination of three planning factors in different settings: *batch production* (standard batch run lengths of 8 hours, 4 hours and free batch run lengths), *capacity usage* (using all available capacity and using only needed capacity) and *inventory control parameters* (free inventory levels, including minimum inventory levels and including minimum and maximum inventory levels). By running these scenarios, we can gain insight in the impact that every planning factor has on our KPIs: the customer service level, inventory holding costs, setup costs and production costs. After running the scenarios, we also analyse the impact of using a standardised production sequence compared to using the optimal production sequence on the setup time and costs.

Based on the model runs for every scenario, we make conclusions regarding possible factors that can structurally improve the production planning process of FrozenBakery regarding costs, while maintaining a service level of 99.5%. First, we find that when the batch run length decreases, setup time increases and inventory levels decrease. We also find that both purposes for keeping inventory, providing for economic efficiencies by using standard batch run lengths and protecting against uncertainties in the process by using minimum inventory levels should be considered simultaneously to prevent excessive inventories.

We find that the production planning process can be improved in order to save total costs when shifting from using standard batch run lengths of 8 hours to using standard batch run lengths of 4 hours, because yearly cost savings of €675,948 can be realised. This is mainly possible, due to a reduction in needed production time of 5% and a decrease in inventory holding costs of 21%. On the other hand, shifting towards a standard batch run length of 4 hours does impose an increase in setup costs of 18%. Next to this, we find that shifting from standard batch run lengths of 8 hours to free batch run lengths can result in yearly cost savings of € 940,108. Relaxing the batch run length leads to a decrease in needed production time of 9%, because in a lot of cases demand can be fulfilled by producing less than 8 hours. Furthermore, producing in free batches leads to a decrease in inventory holding costs of 36% and to an increase in setup costs of 76%. Furthermore, lowering the batch run length results in a decrease of the dwell time in the warehouse. This especially holds for products with unique recipes and for products with a low sales volume, because less products are made per batch run so less products need to stay in the warehouse for a long time.

Furthermore, we find that using minimum inventory levels turn out to be effective in increasing the customer service level to 99.5% while creating the initial production schedules. This provides for more certainty in the production process and in the processes that depend on the planning such as the purchasing of raw material and the deployment of personnel. This also means that there is less need for last-minute changes in the production schedules, so it can provide for savings in weekly setup time. However, the improvement in certainty in the process also comes with additional costs. We find that compared to the current situation, yearly inventory holding costs increase by €484,172 when using standard batch run lengths of 8 hours. When using standard batch run lengths of 4 hours, this equals €193,284 in yearly inventory holding costs. Using free batch runs results in a decrease in yearly inventory holding costs of €17,836. From these results, we can conclude that using minimum inventory levels in the production process decrease the need for last-minute changes in the schedules and therefore can result in less frequent setups in production. However, using minimum inventory levels do increase the inventory holding costs. We emphasise that the combination with the setting for batch run lengths is important in the impact that minimum inventory levels have on total costs.

Furthermore, we find by assessing the difference between using a standardised predefined production sequence and using the weekly optimal production sequence, that using the optimal weekly sequence can save on average 2.95 hours in setup time per week for the three production lines together. This corresponds to yearly setup costs savings of €161,200.

Finally, we look into the differences between the realised production schedules in 2019 and the production schedules generated by our mathematical model. We find that in terms of total costs, all scenarios perform better than the current situation. Within the acceptable scenarios that show service levels equal to or higher than 99.5%, we find that the model-made production schedules show savings in needed production time and costs between 14% and 19%. Also, the 8-hour batches show a decrease of 26% in setup costs and the 4-hour batches show a decrease of 7% in setup costs when using a mathematical model for generating production schedules. Overall, we find that the combination of using the BP model that plans based on 8-hour batches, minimum inventory levels and a predefined production sequence can save €1,313,728 in yearly total costs. Using the BP planning model in combination with minimum inventory levels and using 4-hour batches can result in yearly total cost savings of €1,471,496 and for free batch runs in combination with minimum inventory levels this equals €1,997,320 on yearly basis. We find that our mathematical model achieves this by better combining the timing of production of the SKUs and recipes within the planning horizon.

7.2 Discussion

In this section, we elaborate on limitations and assumptions that we made in this research.

First, our mathematical planning model is a simplified representation of reality. Putting every detailed decision factor into the model would increase the complexity of such models too much. We further discuss three main limitations regarding simplifications in our model:

1) We assume that efficiency rates are constant, but in reality production lines are more unstable just after a setup has been completed. Therefore, in scenarios that include a lot of setups during the week, the realised efficiency rate may turn out to be lower. This is not included in our model, as it requires time-consuming research to quantify this in the model. If taken into account, scenarios that use a lot of setups may become less attractive regarding costs.
2) We use average hourly cost rates for setup and production costs. In reality, these costs may differ per recipe and per shift because the number of employees needed in production differ per recipe and the costs during the day and night shifts differ as well. Taking this into account could lead to better production schedules regarding costs, but also highly increases the complexity and computation time of the model.
3) For our inventory holding costs, we use costs that are incurred with the internal frozen warehouse at FrozenBakery. However, sometimes FrozenBakery also hires external storage space which is more expensive. We did not take into account the external warehousing costs, because not all SKUs are included in our research (products that are produced elsewhere and products from the rework production line are not included), so the decision on which and how much products are sent to an external warehouse can only be approximated. If taken into account, the proposed changes that lead to lower inventory levels result in even higher cost savings or lower losses and the proposed changes that lead to higher inventory levels result in lower cost savings or higher losses.

Second, we make the assumption for the input data of MTS products that if actual demand and forecasted demand in a certain week differ more than the total forecasted demand for the whole month, we use the actual demand. We use the forecasted demand for MTS products otherwise. We make this assumption, because in most of these cases FrozenBakery is informed upfront by the customer if actual demand differs from the forecast. However, it is likely that FrozenBakery is informed in advance by the customer in the case of smaller deviations as well and the same holds for products with ending sales seasons which are still included in the forecast data but are not sold anymore. This allows for making better estimations on what needs to be produced or not. When taken into account on more detailed level, it could be that certain SKUs would not be planned by the model. This could have led to lower inventory levels for these SKUs.

Third, we discuss the methods that we used for calculating the service level. Two frequently used methods are to define the service level: cycle service level (CSL) and the product fill rate (FR). The CSL this is the fraction of replenishment cycles that end with all customers demand being met (Silver, Pyke, & Thomas, 2016) and FR is the fraction of product demand satisfied from production inventory (Silver, Pyke, & Thomas, 2016). In our research, we used the CSL for calculating the safety stocks which are part of our inventory control policy and we used the FR for the assessment of the results per scenario, because FrozenBakery uses this method for their assessment of the service level. Both methods result in different safety factors and therefore in different required levels for safety stocks. In Appendix D, we show an example calculation for both methods. We find from this comparison that using the FR for determining safety stocks instead of using CSL leads to a lower safety factor and therefore to lower safety stocks: 844 boxes instead of 1017 boxes on average. If we would have used the FR method in the safety stock calculations, our results may have led to lower inventory levels and inventory holding costs.

Fourth, in the comparison between the current situation and the results from our planning model we assume that the realised service level at FrozenBakery is 99.5%. However, this is a goal that FrozenBakery strives to, in reality this is not always achieved. From conversations during the research, we find that the service level over 2019 equals around 98%. A lower value for the service level has an impact on the calculation for safety stocks as well. Since we use a 99.5% CSL in our safety stock calculation, the inventory levels and inventory holding costs for the scenarios that use minimum inventory levels turn out higher than when using the realised CSL. To quantify this, we show a calculation example in Appendix D. From this example, we find that using a CSL of 98%

instead of 99.5% leads to a decrease in average safety stock from 1017 boxes to 811 boxes. When taken into account that realised service levels are lower in reality, our minimum inventory level scenario results may have led to lower inventory levels and inventory holding costs as well.

Fifth, in the part of our research were we focus on optimal sequences, we assume that all production sequences are possible. We do include high setup times for changing over from products that contain allergens to any other recipe. However, there may be more recipe combinations that in reality are not logical. More restrictions could lead to higher setup times, because certain combinations are not possible anymore.

Finally, in Section 6.5, we explain that we perform a rerun for part of our results. This is because after analysis of the results from our model, it turned out that assumptions made while scoping our research resulted in a difference between the number of products sold that we used as realised demand in our model compared to the actual number of products that leave the warehouse. It can be seen as a limitation of the results that we rerun the data for 6 weeks and used the absolute difference between the first run and the rerun to re-calculate the rest of the 26 weeks. We realise that rerunning the entire model for all 26 weeks could have given better results to compare the model scenarios with the current situation. However, given the limited time that was left in this research, we consider the way in which we approached this challenge as the best possibility.

7.3 Recommendations

Based on our conclusions and further findings in our research, we make a number of recommendations for FrozenBakery regarding improvements in the production planning process to save costs, while maintaining a customer service level of 99.5%. We recommend FrozenBakery to:

1. Shift from using standard batch run lengths of 8 hours towards using standard batch run lengths of 4 hours.
Our results show a direct link between the standard batch run length, setup times and inventory levels. A decrease in batch run length results in yearly cost savings, especially due to lower inventory levels and less needed production time. We also find from our results that producing in free batches leads to even greater cost savings. However, it has to be kept in mind that using free batches result in more setups and this may influence the efficiency rate of the production lines. Moreover, production in free batches increases the difficulty of hiring temporary personnel as the number of employees needed in production differs per recipe and temporary personnel has to be hired for 4 consecutive hours. We therefore recommend to shift towards using standard batch run lengths of 4 hours and to consider using even smaller batches in situations where a comparable number of personnel is needed per recipe and only small machine changes are needed.

2. Shift from using a reactive method to cope with uncertainty by changing the production planning last-minute, towards including minimum inventory levels in the planning process for critical make-to-stock products.
We find from our results that using minimum inventory levels in the planning process are effective in achieving a 99.5% service level before the production schedules are frozen. This provides more certainty in the entire process of raw material procurement, deployment of temporary personnel and in the production planning process itself. Moreover, it ensures that the production can actually be executed as planned which can lead to a decrease in the need for less setups because recipes do not have to be squeezed in last-minute. However, we find from our results as well that using minimum inventory levels do lead to an increase in the yearly inventory holding costs. We therefore emphasise that the usage of minimum inventory levels in the planning process and the duration for batch runs should be considered simultaneously, as lowering the batch run length results in a decrease in inventory holding costs. In order to further reduce the impact of safety stocks on the inventory levels and costs, we recommend to conduct further research into improving the customer forecasting process and into focussing on classifying make-to-order and make-to-stock products in order to prevent stockouts by keeping safety stocks for critical products, risking stockouts for less critical ones and shifting from make-to-stock towards make-to-order production for highly uncertain SKUs.

3. Start using a production planning model that can serve as a supportive tool to help the planner in making initial production schedules.
We emphasise that both the mathematical model and the planner should be used in its strength. The model should be used for its computation power which allows for finding the optimal combination of SKUs and recipes to produce that minimise total costs within the planning horizon. The planner should be used in its strength as

well: dealing with uncommon circumstances and situations and adapt the initial schedules created by the model thanks to human intuition and experience. The mathematical model developed in this research can be used if a license for the AIMMS software is acquired. AIMMS also allows for automated reading and writing of input and output data in Microsoft Excel. However, it has to be kept in mind that it requires knowledge of mathematical optimisation modelling and programming in case of desired changes in the model formulations. Therefore, another possibility is to look for more user-friendly software.

4. Make the production planning process more future-proof and efficient by documenting important decision-making factors, using recipe-dependent setup times in the schedules and improve schedules by focussing on optimal production sequences.

Currently, one planner is responsible for making the production planning for all production lines. This process is carried out manually and is mainly based on intuition and experience of this planner. This makes FrozenBakery dependent on this one person. We advise to pay more attention to documenting important planning decisions that are crucial in making good production plans, because a company should not be dependent on one person for doing this in a good way. Furthermore, we recommend FrozenBakery to use more precise recipe-dependent setup times in the production planning for two reasons: 1) this allows for better performance and bottleneck analyses in production in order to improve changeover activities and 2) it can serve as a validation step in the setup data matrices that show setup times between recipes. The better this setup data is validated, the more reliable the production schedules become. Analysis of structural differences in expected and realised setup times can provide insight in potential need for training of operators at specific machines, the need for second machines in order to speed up changeovers, or the need for preventive maintenance at specific parts of the production line. Finally, our result show possible improvements regarding costs when using the optimal sequence instead of a standardised natural sequence, therefore we recommend to conduct further research into potential additional restrictions in realistic sequences for weekly production schedules.

7.4 Further research

Based on the findings and relevant remarks gained in this research, we propose to do further research on a number of areas. Our first recommendation for further research concerns the demand side of the process. We recommend to conduct further research into:

1) Focus on ways to make sure that customer forecasts become more reliable. Better forecasts decrease the safety stock levels and thereby inventory levels and improve the certainty in the entire operational process. A possible way for improving the forecasts is to make the shift from monthly customer forecasts towards weekly customer forecasts.
2) Focus on classifying make-to-stock products based on importance and uncertainty in demand and production. We recommend to conduct further research into shifting highly uncertain products from make-to-stock to make-to-order and to make a sub classification between make-to-stock products. From conversations with different departments during our research, we find that future market needs include more variety in packaging and products and we also underpin this in our literature review. Increasing variety in packaging and products leads to a further increase in operational challenges so shifting highly uncertain products towards make-to-order production can assure the right balance between operational challenges and making sure the service level of 99.5% can be met. A sub classification between make-to-stock products imposes a better balance between keeping safety stocks for critical or valuable make-to-stock products and risking stockouts for less critical or valuable ones.

Furthermore, we recommend to do further research into improvement possibilities of the weekly production sequence in which FrozenBakery produces its products. Our research shows that based on our setup data, improvements of up to 28% can be made in weekly setup time when determining the weekly production sequence based on setup data compared to a standardised sequence. Further research into possible additional sequence restrictions is needed in order to support this improvement possibility.

Finally, we discuss in Section 7.2 that we use average hourly rates for production but that in reality the hourly rate depends on the number of employees needed per recipe and on the shift that the corresponding recipe is produced in. We suggest further research into the impact of this on the weekly production sequence. We note that the sequence determination problem is comparable to the Traveling Salesman Problem and is hard to solve to optimality for large problem instances. We find from our model comparisons in Chapter 4 that our MILP-based SLSM model, which determines the timing of production, the production quantity and production sequence, is not able to find the optimal solution within 8 hours of computation time. Therefore, we advise further research into heuristic procedures for exploring the impact that the recipe-specific labour rates and day-night shifts have on the production sequence.

APPENDIX A – SD MODEL FORMULATIONS

Table A.1: Sequence Determination (SD) model formulations

SD model		
Sets		
k, m	Recipe with k, m = 1,…,K	
Parameters		
st_{km}	Setup time when changing over from recipe k to m	
Variables		
CH_{km}	Binary change-over variable that indicates whether a changeover occurs between recipe k and m	
F_k	Binary variable indicating whether recipe k is the first recipe to produce	
L_k	Binary variable indicating whether recipe k is the last recipe to produce	
V_k	Auxiliary variable that assigns the order of production	
Objective		
	$\min \sum_k \sum_m CH_{km} \cdot st_{km}$	
Subject to		
1)	$\sum_k CH_{km} \leq 1$	$\forall\, m$
2)	$\sum_m CH_{km} \leq 1$	$\forall\, k$
3)	$\sum_k \sum_m CH_{km} = (K-1)$	
4)	$\sum_k F_k = 1$	
5)	$F_k + \sum_m CH_{mk} = L_k + \sum_m CH_{km}$	$\forall\, k$
6)	$V_k + K \cdot CH_{km} - (K-1) - K \cdot F_k \leq V_m$	$\forall\, k, m,\ k <> m$
7)	$CH_{km}, F_k, L_k \in \{0,1\}, V_k \geq 0$	$\forall\, k, m$

The first two constraints 1) and 2) prevent that a recipe is occurring more than once in the sequence. Constraints 3) make sure that the number of setups that take place is equal to the number of recipes – 1. There can only be one recipe that is first in the sequence, this is assured by constraint 4). Constraints 5) make sure that there is only one 'sequence-tour' that contains all recipes and constraints 6) make sure that the auxiliary variable V_k gets the right value in order to minimise the total setup time in combination with the objective function. Constraints 5) and 6) are reprinted from literature of the Capacitated Lotsizing Problem with Sequence-Dependent Setups (Almada-Lobo et al., 2007). Constraints 7) again form the basic domain constraints for every variable in our mathematical model.

APPENDIX B - AIMMS PROCEDURE

We show the AIMMS procedure for determining the maximum inventory levels for an SKU. In case of MTO products, the maximum inventory level equals the total demand during the planning horizon and is rounded up to the nearest full batch run quantity. For example, if current inventory is 0, total demand during planning horizon equals 1000 boxes and one batch run of 8 hours produces 800 boxes, the maximum inventory level is 1600 boxes. Because at least 2 batch runs of 8 hours are needed for producing the total demand. In case of MTS products, the maximum inventory level is the predefined maximum inventory level that follows from our inventory control policy if demand is forecasted during the planning horizon. If no demand is forecasted, it holds for both MTO and MTS products that the maximum inventory level equals the initial inventory that is input to the model. This makes sure that no products are produced in the planning horizon if no demand is forecasted.

```
if IsMTS(u) = 0 then
       if SumOfDemand(u) > 0 then
              (ceil((SumOfDemand(u)/NumberOfBoxesPerBatch(u)))
*NumberOfBoxesPerBatch(u)) + InitInvLevelScenario(u,'SCFB-NCMMI-FS')
       else InitInvLevelScenario(u,'SCFB-NCMMI-FS')
       endif
elseif IsMTS(u) = 1 then
       if SumOfDemand(u) > 0 then
              MaxInventoryLevel_FB_NCMMI(u)
       else InitInvLevelScenario(u,'SCFB-NCMMI-FS')
       endif
endif;
```

APPENDIX C – ANALYSIS OF FC SCENARIOS

We do an initial performance analysis of the all scenarios and we find that the Full Capacity (FC) scenarios are not able to create proper production schedules, because we force these scenarios to use all available weekly capacity by purpose. First, we find that the inventory level of the FC scenarios increase over time, as can be seen in Figure C.1. This is not desirable, because inventory has the purpose to protect against uncertainties in supply and demand. We repeat that uncertainty in demand is present, but not increasing over time. Therefore, inventory should not either. In order to find out why the Full Capacity (FC) scenarios show an increasing inventory level, we analyse the capacity usage of the scenarios and we analyse the production schedules that the model creates under the restrictions set in the FC scenarios compared to the scenarios that only use Needed Capacity (NC).

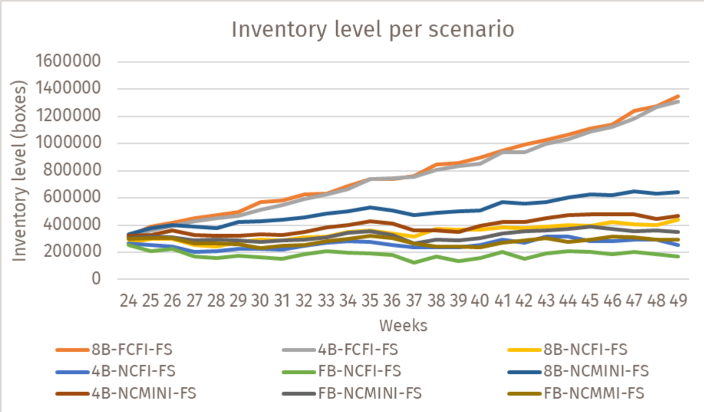

Figure C.1: Inventory level over time per scenario

We find from Figure C.2 that the average weekly used capacity (average over 26 weeks) in both FC scenarios (8B and 4B) is higher compared to the NC scenarios. We repeat that we force the FC scenarios to use all available capacity in a week. In case it turns out that demand can be fulfilled by only using 80% of the production capacity, the remaining 20% is used for production of products that are not needed for demand. Therefore, we further investigate what the model does in these cases.

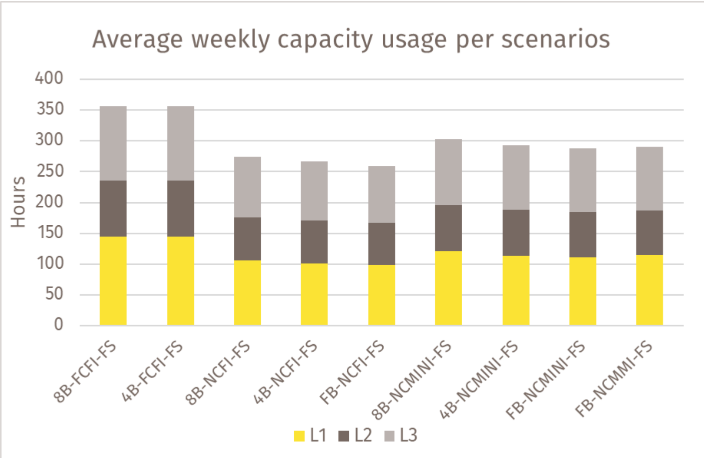

Figure C.2: Average weekly capacity usage

Furthermore, we look into the production schedules that the mathematical optimisation model creates for the FC scenarios to better understand the increase in inventory level. For every production line, we look into the difference between the expected demand (input to the model) and the production quantity (output to the model) over the 26 weeks. For every production line, we note 1 SKU for which much more is produced than demanded. We summarise this in Table C. 1. We compare this with the hourly inventory holding costs that are incurred when producing these SKUs. The hourly inventory holding costs are calculated by multiplying the inventory holding costs per box with the number of boxes that the production line produces per hour. We conclude that the SKUs for Line 2 and 3 correspond to the cheapest hourly inventory costs. For Line 1, there is 1 MTO SKU that is cheaper, but our restriction (explained in Section 6.1.4) prevents over-production of MTO products, therefore SKU 89060 is the cheapest MTS product that is allowed to be produced. We can conclude from this that the model always chooses the products that are cheapest in terms of hourly inventory costs. This is a logical consequence of the method that we have chosen to create the production schedules, namely creating production schedules based on minimisation of costs, but leads to poor production schedules.

Table C. 1: Over-production of cheapest SKU per production line

	SKU	**Total prod. Qty (boxes)**	**Total exp. Demand (boxes)**	**Difference (boxes)**	**Hourly inventory costs**
Line 1	*89060*	428,030	82,932	345,099	€18.10 (range € 17.05 - € 321.55)
Line 2	*86215*	139,844	65,752	74,092	€12.69 (range € 12.69 - € 48.60)
Line 3	*81539*	379,068	4,177	374,891	€16.31 (range € 16.31 – € 234.90)

The FC scenarios are forced to use all capacity and from Figure C.2 we conclude that the NC scenarios need less capacity to fulfil demand. The over-capacity of the FC scenarios is filled with the production of the SKUs with the cheapest hourly inventory costs. This leads to unrealistic production schedules that would never be executed at FrozenBakery. We therefore conclude that using a mathematical model that creates schedules based on minimisation of costs in combination with the restriction to always use all available capacity, is not a proper combination and does not lead to proper schedules. We therefore decide to not further investigate the FC scenarios. All other scenarios (NC) do not have the restriction to always use all available capacity and therefore do not show such differences between total production quantity and total expected demand.

APPENDIX D - SERVICE LEVEL CALCULATIONS

We elaborate on a comparison between calculation methods for the service level and we evaluate the impact that the value that is set as goal for the service level has on safety stock calculations.

Comparison between calculation methods for the service level

We compare two methods that we used for determining the service level in Table D. 1. The first method is by using the cycle service level and the second method uses the fill rate. Based on an example with historical average demand data of week 24 until week 29, we work out what the impact is of using these different methods on the safety stock calculations.

Table D. 1: Calculation methods for service levels

<table>
<tr><td colspan="2">Input data (based on demand data – averages from week 24 until week 29)
Reorder point $ROP = TRP \cdot d_u^{AVG} + ss = 0.5 \cdot d_u^{AVG} + SF(99.5\%) * \sigma_u^F * \sqrt{0.5}$ (see Section 5.3.1)
Replenishment time = 0.5 week
Average demand during replenishment time D_L = $0.5 \cdot 858 = 429\ boxes$
Average standard deviation of forecast error during replenishment time σ_L = $\sqrt{0.5} \cdot 560 = 395\ boxes$</td></tr>
<tr><td>Cycle service level calculation
$$\boldsymbol{CSL = F(ROP, D_L, \sigma_L) = F_s(z)}$$
Control calculation:
$ROP = 0.5 \cdot 858 + 2.57 * 560 * \sqrt{0.5} = 1446\ boxes$
$CSL = F\left\{\frac{ROP - D_L}{\sigma_L}, 0{,}1\right\} = F\left\{\frac{1446 - 429}{395}, 0{,}1\right\} = 0.995$

For CSL = 99.5% → z = 2.57</td><td>Fill rate (with lost sales) calculation
$$\boldsymbol{FR = 1 - \frac{\sigma_L \cdot G(z)}{D_L + \sigma_L \cdot G(z)} \rightarrow G(z) = \frac{(1 - FR)D_L}{FR \cdot \sigma_L}}$$
Calculation:
$$G(z) = \frac{(1 - 0.995) \cdot 429}{0.995 \cdot 395} = 0.00546 \rightarrow z \approx 2.13$$

For FR = 99.5% → z ≈ 2.13</td></tr>
<tr><td colspan="2">Effect on safety stock
According to CSL calculation method: $safety\ stock = 2.57 * 560 * \sqrt{0.5} = 1017\ boxes$
According to FR calculation method: $safety\ stock = 2.13 * 560 * \sqrt{0.5} = 844\ boxes$
Difference = 1017 – 844 = 173 boxes</td></tr>
</table>

Silver, Pyke, and Thomas (2016) show that the difference between the z value for CSL and FR depends on the ratio between the replenishment quantity (in our example D_L) and σ_L. The difference becomes large if the replenishment quantity is large compared to σ_L. In the example depicted in Table D. 1, we find that the ratio equals 1.09 (429/395 = 1.09). When re-calculating the safety stocks by using the fill rate, we find that the required safety stock equals on average 1017 boxes when using CSL compared to 844 boxes when using FR. In conclusion, when using FR in the calculation method for the safety stocks, the inventory levels would turn out a bit lower.

Impact of value of service level on safety stocks

In addition to the calculations made in Section 8.4.1, we elaborate further on the impact that the goal value of service level has on the calculation of safety stocks in Table D. 2. See Section 5.3.1 for explanations of symbols and abbreviations.

Table D. 2: Current and realised goal for service level at FrozenBakery

Current goal for service level: 99.5%	**Realised service level: 98%**
$Safety\ stock = SF(99.5\%) * \sigma_u^F * \sqrt{0.5}$ *(see section 5.3.1)*	$Safety\ stock = SF(98.0\%) * \sigma_u^F * \sqrt{0.5}$ *(see section 5.3.1)*
For CSL = 99.5% → z =2.57	For CSL = 98.0% → z =2.05
$Safety\ stock = 2.57 * 560 * \sqrt{0.5} = 1017\ boxes$	$Safety\ stock = 2.05 * 560 * \sqrt{0.5} = 811\ boxes$

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