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Faculty of Behavioural, Management & Social Sciences

Matching Input Stream to End Product with Production Restrictions

Improving Business Processes

Industrial Engineering & Management
-
Master Production & Logistics Management

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Preface

It is with great pleasure that I present this report, the result of my graduation project for my master's degree in Industrial Engineering and Management, with a specialization in Production and Logistics Management. The journey towards this moment has been filled with challenges, growth, and invaluable experiences, and I am thankful to have had the opportunity to pursue my passion in this field.

During my thesis, conducted at Morssinkhof-Rymoplast, I had the privilege of delving deep into the world of production and logistics management of the recycling industry and exploring the various aspects that contribute to successful operations. The project was a challenging and rewarding experience, and I am grateful for the guidance and support of my advisors and colleagues throughout the process.

Furthermore, I would like to express my gratitude to all the individuals who have played a role in my academic journey, from my teachers to my fellow students. Their contributions have not only helped me grow as a professional but also as an individual.

I would like to extend my appreciation to all those who have contributed to the successful completion of my thesis. Firstly, I would also like to thank Rik Eppingbroek and Lode Smeekens, for their insightful guidance and for sharing their experiences with me. Their feedback and support were instrumental in helping me to navigate the challenges and opportunities that arose during my research.

I would like to express my gratitude to Willie, Jarne, Stefan, and Eddie, for their invaluable assistance, and for sharing their expertise and knowledge with me. Their guidance was vital to the development of my thesis, and I am thankful for their contributions.

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I would also like to thank Mark Langenhof, for his introduction to the company, and for providing me with the necessary support throughout my research. Esther and Andre, also deserve my gratitude for their time and assistance, and for creating a welcoming and enjoyable work environment.

I am grateful to Morssinkhof-Rymoplast, for providing me with the opportunity to undertake this research, and for their support throughout the project.

Finally, I would like to extend my thanks to my family, friends, and housemates, who provided me with encouragement and support throughout my academic journey, in particular Frits, Max and David. Their unwavering support was an essential component of my success, and I am truly grateful for their contributions.

I hope this report serves as a useful resource for those interested in the field of production and logistics management. It is my sincerest hope that the knowledge and insights gained during my thesis will prove valuable to others, as it has for me.

Mart Nijkamp
May 2023

Management Summary

Conclusion

This thesis addresses the challenges faced by Rymoplast in supply chain scheduling in the recycling industry. The aim is to propose a more transparent and efficient method that considers the constraints on production, variability in supply and demand, and competing commercial interests towards customers and suppliers. The study develops a versatile and adaptable model that combines a supply chain scheduling problem with a blending problem, accommodating different configurations, economic situations, and input data. The model adheres to all set constraints and provides valuable insight into the impact of different policies and economic situations on the supply chain. Overall, the thesis offers a transparent and effective method for enhancing the efficiency of the supply chain scheduling process in the recycling industry.

Research objective and context

The company Rymoplast, part of Morssinkhof-Rymoplast company group, is a recycling company that processes plastic waste and turns it into regranulate. In the production process, the input materials are homogenised, shredded, washed, mixed and remelted to turn waste into a new usable end product. The company depends on a steady supply of materials that meet the required quality standards, to ensure a consistent outflow of products to their customers. However, this is endangered by the nature of the recycling industry, as it is known for the variability in both quality and quantity in supply of input materials, as waste cannot be made to order. In practice, the company experiences bull whip effects which exert pressure on the relationships with their suppliers.

The objective of this thesis is to provide Rymoplast insight into the general scheduling process, in which the sales, purchase and production capacity schedule are constructed. The scheduling process needs improvement in terms of transparency and effectiveness. The company is currently missing a structured approach, and relies on intuition, experience and knowledge of the managers, which is prone to risk of harm in case a manager drops out. Therefore, the research question of this thesis is:

> *How can Rymoplast improve their purchase and sales schedule, given restrictions on production capacity, while keeping in mind the commercial interest, cost-effectiveness and variability?*

In the general schedule, which combines the sales, purchasing and production schedule, the movements of input material quantities from suppliers to the factories are detailed for purchasing, and the movements of end product quantities from the factories to the customers are detailed for sales. These movements influence the production decisions for Rymoplast's factories and are limited by their production and storage capacity. The purchasers aim to purchase sufficient input material of sufficient quality and quality, and the sales manager aims to sell all scheduled freights. Both keep the commercial interest and cost-effectiveness in mind.

Methods

The solution has to consider a supply chain constructsscheduling approach that includes multiple factories, which are fed by multiple suppliers, and send theoir end product to multiple customer locations. Additionally, the production facilities of the company have to be modelled accordingly, keeping in mind the various production restrictions.

To find a suitable solution to fit the supply chain scheduling problem, various methods to manage or schedule supply chains from the literature are analysed, such as the supplier selection problems, capacity allocation problems, supply chain planning problems and blending problems. As found in

the literature, mathematical programming techniques, such as mixed integer linear programming, have been commonly used to develop suitable models for these scheduling problems.

As the supply chain of Rymoplast is subject to variability and uncertainty, various strategies are considered to incorporate these factors into the model. One of these strategy is the Rolling Horizon Strategy, which takes into account the distant future to mitigate short-term margins and maximize long-term margins. We also consider other strategies to solve the model within an acceptable amount of time, given that the problem is considered NP-hard.

The selected MILP supply chain scheduling model maximizes long-term performance and is able to handle multiple factories and suppliers, as required by the company. Integrating sales, purchase, and production planning improves the margin between purchasing and sales revenue, but it also increases complexity. The supply chain scheduling model is the most suitable for Rymoplast's internal supply chain as it covers transportation between suppliers, factories, and customers and incorporates a blending problem that models the production lines.

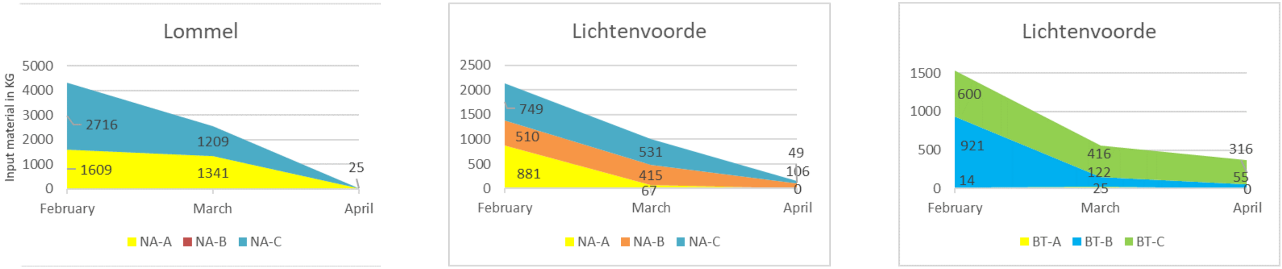
Due to a lack of data, the extraction of necessary probability distributions for uncertainties in the supply chain was unfeasible. To address this, a Rolling Horizon Strategy is used to incorporate uncertainty in the model without requiring a known probability distribution, as is the case with approaches e.g. stochastic programming. A second measure is the Chance Constraint Programming, which helps make the model robust against uncertain events by allowing decision-makers to choose different risk profiles. Both approaches are necessary to mitigate uncertainty and ensure the production of sufficient end products to satisfy customers.

A dataset described the base situation to initially test the model and provide the decision-makers with results in order to validate the model. The base situation represents the current situation and incorporates all their current customers, supplier and factories. If decision-makers decide to so, they can use the data set to implement the model immediately into their scheduling process.

To demonstrate the functionality and efficacy and further validate the model, a sensitivity analysis is performed to measure the effect of parameter modification on the model's outcome. These situations provide insight in the impact on the company's performance. The first situation aims to maintain good relationships with its suppliers by implementing a minimum supply quantity policy for its "regular" suppliers. The second situation explores the effect of a decrease in sales on the company's overall performance. The third situation pertains to a situation where the company cannot find adequate tonnage of input material in the market.

Results

The objective value of the base scenario yields a margin of €6,412,584. The sales revenue amounts to €14,471,400, the costs of purchasing and transport are €7,679,907 and €378,907, respectively. The sales results show that the maximum amount of end product Rymo22 is sold, as it has the biggest margin between sales revenue and purchasing costs, while the dark-coloured Rymo51 and Rymo81 remain close to its minimum sellable volume. In the production results, the mixture of input material gives a resulting Melt Flow Index (MFI) at the maximum of the end product specifications, as this gives the lowest purchasing costs. Most notable in the purchasing results, is the maximum amount of input materials available is purchased in the beginning months, as shown in Figure 1, as the purchasing price is increasing towards the final months as shown in Figure 16.



(a) Lommel **(b)** Lichtenvoorde **(c)** Lichtenvoorde

Figure 1: The inflow of input material

The results of the minimum supply-situation gives a more stable supply of input material over the whole planning period with only a minor decrease of 5% for the top 20 suppliers and 10% for top 10 in objective value, as expected.

The second situation, the lowered maximum demand situation shows most notably for the 50% case that less end product is sold and consequently less input material is purchased, and also a decrease in used production capacity is observed, as expected. As a consequence, the objective value decreases with 2% and 26% for the 75% and 50% situations, respectively.

The effects of the insufficient input material available-situation is most notable when there is insufficient naturel input material available, where a low availability of naturel input material consequently decreases the end product production, which is as expected. Since the supply of naturel input material is at its maximum, more bont end products are sold.

Recommendations and further research

The success of the model depends on a large volume of specific and constantly changing data, and it is recommended to regularly update the scheduling and follow clear guidelines and manuals for data maintenance. An automated workflow helps to mitigate the impact of data errors. Maintaining a healthy and collaborative relationship with the primary supplier of the company's essential material is crucial, and the company can implement policies to ensure a stable and reliable supply, such as prioritizing regular and consistent supply and incorporating a minimum supply requirement into their business model, as can be outlined in a contractual agreement.

Contents

Glossary

APP	Aggregate Production Planning.
CCP	Chance Constraint Programming.
CE	circular economy.
commercial interest	The commercial interest represents the interest of stakeholders, such as suppliers and customers, that play a role in the planning process..
cost-effectiveness	The cost-effectiveness gives the best economic option compared to the relative costs..
decision support tool	Tool which helps to make a better and faster decision..
end product	The final product that is sent to the customer thus leaving the process of Rymoplast. This can be regranulates or compounds..
GA	Genetic Algorithm.
gel	Small hard seeds found in the end product, formed during the extruding process.
general schedule	The definition is mentioned in Chapter 1.2.1..
general scheduling process	The definition is mentioned in Chapter 1.2..
GRSC	lobal Reverse Supply Chain.
HDPE	high-density polyethylene.
ICT	information and communication technology.
input material	The raw material from suppliers, before it enters the process of Rymoplast. This concerns LDPE end-of-life foils and f bales, which can come from different suppliers and differ in type, volume and quality. In addition, it can also be additives, such as colouring or moist absorber..
input stream	The supply of input material used in the process of Rymoplast. This can come from different suppliers..

KPI	Abbreviation for Key Performance Indicator, variables that monitor the performance of a company.
KPIs	Key Performance Indicator.
LDPE	low-density polyethylene.
MFI	MFI or melt flow index is a measure of the ease of flow of the melt of a thermoplastic polymer..
MP	mathematical programming.
MPS	master production schedule.
MPSM	managerial Problem Solving Method.
OTIF	on Time in Full.
PET	polyethylene terephthalate.
PH	planning horizon.
post-consumer recycled waste	The waste that is collected, after it has been disgarded by the end user. plural.
post-industrial waste	The definition is mentioned in Section 2.1..
PP	polypropylene.
recipe	A description of the input materials and their proportions necessary to create a standardized end product. The aim of following a recipe is to produce the final product consistently, adhering to the specifications, while ensuring cost-effectiveness and maintaining a satisfactory quality level. For example, to produce an transparent end product, the input material has to be transparent. Vice versa for translucent and bont end products..
RHS	Rolling Horizon Strategy.
RL	reverse logistics.
rLDPE	LPDE recyclate made up from end-of-life LDPE.
RO	Robust optimisation.
RP	re-planning periodicity.
SA	sensitivity analysis.
SAA	Sample average approximation.
SCSM	supply chain scheduling model.
SP	Stochastic programming.
yield	The weight of plastic waste bale left after it has been processed. This is calculated by dividing the total produced output, by weight of the waste bale..

1 Introduction and motivation

This research is conducted as a graduation thesis for the master Industrial Engineering and Management for Rymoplast, part of Morssinkhof-Rymoplast. In this research, the aim is to improve the current scheduling process, which involves the purchase, sales and production in terms of transparency and effectiveness, while taking the production restrictions in mind.

To start off, the chapter begins with an introduction to the company in Section 1.1. Section 1.2 provides an overview of the scheduling process and supply chain. Section 1.3 gives the problem statement, and Section 1.4 mentions the research objective and scope. Lastly, Section 1.5 mentions the solution approach with research questions.

1.1 Introduction to the company

The company group is one of Europe's largest producers of high-quality recovered raw materials and serves the European market, ranging from small companies to the world's largest multinationals in the plastics converting industry. Within Europe, they have eleven processing locations, which together process 400,000 tons of recycled material each year. They offer recyclates in the form of regrind, regranulate, and compounds. They also offer advice to companies and end consumers on the processing of plastic waste flows.

The company can be split into two separate companies. One company, Morssinkhof Plastics, focuses on recycling high-density polyethylene, polypropylene, and polyethylene terephthalate. Their recycled polyethylene terephthalate (PET) is, among other things, used in beverage bottles from various soda brands.

The other company, Rymoplast, focuses on recycling flexible plastics such as low-density polyethylene (LDPE). They provide, among other things, the regranulates for the production of refuse bags. The regranulates are an end product based on a "recipe". A recipe for an end product is used as a guideline to produce an specific end product from different input materials. An input material, vice versa, can be used for multiple end products. So each time the recipe may change depending on the availability of the input streams and the sold end products. A recipe aims to produce the same material as end product from the same input material in a costs-effective manner and that has a certain quality level.

1.2 The process

Rymoplast has three factories located in Lichtenvoorde, Lommel and Łubianka and in the near future in Markranstädt. The creation of the general schedule involves the companies purchasing, sales and production departments.

1.2.1 Schedule

The general schedule integrates the purchasing, sales, and production schedules, ensuring coordination and alignment among them, as depicted in Figure 2. The purchasing schedule specifies the quantities and type of input material to be purchased from each supplier and delivered to each factory, along with the corresponding timing. Likewise, the sales schedule outlines the quantities and type of end product to be delivered to each customer, indicating the supplying factory and the respective timing. Finally, the production schedule dictates the quantity and types of end products that have to be produced, the quantity and types of input materials. This is elaborated on in Chapter 2. The general schedule is made for all factories each month. The LDPE product manager is responsible for the general schedule and the coordination between the production leaders and the purchasers.

Good to note is the difference between planning and scheduling in this context. The scheduling of this supply chain involves the management of movement from suppliers to factories or from factories to customers, which covers a much shorter planning horizon. A supply chain planning on the other hand, determines the position of plants and their production capacity, thus covering a bigger planning horizon.

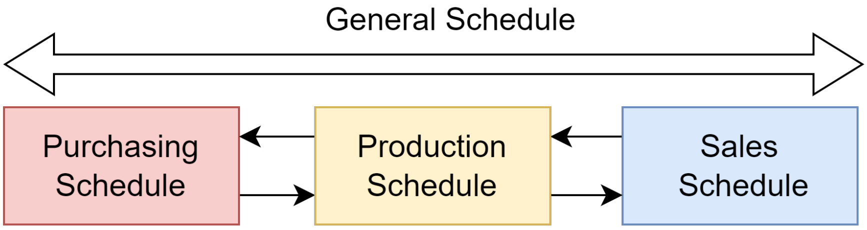


Figure 2: The general schedule and its component.

Firstly, the production managers determine the production capacity per production line for each factory, considering among other things, maintenance and improvements to the line, and the available staff. The aim is to keep the lines running 24 hours a day, 7 days a week. The purchasers predict the input they can acquire. Then the LDPE product manager, referred to in this thesis as sales manager, determines the quantity of end product they can sell. At the end, the production, sales, and purchase schedule are finalised such that they can be executed.

Rymoplast proposed to come up with a scheduling method that gives a structured and insightful overview of the process, that finds a good balance between the interests of the stakeholders, in this research referred to as commercial interest, and cost-effectiveness. The cost-effectiveness pays attention to the costs. The commercial interest involves all actions taken by Rymoplast that secure a consistent long-term input and output at minimum costs to satisfy the interest of the most important stakeholders in the supply chain, such as the customers, suppliers and purchasers, sales, production managers and board members of Rymoplast. Section 1.3 elaborates on this.

1.2.2 Schedule

Scope schedule The scope of the general schedule involves the purchase and sales schedule, while considering the production. The purchase schedule states which raw input materials to buy from which supplier. The sales schedule states the quantity of end product to sell to which customer. The production uses two schedules, the capacity planning schedule and the operational schedule. The capacity planning schedule is used as input for the sales and purchase schedule, and budgets for the number of production hours available and the amount of end product expected to produce. The capacity planning schedules are relevant to this thesis. The operational schedule is based on the sales and purchase schedule and indicates which production lines produce which end products and use which input material. This schedule is made weekly, and left out of the scope for this thesis.

1.2.3 Supply chain

The research focuses on the supply chain of Rymoplast. Section 2.2.1 gives an elaborate overview of the supply chain to give more insight, focusing on the production process. Figure 3 shows the generic supply chain for plastic waste, where Rymoplast is actor at stage 4. Rymoplast recycles the material that comes from sorters or trading companies and turns it into a recyclate that can be used by producers at stage 5 as input material for their product. The recycling facilities of Rymoplast aims to remove contamination left after the material is sorted, and remelts it into a usable product for the producers.

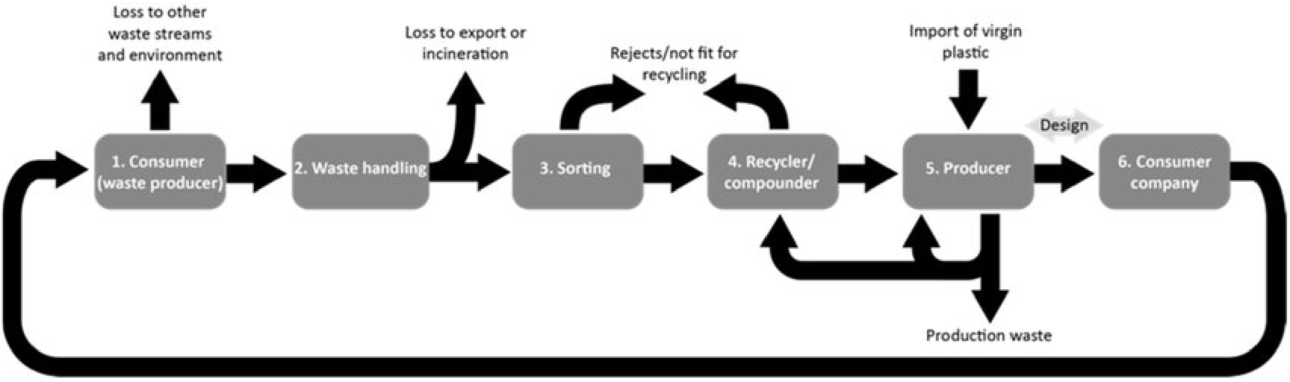


Figure 3: Graphic overview of supply value streams in plastic waste recycling. Waste handler collects the waste from the consumers. Sorting facilities pre-process the waste by separating it in different waste streams based on material type. Consumers (persons and companies) dispose the product after usage.

Only primary and secondary recycling is done by Rymoplast. Primary recycling recover pre-consumer or post-industrial recycled waste material and produces new products (Schwarz et al., 2021) and secondary recycling physically reprocesses post-consumer waste to produce new materials, also known as mechanical recycling.

Primary recycling is the most common approach for the recycling of plastic solid waste (Li et al., 2022). Both primary and secondary recycling involves mechanical recycling. Mechanical recycling consists of collecting, sorting, cleaning and drying, shredding, colouring, extruding and manufacturing a certain end product. Primary recycling maintains the plastic's properties, whereas secondary recycling degrades the properties (Li et al., 2022).

1.3 Problem description

This section gives an overview of the problems experienced by the company. Figure Appendix 4 represents the cause-and-effect analysis and gives the relations between problems, and is used to find the relationship between the problems and ultimately identify a single core problem. The information was gathered using interviews with the managers involved in the process.

Currently, the scheduling process is coordinated by one sales manager, in collaboration with the purchasing and production managers. The scheduling process relies on the knowledge, experience, and intuition of the managers to deal with the variability of the reycling market. If a manager were to drop out, then the scheduling process could get a setback in knowledge and effectiveness. This is considered a risk of harm for the company.

The overview and structure of the general scheduling process is in parts unknown to the company, because there is no fixed scheduling method. This is indicated as the main core problem. The company has an influence on this problem and is considered the most important problem.

The sales orders are put in by the customers, one week before the start of the month for the following month. The company finalises the schedule and thus the orders to produce, based on the maximum amount of production capacity available. The company anticipates that the planned freights will be accepted. In reality, it is possible that customers refuse a freight due to quality concerns. This creates additional end products that has to be produced in the same month, while the production capacity is already at its maximum. As a result, the already planned order for that month are delayed and moved to a later date. This consequently puts pressure on the production crew and the production capacity.

The scheduling method lacks indicators to monitor the process, so the other managers cannot be informed properly, making the process less transparent. Secondly, a lack of indicators makes it hard to monitor the strategy and effects of decisions.

1.3.1 The recycling industry

For the sake of completeness, we broaden the scope of the problem context to reach beyond the scope of the company to also include the customers and suppliers of Rymoplast. This helps to understand the whole problem context and the challenges that the company faces, but is not necessary to understand the core problem.

The recycling industry is known for its variability. The supply of input has variable volumes and qualities. The main challenge lies in creating the same end product of a sufficient quality and quantity on a continuous basis, with an unstable supply in quality and quantity of input material. Next to that, the production process contains variability which is often due to technical difficulty, for example a production line that needs unplannend maintenance.

The key insight is that waste cannot be made to order. A recycling company is dependent on the supply of (recyclable) waste as input material. The amount of waste supplied cannot be increased on demand. The input material has to be bought when it is available. Consequently, the number of recycled products that can be manufactured and sold is limited. This is different from the regular processing industry, where supply can increase to match the demand. For example, more or less oil can be extracted from oil wells, to meet the demand. Waste creation is a side effect of consuming products, so an increase in supply of waste is not a consequence of an increase in demand for waste. An unstable supply of plastic waste in quality and quantity is one of the main factors for a plastic recycling initiative to fail (Qureshi et al., 2020). The company places customer demand as the leading factor in determining the end products they aim to produce. However, the main bottleneck and basis for sales lies in the purchasing process, as the production of end products depends on the available quality and quantity of input material. Therefore, the company is both sales and purchase-driven, which is a characteristic of the recycling industry.

The company also has a commercial interest. Trading plays a role in the recycling supply chain context, especially during the purchasing process. The suppliers know the need of the company. Vice versa, the purchasers know by experience the quality and quantity the supplier will offer and deliver. Suppliers benefit more from a steady and consistent purchase by their customers, thus are more willing to deliver a constant quality in order to satisfy the company. Vice versa, the manufacturer benefits from a constant quality of input material, in order to produce a constant quality end product. This is done by steadily and consistently purchasing from the suppliers. This results in purchasing input material, even though there is no end product in which the input material can be used. Therefore, both parties have a commercial interest to makes sure those relations are good.

This trading mentality helps to deal with the uncertainty in input material supply and ensures to a certain degree a consistent output of end products by a consistent input of input streams. Consequently, a consistent delivery to customers is ensured. This is expected by the customers to a certain degree.

In this thesis, a distinction between regular and non-regular suppliers is made. Generally, regular suppliers are those who provide the necessary quality and quantity to produce the required end products on a regular basis. As such, the company has a comercial interest in maintaining healthy relationsships with these suppliers. Non-regular suppliers deliver occasionally and are not considered essential to provide the adequate input material.

The price in relation to the quantity and quality of input material depends on the market situation. In a tight market, meaning the demand for input material is high and supply of input material is limited, there is little room to negotiate about the price. If the company were to lose an input stream, because the price was too low, then they would not be able to produce an end product, consequently unable to meet the customers' demand. Vice versa, in a large market, meaning the demand for input material is lower and the supply remains similar, there is more room to negotiate a lower price, as the company is able to source a different input stream to produce their end product.

Next to that, the timing and duration at which the export market close is unpredictable. Waste production of input material continues, while the level of demand remains similar. This has an impact

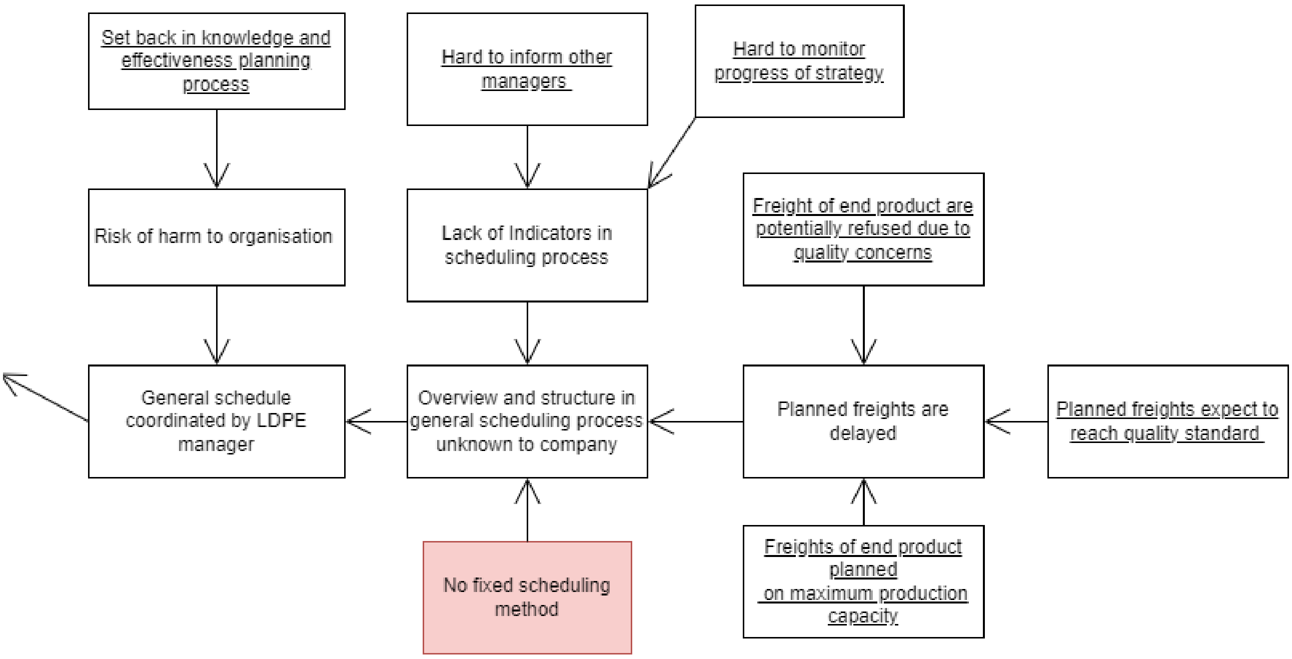


Figure 4: Partial cause-and-effect analysis diagram

on the price, providing a temporary opportunity for the Rymoplast purchasers to buy more input materials at a lower price, that would normally be sent to export.

The supplier also has commercial interest. The supplier reduces the dependency on recyclers to consistently purchase an input material by distributing their material among suppliers. So if the recycler wants to get all the good and desirable qualities input material, the recycler also has to take the bad and undesirable qualities input material.

These insights underline the importance of relations, knowledge, experience, and intuition of the managers to deal with these situations.

1.3.2 Cause-and-effect analysis diagram

To understand the relationship between the different problems previously mentioned, a cause-and-effect analysis is used. A cause-and-effect in Figure 4, is a tool to identify the causal relations between the problems mentioned earlier. This helps to identify the core problem and to pick the most important one. The full cause-and-effect diagram is mentioned in the appendix in Figure 43. The managerial Problem Solving Method (MPSM) (Heerkens & van Winden, 2012a) is used for identifying and choosing the potential core problem. The diagram is used to identify multiple core problems. One core problem is highlighted in red: There is no fixed scheduling method. This is indicated as a core problem for several reasons. Firstly, the problem can be influenced by the company. Secondly, it has no causes of its own and lastly, it is considered the most important problem by the company.

From the problem description, the research problem follows:

"The scheduling process is non-standardised and relies on intuition, experience, and knowledge of the managers, which makes it prone to risk of harm in case a manager drops out."

1.4 Research objective and scope

In the following section, the research scope and objective are discussed.

1.4.1 Scope

The research scope is on the supply chain of Rymoplast that is limited to the supply of input material from all current suppliers, recycling of waste, and the delivery of end product to all current customers, as mentioned in Section 1.2.3. The factories in Lichtenvoorde in the Netherlands, Lommel in Belgium and Markranstädt in Germany are included. Of those factories, only the production lines that process wash-quality post-consumer (PCW) input material are included, and the production lines that process non-wash quality post-consumer and post-production waste (PPW) are excluded. The difference is elaborated on in Section 2.1. Markranstädt is included, even though it is not operational at time of writing. The factory in Poland does not process wash-quality post-consumer input material and is therefore excluded.

The scope involves the general scheduling process that includes the production capacity, purchase and sales scheduling process. The operational production schedule is based on these. The decisions taken in the schedule process are on an operational level. Operational-level decision include the purchase, sales schedule and production. The purchase schedule contains which raw input materials to buy from which supplier. The sales schedule contains which end product to sell to which customer. The production capacity schedule accounts the amount of production capacity available on which production lines produce for a certain end products. The operational production schedule is left outside the scope.

Strategical and tactical decision are excluded. Strategical decision include e.g. configuration of production lines placements of the factories. Tactical decision include e.g. the sales and purchase decisions. These are left for future research, for which this research can serve as a base. Next to that, the forecasting of input material and end product are excluded. They are considered given input for the solution.

1.4.2 Objective

The objective it to provide Rymoplast insight into the whole general scheduling process, containing the sales, purchase and production capacity schedule. Therefore, the schedule method needs to be more transparent and give a better overview of the steps involved to make a general schedule, which is elaborated on in Chapter 2 and described in Figure 9. The company maintains the knowledge used and needed to make the general schedule effective, in the case the manager drops out for unforeseen reasons. In this process, knowledge, experience and intuition of the manager is key, due to variability in the recycling supply chain. There is a need within the company for a new scheduling process that gives a better overview of the planning process compared to the current method. The method matches each input material with an end product and production line, while maintaining the commercial interest of the company, dealing with the restrictions on the production process, the variability in the input material, while being cost-effective.

In order to understand the problems in the scheduling process, the current situation including its Key Performance Indicator (KPIs) is described. To understand the underlying process of the schedule, the production process including input material and end product is also described.

Because of their interdependence, the purchasing, sales and production capacity schedule are taken into account. Purchasing depends on the suppliers for providing sufficient quantity and quality of input materials. The sales is dependent on purchasing, to deliver its customer the desired quality and quantity end product. The production is restrictive given its production capacity to process input material and produce the sold end product. In order to achieve the objective of this research, the literature is used to generated methods for a general scheduling process and their KPIs to solve and monitor the process. In advance a list of requirements is made. Recommendation on the methods are given to the managers of Rymoplast.

1.5 Problem approach

In order to solve the core problem, a strategy is discussed. It is used to solve the research problem described in Section 1.3. The Managerial Problem Solving Method (MPSM) (Heerkens & van Winden, 2012b) is used as the general framework and methodology to find the problem and the solution for the problem experienced by the company. In order to solve our research problem, the following main research question is formulated:

> *"How can Rymoplast improve their purchase and sales schedule, given restrictions on production capacity, while keeping in mind the commercial interest, cost-effectiveness and variability?"*

1.5.1 Research questions

We formulate sub-questions to solve the research problem. Each individual sub-question is elaborated further on using sub-questions.

Sub-question 1: What is the current general scheduling process and production process of Rymoplast? The goal of this question is to get an overview of the supply chain, which includes the production process, and the sales and purchasing process in the current situation, to get a good understanding of the problem context. Next to that, Firstly, an overview of the current scheduling method is made and the evaluation method e.g. KPIs, to get an understanding of the process and potential bottlenecks and dependencies. The information is gathered by interviewing the LDPE product manager, plant manager, production leaders, and purchasers about the production process and their scheduling method. The data is collected with the help of the ICT-department. This forms Chapter 2 of this thesis.

1.1 How does the current supply chain of Rymoplast look like?
    (a) How does the production process look like?
        i. What are the restrictions of the production process?
    (b) What are the inputs and outputs of the production process?
    (c) What are the characteristics of the input materials and the end products?

1.2 What does the current scheduling process look like?
    (a) How are the sales, purchasing and production capacity schedules, which are sub-parts of the scheduling process, made?
        i. How is the supply of input materials determined?
        ii. How is the demand for end products determined?
    (b) What are the restrictions of the scheduling process?

1.3 What data is available regarding the schedule and production process?
    (a) What KPIs are tracked?
    (b) Which KPIs are important to track for the company?
    (c) How are the KPIs determined?

Sub-question 2: What solutions found in the literature, be applied to solve the problem experienced by the company? The goal is to find a method or combination of methods that can be used to solve the main research question in the available literature. The relevant information gathered in sub-question 1 is used as input for sub-question 2. First off, the recycling supply chain has to be specified further in order to understand the problem context. Secondly, the models have to schedule a supply chain. To specify this further, a preference to the recycling supply chain's scheduling methods is given, which deal with the same challenges as mentioned in the problem context. Also mentioned in the problem context, the recycling industry deals with variability at several stages, so the schedule should be robust. Lastly, KPIs are researched to evaluate the effectiveness of the realised general schedule. This forms Chapter 3.

2.1 What are the characteristics of a recycling supply chain?

2.2 What models does the literature suggest regarding the scheduling of a supply chain?

   (a) What models are available regarding supply chain scheduling?
   (b) How can the models make a robust supply chain schedule?
   (c) What are the advantages and disadvantages of the models?

Sub-question 3: What solution from the solutions mentioned in Chapter 3 should Rymoplast opt for? The goal is to generate solutions and finally select a solution for Rymoplast to solve the research problem mentioned in Section 1.3, taking into account the company's requirements. This chapter describes the decision-making process, and the final decision for a solution. The selected solution is tested in Chapter 5. The models found in Chapter 3 are described and distinguished to simplify and clarify the decision-making. Important stakeholders in the supply chain, and more important the decision makers, are identified for the decision-making process towards a solution. The aim is that the solution is used by the decision makers of the scheduling process. In order to match the needs of the company with the found models, a set of requirements is made by the company. Here the KPIs used by the company identified in sub-question 1 and the KPIs found in the literature from sub-question 2 are compared, and discussed with the stakeholders to choose a solution. In order to identify the requirements for the model and identify the stakeholders, multiple interviews and meetings are held with the stakeholders. This forms Chapter 4.

1. What are relevant models to solve the research problem experienced by the company?
   (a) What are the requirements set by the company for a scheduling method?
   (b) How can the solutions be distinguished?
   (c) What models does the company have in mind?
2. Which KPIs do the company want to include in the model?

To come to a final solution, multiple meetings are held with the goal to answer the aforementioned questions and eventually select a solution.

Sub-question 4: How can the chosen solution be applied to solve the research questions? The chosen solution from the solutions mentioned in Chapter 3 is discussed into further detail in Chapter 4. Chapter 5 describes how the method should apply to the problem and the results. It also includes a method to validate and evaluate the schedule. This includes a description of the relevant input. Chapter 6 presents sensitivity analysis. Chapter 7 gives the conclusions, discussions, recommendations and suggestions for the company to do future research.

1.5.2 Deliverables

At the end of this research, the following will be delivered:

1. The model that acts as a decision support tool. The decision support tool gives advice on input material the company should buy.
2. Manual, containing information on the proper usage of the model and how to update the model. This also includes an approach on how to interpret the results.
3. This thesis report, with the problem-solving approach.

1.6 Conclusion

The research is conducted at Rymoplast in collaboration with the production, purchase and sales departments. The research problem is the following: “The scheduling process is non-standardised and relies on intuition, experience, and knowledge of the managers, which makes it prone to risk of harm in case the manager drops out.” The problem is caused by a lack of a fixed scheduling method. The company relies on the know-how of the managers, in order to deal with the variability throughout the supply chain. The scheduling method needs to be more transparent and give a better overview of the steps involved to make a general schedule. The main research question is: “How can Rymoplast improve their purchase and sales schedule, given restrictions on production capacity, while keeping in mind the commercial interest and variability?”. The research aims to answer the main research question, using sub-questions. This is done in five steps, by describing the current situation, doing a literature study, generating solutions, choosing and describing the solution, reflecting on the results and giving recommendations.

2 Current Situation

In this chapter research question 1 is answered: **"What is the current general scheduling process and production process of Rymoplast?"**, by describing the current situation at Rymoplast to understand the production process. It begins with the description of the input materials and the resulting end products. Thereafter, Section 2.2 gives a description of the production process. Section 2.3 gives a description of the scheduling process. Subsequent, Section 2.4 gives a description of the available KPIs and data. The chapter ends with a conclusion in Section 2.5.

2.1 Input material and end product

The input material concerns the material that arrives at Rymoplast coming from a supplier and is processed on the production lines. It arrives as LDPE plastic waste bales which are compressed pieces of waste foils. They can differ in quality and characteristics, which is elaborated later on. The characteristics of the input materials define the end products are made, and the end product defines the input materials that can be used. The mixture of different input materials is defined in a recipe, which assures that an end product is realised according to specifications. In order to understand the elements of the model defined in Chapter 4, such as the recipe and the characteristics of the input have to be understood.

2.1.1 LDPE

LDPE is the thermoplastic that is at the basis of both the input material and the end product and therefore mentioned seperatly. LDPE is short for low density polyethylene, which is moldable when heated and crystallised when cooled. During the crystallisation, the molecular chains align and the plastic gets its desired properties. Virgin plastic is defined as newly formed plastics, coming through polymerisation from mainly crude oil. RLDPE is reprocessed virgin plastics and recyclates. All recyclates started their life as virgin plastics.

Applications for LDPE are flexible packaging material, which Rymoplast mostly processes, such as plastic bags. The most known application for recycled LDPE or rLDPE is plastic waste bags. A downside of LDPE is that the strength of plastics deteriorates after recycling due to thermal degradation (Singh et al., 2017).

2.1.2 Input material

In this section, the characteristics of the input materials are described to understand the relation between the input material, the end product and recipe. Therefore, the different waste streams and characteristics such as colour, MFI and quality grade are described. These descriptions are input for the model which can be found in Chapter 5.

Post-consumer and post-commercial waste The input stream can be subcategorised in post-consumer recycled waste and post-industrial waste. The post-consumer recycled waste input streams originate from consumers at the end of a material stream originating from industry or agriculture at the end of a product lifecycle. The waste can for example be the foil wrapping soda bottles, being transported from the factory to the supermarket's distribution centre. The second post-consumer recycled waste input stream processed comes from agricultural waste. For example, the foil that is used to wrap hay bales. Agricultural waste considered to be heavily contaminated with organic materials, such as hay, stones and soil. This specific input stream is treated upfront by a sorter and upgraded until a quality standard is reached, such that it can be processed by a recycler such as Rymoplast.

Post-industrial waste, often referred to as pre-consumer waste, is outside of the thesis scope, but also processed at Rymoplast. This stream is inconsistent in quantity and for the long-term not the company's focus. This differs from the post-consumer recycled waste input stream, which is considered to be relatively stable. Therefore, the focus is on wash-quality post-consumer recycled waste. This waste contains a certain level of contamination, which has to be removed in the washing process before it can be processed.

Colour The visual property of the input material can be characterised in three groups, namely natural, pastel or bont, which is also refered to as mix-colour. This is visually assessed during the unloading and production, which is elaborated on in Section 2.2. The colour of the end product is determined by the colour of the input material. The colour of the input is used to create the required colour of the end product specified by the customer.

(a) (Waste bale natural **(b)** Waste bale pastel **(c)** Waste bale mix-colour

Figure 5: Example of a (a) natural, (b) pastel and (c) mix-colour waste bale

Melt Flow Index (MFI) The post-consumer recycled waste can also be divided in thick or thin material, or a mix of both. The thickness of the material can be related to the MFI (Melt Flow Index) of the input material. This mixture of input material is used to stear the MFI of the end product, which is a requirement of the customer. The MFI measures the speed at which the material flows in a liquid state, and is an industry adapted measure for thermoplastic polymers.

Quality grade A freight is often rejected due to the found contaminations. Each individual bale gets a grade of 1, 2 or 3. Grade 1 is considered to be the highest grade, thus least contaminated, and 3 the lowest grade, considered most contaminated. The quality grade is based on the freshness and the contaminations found. In this context, contaminations are items found in the input material, which prevent the production process from making the same end product as the input material and thus influence the quality of the end product. For example, in order to create a transparent rLDPE foil, LDPE foil waste is used as input materials. The quality assessment is discussed in Section 2.2

The recycling process can be disturbed by the following contaminations:

- **Foils made from different types of plastics:** depending on the material, a part is filtered out by the process. The other part remains in the process and creates gels during the extruding process. Gels form when different types of plastics cross-link with each other. Gels are hard spots in the foil.
- **Multilayered plastics and stickers:** foils that contain multiple layers of different materials or stickers from a different material, such as the potatoe chips bags containing an aluminium

inside and plastic outside. This clogs up the filters during the extruding process. Also the contamination could stick to the extruder screw. Both could decrease the production speed.

- **Surface contaminations such as sand, metals, wood and other organic material:** contaminations create pips in the end product, consequently have a negative effect on the yield and the draining costs, depending on the contamination. The filters could clog up, if the washing process was not effective. The contamination, mostly wood and other organic material, could also stick to the extruder screw, decreasing its production speed.

Yield These contaminations all have a negative effect on the yield of the production process. To be more specific, yield is the amount of end product divided by the total amount of input material used in production. For natural input material, this is typically around 90% and for bont input materials this is typically around 85%.

2.1.3 End product

The end product is created after mixing the input materials together using a recipe on the basis of colour and MFI, while being restricted by the contamination count, which is elaborated further on in this subsubsection. An example of a natural pellets can be found in Figure 6.

Figure 6: End product in the form of LDPE pellets. Shown in picture are natural pellets.

In this thesis, the end products Rymo21, RYmo22, Rymo81 and Rymo51 are under consideration. The end product depends on the customer specification and can be achieved using the input materials as ingredients for the recipe:

1. **Colour:**natural (such as the Rymo21 and Rymo22), pastel (Rymo51) or black (Rymo81).
2. **MFI:** range spans from a thick material, starting at a minimum thickness of 0.16, to a thin material, reaching approximately 1.2 in thickness.
3. **Contamination count:** the contamination in the end product are counted, for which maximum is set. This indicates the contamination remaining in the end product and has a negative effect on the mechanical properties. The contaminations can be divided in both pips and gels:

Name	Characteristic 1	Characteristic 2	Characteristic 3
Waste stream	Post-commercial	Post-Consumer: wash-quality or non wash-quality coming from agricultural waste or companies.	
Colour	Natural: transparent foil with little to no prints.	Pastel: mixture of different colours excluding black.	Mix-colour: mixture of different colours, including black.
MFI output	Thick MFI range: 0.2-0.35	Mix thin-thick MFI range: 0.3-0.5	Thin MFI range: 0.5-0.8
Quality grade	A: the highest grade	B: medium grade	C: lowest grade
Pellet colour	Transparent, light grey or light brown pellet	Dark brownish, blueish pellet	Black pellt
End product	Transparent foil	Blue or brown coloured foil	Black foil

Table 2: Overview of characteristic of plastic LDPE waste bales

(a) **Gels:** caused by different types of plastics in the input material.
(b) **Pips:** various impurities such as sand, wood or metals. These can often stick out from the pallet, such as a small piece of metal. Pips can cause problem in the production process of the customer.

The end product is checked during the production process, and rejected if one of the following is detected:

1. **Moisture content:** The pellets contain moisture, if the drying process was not sufficiently effective. This causes problems in the production process of the customer. This is checked by weighing the end product and measuring the volume. If the weight relative to the volume is too large, then it is rejected by Rymoplast.

2. **'Pofkorrel':** Too much gas or moisture contained in the pellet. The volume of the material is too large for the weight. The shape is recognisable in that it look like the pellet has exploded, thus given the name 'plofkorrel'. The shape could also be similar to a blood cell.

3. **Different colour:** The end product is checked to see if it matches the customer specification. For example, a small fraction of black foil in natural input material could cause the end product to become black.

4. **End product weight relative to material specific weight:** the end product is put in spiritus, to see the material specific weight, which gives an indication for the contamination amount.

To summarize this subsection, Table 2 is used to give an overview of the characteristics of the input and the output.

2.1.4 Recipe

The recipe is at the centre of the production process and matches the aforementioned input material to get the desired end product. The recipe is used as a tool for the production staff to get the right input material for a certain end product, such that it can be processed. It matches inputs to end products. The recipe has an influence on both the purchasing strategy and sales strategy.

A description of the input materials and their proportions is necessary to create a standardized end product. The aim of following a recipe is to produce the final product consistently, adhering to the specifications, while ensuring cost-effectiveness and maintaining a satisfactory quality level.

The operational recipes are made for production schedule, and are not accounted for during the purchasing process. However, the recipe influences the purchases and sales strategy and is therefore important. Mixing and blending is one of the modelling challenges and is an important aspect in the production process according to the company. Therefore the input material, end product and recipes are discussed. The quality of an end product is related to the quality of the input material. If an end product is rejected, then it is often due to low quality input material or a wrong recipe.

Depending on the customer specified end product, different input materials with different characteristics, as mentioned in Section 2.1 are mixed as shown in Figure 7. The desired MFI is achieved by mixing different thick and thin films together. The desired colour is achieved by mixing different colours. For example, to produce a transparent end product, the input material has to be transparent. Vice versa is true for translucent and bont end products. The desired quality is achieved by mixing different quality grades.

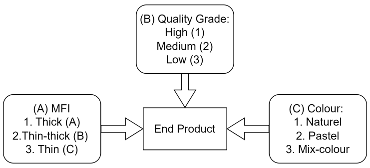


Figure 7: The three elements that create the desired end product, namely (a) MFI, (b) quality grade and (c) colour.

Theoretical and realised recipe Within the company there are two types of recipes, a theoretical recipe and a realised recipe for a certain end product. The theoretical recipe is the mixture of different qualities plastic waste bales that the production staff is supposed to aim for, and is known before the start of production. The realised recipe is the actual mixture of qualities and quantities that the production staff has put in the production process. The realised recipe is also depending on the market situation, whether the purchasers are able to find sufficient qualities. Therefore the recipes change over the course of time.

Good to note is that recipes are developed and improved throughout the year. They are based on the process capabilities of the factories and the developments in customer demand and feedback. Lastly, the company continuously experiments with the available input materials to improve the end product.

2.2 Production

This section gives a global overview of the production process of Rymoplast and is applicable to all production lines in the scope of this thesis. The aforementioned input material are processed and end product are produced here.

2.2.1 Production process

There are three factories, with each their own set of specialised production lines. The specialisation is based on their processing capabilities of a type of input material, and the desired end product. Lichtenvoorde (Netherlands), Lommel (Belgium) and Markranstädt (Germany) have production lines that are able to process wash-quality waste. Each factory works in 5 shift and produces 24 hours a day, 7 days a week. All production lines follow in big parts the same process, and only differ in configuration based on their specialisation. Therefore, a general description of the production line is given. The whole process is mentioned in Figure 8, including the suppliers and the customers.

The production lines contain extruders, use heat to melt and mix the LDPE input materials together to create the desired pellets. Before an extruder is fully operational, it has to reach a certain temperature. This is costly in both time and money, thus a continuous production is aimed for. Consequently, the companies maximises the production capacity during the production schedule. This characteristic makes the production capacity a limiting factor, as both a maximum and minimum.

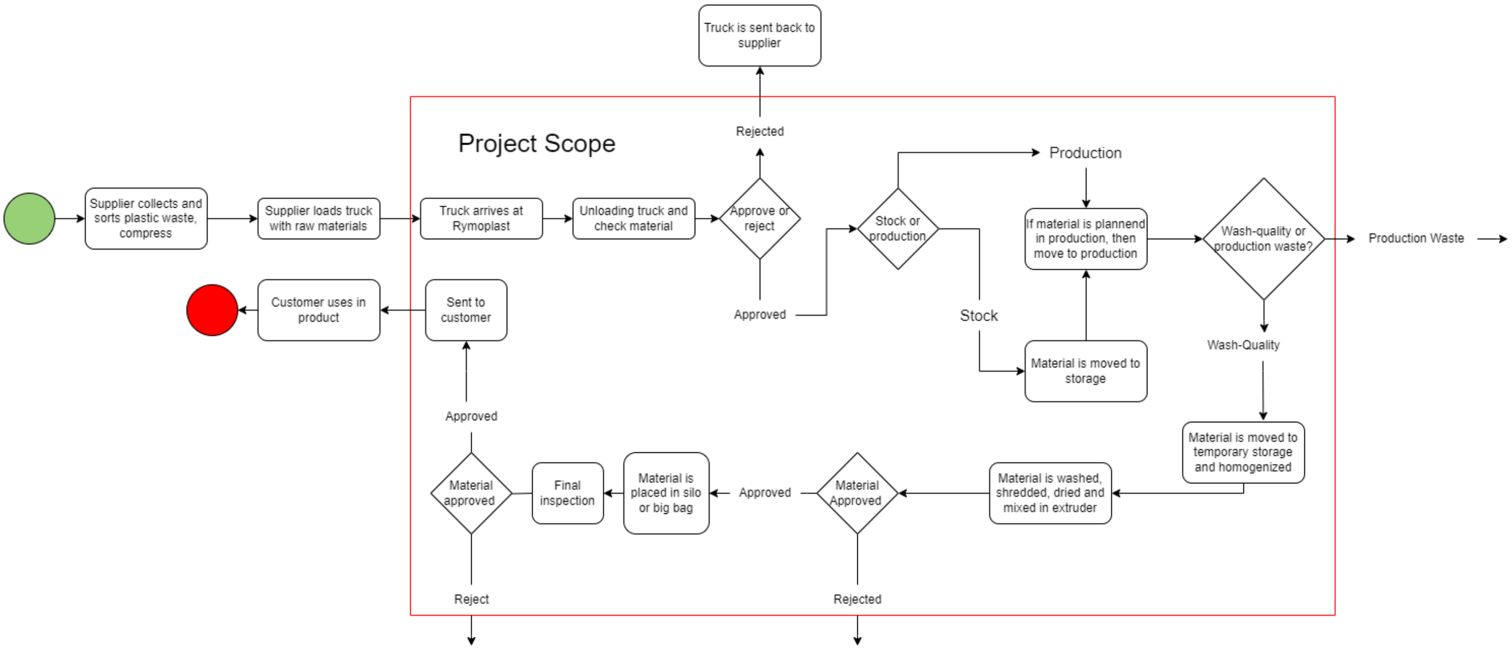


Figure 8: Supply chain of Rymoplast including production process, suppliers and customers

Unloading A truck delivers the input material. It is weighted, checked on quality, registered and if the material passes the inspection, it is approved. The truck is then unloaded, and the material is moved to storage. The input material is registered on origin, type of input material, weight and a quality grade. This is in an important step to assure a certain quality level of input material.

Homogenising area This is the start of the production process. The bales are moved out of storage or directly from the truck. The bales are dispersed and mixed to create a homogenised input. This helps to spread possible contaminations in the input materials and create a more homogenised quality end product. The bales are dispersed, which gives the operator the chance to look inside the bale to further assess its quality and sort out further contaminations.

Shredding, washing and drying The homogenised input material is put into the shredder, thus creating a bigger surface that can be reached by the water for an effective washing process. During the washing process, the material is soaked in water. Paddles mix the material, while the soap removes all kinds of pollution. The LDPE input material is less dense than water, so it floats on top. The fraction that is heavier than water sinks to the bottom, such as sand and metals.

Extruding The material is fed into the extruder, where is it heated and melted, mixed together and filtered. The filters remove the contamination left after the washing process. Contaminations e.g. non-LDPE thermoplastics, aluminium and rubber are filtered out. Due to the different melting temperature, pips and gels are created.

After the filtering, the material is cut into small pellets, and then cooled and dried. Optionally the pellet is degassed, which aims to remove the smell. Figure 6 shows a natural rLDPE end product.

Quality inspection There are quality checks at three stages in the process. The first inspection is after the extruder, where the material is checked both visually and on moisture content.

The approved material is moved to a silo or placed in a big bag. A sample is taken for the second quality inspection, where they check on MFI and on the gels and pips count. It is transported to the customer after it has been approved.

2.3 Scheduling process

The objective of the general schedule is to ensure that the sold end product is delivered to the customers, while taking cost-effectiveness and commercial interest in mind, and that the lines have to produce continuously. Purchasing, sales and production are an integral part of the general scheduling process. In Sections 2.3.1, 2.3.2, 2.3.3 and 2.3.4 more details regarding the sales, purchase and production schedule are given. All factories have their own purchasers and production managers. The process is centrally coordinated by the LDPE product manager.

2.3.1 General scheduling process

As shown in Figure 9, the general schedule starts with the production leader, who determines the production capacity per production line. After that, the purchaser determines the input material he needs for the end product and what they currently have in stock. Then the LDPE product manager determines the end products he can sell, taking into account the commercial interest and cost-effectiveness. The final check and adjustment are made to the amount of end product and input material by the purchasing manager and the plant manager, resulting in a schedule, which concerns the purchase and sales schedule. The production schedule is based on these. The purchasers are informed and start the purchasing process.

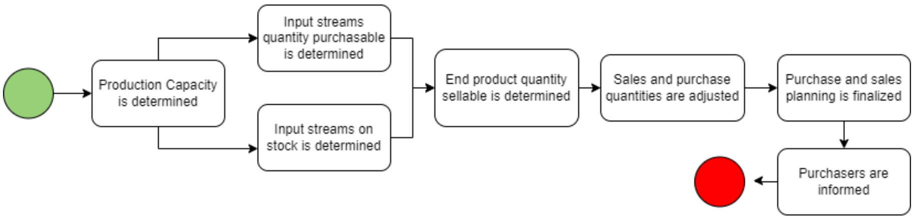


Figure 9: Flow Scheduling

2.3.2 Sales

First off, the sales process is introduced, which drives purchase and production. The objective for sales is to sell the end product with a degree of certainty to the customer. The LDPE product manager is responsible for sales and contact with the customers. The company distributes their end products among their customers based on their commercial interests. The demand is greater than the end product they can deliver, due to the constraint in available input material and production capacity. Therefore, sales is largely limited by the available input material.

There are two different sales approaches depending on the factory and produced end product. The first is used in Lommel (BE), where a large part of the expected end product is sold one year upfront. The remaining fraction is sold throughout the year, depending on the need of the customers.

The second is used in Lichtenvoorde, where the factory indicates the quantity of end product they can produce for the month. Propositions towards customers are made based on this. This happens a week upfront for the entire month.

The end products price is determined in three ways, depending on the agreements with the customer. First, the price combines a base price with a rLDPE price index from ICIS ("ICIS r-PE Index Report", n.d.). The price in- or decreases with the delta of this index. The other two ways entail quarterly or monthly negotiations. ICIS is an international platform that publishes market prices of virgin and recycled polyethylene.

2.3.3 Purchasing

Due to challenges in procuring an adequate quantity and quality of input materials, the purchasing process is often seen as a bottleneck for the sales department. The purchasers aim to address this issue by sourcing sufficient quality and quantity input material at a market conform price. The washing-quality input material is considered to be a relative stable input stream in quality and quantity.

Commercial interest The company considers their commercial interest by maintaining long-term relations with their regular suppliers and ensuring the desired quality and quantity of an input material, and consequently a continuous delivery of end products. This has created a relatively stable supply from the same input stream over the year. Depending on the situation, input material can also be transferred between locations.

The input materials are continuously offered to the purchaser, since the supplier knows the need. The company knows the amount of end products sold, so know the needed input material. A freight of input material is accepted for delivery depending on the current stock, the suppliers previously delivered input material, market demand for end product and the commercial interest. The purchasers know the quality of the incoming freight in advance. The first purchaser estimates the quality based on the previous delivered freights by a supplier. The other purchaser estimates the quality based on pictures, before purchasing. This is the main difference between the purchasers. The input material quality is assessed during unloading and during production, as mentioned earlier in Section 2.2.1. However, the purchasers also have to buy the lower, less desirable qualities, if they want to buy the higher quality input material from their suppliers and cannot solely cherry-pick the best freights.

The build up of inventory ensures there is sufficient input material available to continuously produce an end product and deliver to their customer, satisfying a commercial interest of the company. The company produces continuously with a limited storage capacity. If the supply were to halt, the storage could run empty, endangering the continuous delivery of an end product to the customers. The supply of a certain type and quality of input material is variable and depends on the market situation. This issue is more relevant for Lichtenvoorde than Lommel. At Lommel, the purchaser can react more to the market, since the production speed relative to available storage capacity is lower.

Input material price A price overview is determined for each type of LDPE waste bale, based on the current export prices, production margins, market index prices for input material, the current stock and the offers of input material by suppliers.

The price is set in two different ways. First, the price is set at the beginning of the month per quality and type of input material and sent to the suppliers. The final price for a delivery is set, after the quality of the whole freight has been assessed during unloading. The final price is agreed upon by the purchasers and suppliers, based on the delivered quality and the commercial interest of the company. A second way is that the price is agreed upon after it has been offered by the supplier and before the freight is delivered. Upon offering, a first visual quality check is made using pictures, based on the outside cleanliness of the material and the ratio thick and thin material. The final price can be renegotiated, after issues regarding the quality have been assessed during unloading.

2.3.4 Production

And to conclude the schedule process section, production is discussed, which stands central between purchase and sales. The production leader determines the amount of end product freights that can be produced on which production line, keeping in mind the production speed limitations on certain production lines for a certain end product. Based on this information, the purchasers and the LDPE product manager make the sales and purchasing schedule.

Next to the input material in this department, the production process can be considered a bottleneck in the schedule. In order for the factory to run optimally the maximum available production capacity is used. This is a bottleneck depending on the market situation.

The production capacity in hours includes the actual time a production line can produce end product and excludes the time a line cannot produce due to maintenance or changeover. The variability in the production process, due to e.g. a malfunction or production of rejectedend product, is not taken into account.

2.4 KPIs

KPIs, short for Key Performance Indicators, are indicators for change, performance management and sustainable business improvement, as well as monitor and sustain ongoing business performance(Greeff & Ghoshal, 2004) within an company. The KPIs mentioned in this section are related to the production, sales, purchase and schedule process. A selection of KPIs is made that are relevant to the schedule. They also provide insight in the available data of the company. Table 3 gives an overview of KPIs with the corresponding departments.

Table 3: Overview of KPIs used by sales, purchasing and production.

Department	**KPI**	**Calculation**
Sales	-	-
Purchase	Inventory build-up	Received weekly tonnage of input material - used input material
Production	Production speed	Tonnage input material in silos / Actual production time
Production	Quality grade	Based on intuition

2.5 Conclusion

The general schedule is centrally coordinated by the LDPE product manager, together with the production leaders and purchasers. The general schedule takes into account the production capacity and the available input material, both currently on stock and in the market available. The input material for the production process are waste bales of different input streams, characterised by the quality, colour and the thickness of the material. The recipe mixes different input streams together based on their characteristics to get an output according to the customer's specifications. Characteristics of the input are related to the specifications or characteristics of the output material. Thickness of the input material defines the MFI of the output. Colour of the input defines the colour of the output. The quality grade is related to the contamination grade of the input. The recipe mixes the input materials together to produce a end product that according to the customers quality standard and specifications.

The production process of Rymoplast homogenises, shredders, washes, mixes the waste bales using a recipe and remelts the waste into end product pellets. The input material comes from suppliers and the end product is sent to the customers.

The purchasers aims to buy sufficient quality and quantity input material for a market conform price, and maintain long term relations with supplier and sufficient stock. The production leaders aim to keep the production lines running continuously. The sales manager aims to sell all planned freights, while keeping in mind the commercial interest and cost-effectiveness. KPIs are used by the company to keep track of the performance of the processes. The purchasers monitor the stock. Production keeps track of the throughput of the production lines over time. Also the quality of the input material is monitored. Sales monitors the production margins.

3 Literature Study

This chapter answers the second subquestion, namely: **"What solutions found in the literature can be applied to solve the core problem experienced by Rymoplast?"**

The literature is used to find relevant topics that can help to solve the research question. Section 3.1 starts with an overview of the challenges experienced in the supply chain. Section 3.2 states planning and scheduling models available to aid the general scheduling process. Section 3.4 states the KPIs available to monitor suppliers and supply chain performance. At the end, a conclusion regarding the findings in the literature is given in Section 3.5

3.1 Recycling supply chain

In this section, the subquestion of Chapter 1: **"What solutions found in the literature can be applied to solve the core problem experienced by Rymoplast?"** is answered.

Firstly, the literature improves the understanding of the general supply chain from a literature point-of-view and helps to develop a model that accurately represents the supply chain based on the existing body of knowledge. Next to that, the company deals with various sources of uncertainty across their supply chain, as explained in Chapters 1 and 2. The literature helps to gain more insights in the sources of uncertainty experienced and helps to make modelling choices regarding the supply chain uncertainty experienced by Rymoplast.

3.1.1 Circular economy

The circular economy has the objective to close materials cycles through value-generating recycling. This is done throughout the chain by regenerating and restoring material cycles, keeping up the material value at each point in a product's life and minimising waste (Djuric et al., 2018; EuropeanCommission, 2015; Govindan & Hasanagic, 2018; Taelman et al., 2018).

Figure 10 reflects the shift from the unsustainable linear economy (Salmenperä et al., 2021), in which raw materials are gathered and converted into goods that people use until they discard them as garbage without thought to their impact on the environment, to the circular economy where the various material loops are closed. The arrows represent the material flows between different stages of consuming, producing, waste collection, processing, and recycling. The European Union (EuropeanUnion, 2016) describes a similar transition.

Recycling business models are based on the idea of closing this loop between post-use and production and creating value via up- or down-cycling of material streams (Lüdeke-Freund et al., n.d.), to make that transition for linear to the circular economy. Up-cycling e.g. turns ocean waste into clothing or carpets, which are considered higher-value materials. The opposite is down-cycling, e.g. turning clothing into stuffing, which turns material into material of a lower value. In order to accomplish this, the business models rely on well-organized reverse logistic systems involving users, raw material suppliers, and parts manufacturers.

The management of material flows from the users back to the producers concern the 'reverse logistics', where the reuse or recycling of materials is designated as a new material flow (Fleischmann et al., 1997). This is the management of material flow opposite to the conventional supply chain and entail process where the used product, that is no longer of use to the user, is processed back to a usable product. The RL planning entails three components: the distribution planning, inventory management and production planning (Fleischmann et al., 1997).

3.1.2 Challenges of Recycling

The recycling industry is facing uncertainties throughout their supply chain.

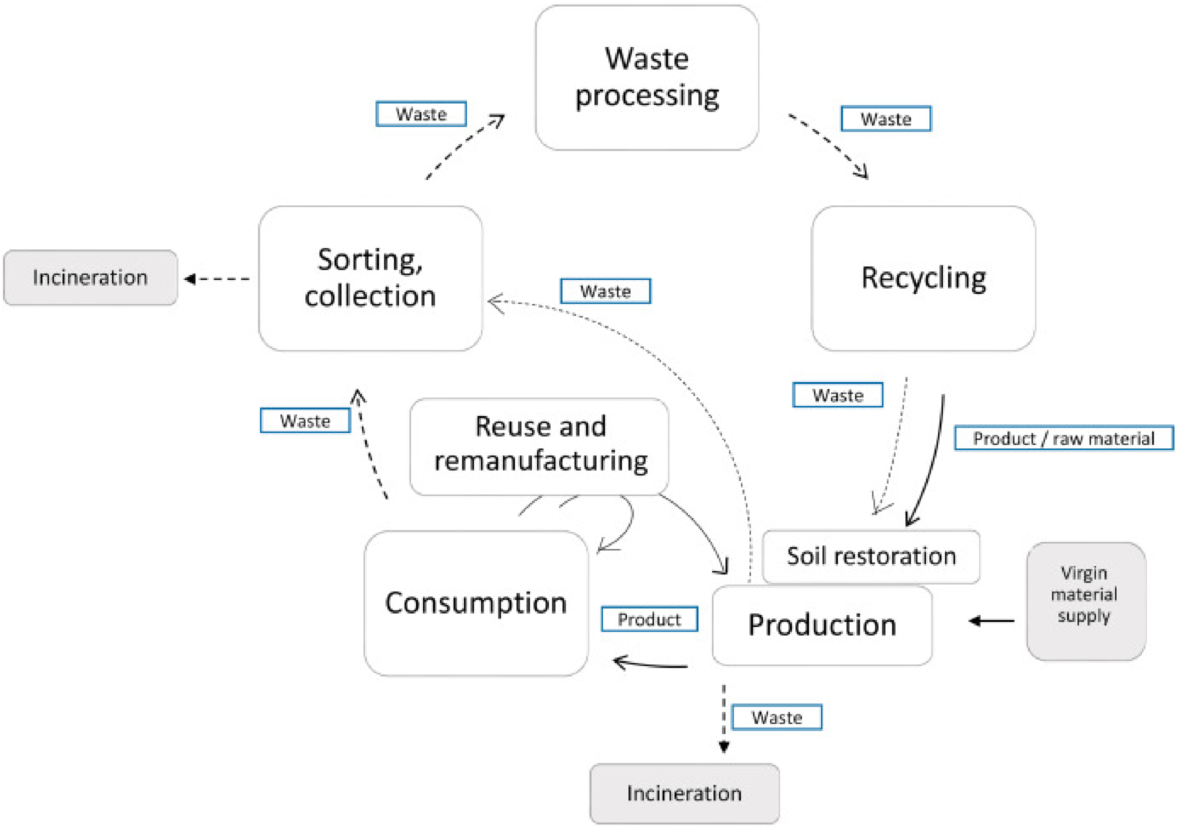


Figure 10: The figure shows the shift from the traditional linear economy with a focus on waste management, to a more cost-effectiveness with a focus on waste and material. It shows a closed-loop system. The arrows show the path of the waste or materials through the different stages, from waste to material back to waste (Salmenperä et al., 2021).

The quality of input material is one of the key components, since it affects the quality of the end product. However, the quality of the input materials is hard to predict. There are fluctuations in different types of plastic content during e.g. the holidays (Li & Aguirre-Villegas, 2022). During Christmas, there is an increase in food containers from dinner parties e.g., which makes it hard to predict the quality of an input stream. Sorting companies have to adapt to that situation.

The produced plastics, already in circulation, can have material properties that affect the quality during production. Mechanical recycling has difficulties with e.g. multi-layered plastic products that have different layers of different materials (often other plastics) and other plastic foils (Li & Aguirre-Villegas, 2022). These materials often have different melting temperature, such that they cannot be mixed together during extruding, making them hard to recycle. Therefore, the quality of the end product is lowered if the input was not separated correctly.

Another property affecting the quality of an end product with mechanical recycling is caused by the degrading material property of plastic, which deteriorates quality of plastic. This affects the material's mechanical capabilities both during the recycling process and over its lifetime. Degrading is caused by the heating and mixing stage of the recycling process and lifetime degradation i.a. due to UV-light and mechanical usage.

These input quality problems affect the end product's quality, and give limitations to economies of scale and fluctuations in the price of recycled materials (Ragaert et al., 2017). The quality can be improved to create a stream of input materials that has a higher degree of homogeneity, by improving the separating techniques and using additives in the extruding process.

In order to recover base materials components by up- or down-cycling of materials, knowledge regarding product design and materials is required to deal with the different mechanical and chemical properties of different composite materials (Lüdeke-Freund et al., n.d.). Recyclers require this knowledge to ultimately create value. Therefore, recycling supply chains rely on a reverse logistics (RL) of collaborating users, raw material suppliers and parts manufactures, in order to achieve this.

These input quality problems affect the end product's quality, and give limitations to economies of scale and fluctuations in the price of recycled materials (Ragaert et al., 2017).

From a customer's perspective of the supply chain, there are uncertainties in the supply quantities and prices (Rogetzer et al., 2018). There is uncertainty in available recycling quantities, which may be caused by different qualities of quality and purity of materials (Linton et al., 2007). There is uncertainty in the available quantity of recycling end product due to variations in the quality and purity of the recyclable materials. The final price of an end product depends on components that are subject to uncertainty, e.g. input material, the recycling processes used and the quantities of input material that is available (Reuter et al., 2013)

These fluctuations and also the constrained market of recycled end product undermine the economic incentive for manufacturers to adopt recycling in their process, making the practise not always lucrative (Ragaert et al., 2017).

3.2 Planning and scheduling

The general scheduling process, which the thesis' core problem evolves around, needs to be more transparent and fixed. In this process, the purchasing, sales, and production departments are involved and takes into accountuch as suppliers, factories, and customers. Maximizing the profit each month is the aim. The coordination of products as well as the movements between different players in the supply chain is typically described as a supply chain planning and scheduling problem. These problems are frequently framed as supply chain scheduling and planning problems.

Next to that, the supply chain of Rymoplast deals with various uncertainty as mentioned in Chapter 2 and Section 3.1.2. As a result, the intuition and experience of the managers is key, which is considered a risk of harm for the company. Hence, there is a motivation to investigate planning methods that deal with these uncertainties.

This section outlines the models found in the literature for supply chain planning with and without uncertainty. The literature found is used as a foundation for the solution formulated in Chapter 4.

3.2.1 Mathematical programming

Mathematical programming (MP) is used in most of the found literature regarding supply chain planning and scheduling. Therefore, first an introduction regarding MP is given.

The term mathematical programming (MP) entails the use of mathematical models to address decision problems (Naud et al., 2020). MP optimizes and solves these problems at different hierarchical levels, e.g. on tactical, strategic and operational levels in supply chain planning and scheduling. The formulations for these problems often have similar structures and input data, such as sets, parameters and variables. If the problem changes, the input data is updated or constraints are added (Dombayci & Espuña, 2017).

Within MP, there are different approaches to represent a problem. In other words, a distinction is made between how a problem is mathematically represented, e.g. a supply chain planning problem, capacity allocation problem or blending problem, and how it is solved, e.g. with simulated annealing. This distinction is also made in this section.

MP is based on the idea that a problem can be described in a way that allows for generic solution methods. A decision problem can be represented by a graph, where variables can indicate whether certain vertices and edges are present or absent in the answer. MP is used to plan production schedules, in transportation, in military logistics, and to determine economic development (Britannica, 2020).

Uncertainty There are various mathematical optimisation methods mentioned in the literature that deal with uncertainty, namely Robust optimisation (RO), Stochastic programming (SP), Rolling Horizon Strategy (RHS), Chance Constraint Programming (CCP) and sensitivity analysis (SA). All methods deal with uncertainty in different manners. SA mostly deals with uncertainty after a solution is found.

1. Robust optimisation (RO) best fits decision problems where the probability distribution of random parameters is unknown, and decision-makers lack the information needed to determine the decision-making environment (Govindan & Cheng, 2018).

   RO models consist of two terms, where the first part is fixed and free of input noise. The second part is subject to input noise. The second term in the objective function is used to control the model's robustness, which is given as a penalty function and represents the risk profile of the user. RO is able to deal with uncertainties in the realisation of data in different scenarios, by creating a solution (Mulvey et al., 1995) that is less sensitive to the changes in the input.

   In terms of robustness in optimisation modelling, a distinction between model 'robustness' and solution 'robustness' can be made. "Solution robustness" gives the solution that is close to optimal solutions in all scenarios, and "model robustness" gives the solution that is feasible in almost all scenarios.

2. Stochastic programming (SP) best fits decision problems, where a probability distribution is known, such that the expected value of the objective function can be optimised. This is done by averaging over the possibilities of events and their objective values (Sahinidis, 2004).

   The problem is formulated as a two stage problem, where stage one decisions are taken by means of a 'here-and-now' approach, at the beginning of a period before the realisation of uncertain parameters. Stage two decisions are taken by means of a 'wait-and-see' approach, during the realisation of uncertain parameters. These decisions can be altered during the period in response to these uncertainties, therefore known as corrective or recourse measures if a solution becomes infeasible under uncertainty.

A famous example is the news vendor problem (Ruszczyński & Shapiro, 2003), where a news vendor has to decide upfront on the number of newspapers to purchase before the demand for that day is known. The objective is to maximise the expected profit, where the realised demand is a random variable from a known distribution.

3. As a substitute for multi-stage SP or RO, the Rolling Horizon Strategy (RHS) can be used.

   The RHS aims to minimise schedule instability. E.g. in a production environment, orders are not moved back and forward, creating instability in the inventory (Sahin et al., 2013). Next to that, the method is able to yield a long-term solution.

   The RHS is solved iteratively in cycles (Sahin et al., 2013) in a series of linked and overlapping planning problems, which span a planning horizon (PH). After awaiting a re-planning periodicity (RP), a stream of new information enters the systems, i.a. demand data. Then the planning problem is solved again for the next cycle again spanning a PH. Each planning cycle consist of a frozen interval and a free interval. The frozen interval consist of orders which are set and cannot change, while the free interval can be changed thus rescheduled for each successive RP.

   In order to illustrate the RHS, Figure 11 is provided. The standard rolling horizon works as follows (Silvente et al., 2015): The model is first applied to the first cycle, which covers the initial PH The model is reapplied one cycle later, after the first RP has ended or enough information is known to base the decisions on for the next cycle. The model covers then the same length PH as the initial PH, only using the newly acquired data, i.a. demand forecasts (de Araujo et al., 2007). After the second cycle has ended, the same is done for the third and subsequent cycles using covering the same length PH, using renewed data each time.

   The length of the intervals, such as the RP and PH, are subject to policy decisions. The frozen interval is often derived from the order time.

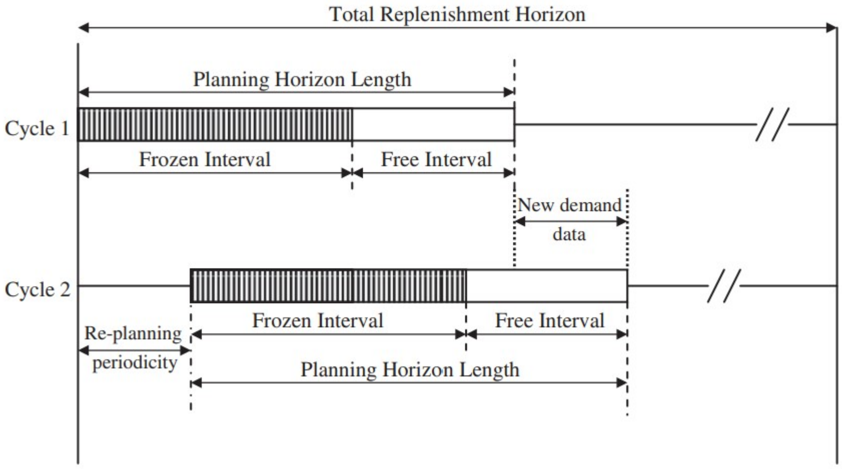


Figure 11: The rolling horizon planning concept put into perspective (Narayanan & Robinson, 2010).

4. Chance Constraint Programming (CCP) (Charnes & Cooper, 1959) is able to handle uncertainty, by implementing specific constraints into their model that deal with uncertainty. These chance constraints contain an explicit measurement of the reliability or probability with which the constraints must be fulfilled. The chance restrictions must be converted into what are known as deterministic equivalents in order for a conventional mathematical programming model to be solved.

5. Sensitivity analysis (SA) is reactive to controlling uncertainty, since it measures how the optimal solution reacts to changes in the input data. It helps in understanding the relationship between the input variables and the output, and how changes in the inputs affect the outputs or decision variables. SA can be performed by varying one input variable at a time while keeping others constant, and observing the resulting changes in the output or solution.

There is a difference between RO, SP and SA. Stochastic programming (SP) aims at optimising the expected value, so large changes in objective value can be observed when scenarios with a small expected value unfold. In contrast to SP, Robust optimisation (RO) uses higher moments, such as variance, such that smaller changes in the solution are observed when the scenarios unfold.

Next to that, scheduling problems use Rolling Horizon Strategy (RHS) to deals with uncertainty (Silvente et al., 2015). RHS is different from the previous methods, in that it is considered a reactive scheduling method. Each iteration the scheduling horizon moves forward, and a deterministic scheduling problem is solved, after enough previously uncertain parameter become known.

The key concept for this approach is the information structure, where the decision variables in each stage depend on the deterministic information that is currently available, but account for the uncertain future (Cui & Engell, 2009b). Particularly, the possibility of reacting to the future development by adapting those decision variables that do not need to be implemented right away. By including the uncertain future, the solution considers the benefits on the long term and rules out unrealistic solutions.

3.2.2 Supply chain planning and scheduling

In the previous section, the individual elements are discussed, which are part of the models discussed later. This helps to understand their functioning. After that, the mathematical programming (MP) and the available methods to deal with uncertainty are explained, which is the basis of the models. This section introduces the supply chain planning and scheduling models. At the end, the solution methods are discussed.

Supply chain planning connects facilities on various levels with each other (Kallrath, 2002), e.g. supply depots and production facilities. At the bottom levels demand from customers is shown, and suppliers corresponds to the top level. A well-functioning collaboration between these levels in the supply chain guarantee delivery of the good or service. The economic activities that connect the flow or service of materials or services from input material at the beginning stage to the end product at the final stage, are called network activities. The supplier delivers input material to producers, while the producers produce end product for their customers. The general schedule describes the tasks that have to be performed by the different levels of the supply chain to successfully deliver a good or service, and puts the planning into practice.

The distinction however between planning and scheduling are vague and strongly overlap (Kallrath, 2002). So both strategic planning and or supply chain management scheduling and planning have significant overlaps.

Supply chain In order to deal with uncertainty by controlling the overall costs on a long- and short-term, and also able to deal with any type of circular business model, a global Reverse Supply Chain (GRSC) is proposed (Xu et al., 2017). The robust model deals with uncertainties that occur in the supply chain i.a. waste collection rate and costs. A similar supply chain planning and scheduling model also takes into account demand-supply capacity (Santoso et al., 2005), which is analogous to the limited supply. Next to that, the model also uses a two-stage approach, with the distribution of the products and the purchase of the materials and quantities taking place in the second stage. A similar approach is used to determine a production loading plan, which consists of i.a. the production quantity (S. C. H. Leung et al., 2006). The method deals with uncertainty in demand, which can be altered to deal with supply. In the current form, the supply constraint is deterministic. Lastly, a supply chain model with different scenarios with known probabilities for uncertainty in both demand and price is proposed (Chen & Lee, 2004). Here, the goal is to distribute the profit equally across the different participant of the supply chain, different from the approaches mentioned earlier that minimse costs.

During the literature study, it was observed that most RO and SP models start with a deterministic formulation. However, they fail to account for the stochasticity in the supply chain. Therefore, a deterministic model that accounts for a finite set of raw materials is proposed (Galindo et al., 2021), which takes into account the supply constraint. The model optimises a plastic company supply chain, with a fixed set of suppliers, plants and customers. It aims to minimise the total costs, including production, transportation and raw material costs.

Capacity allocation problem Rymoplast has the option to produce multiple end products on the same production line, therefore a production capacity allocation problem is developed. This problem allocates certain end products on a certain production line as input for the general schedule. A first capacity allocation problem with an integrated supply chain operation is proposed (Li et al., 2009), where the production capacity for a certain end product can be distributed among different production facilities. The goal is to establish how capacity for end products should be distributed among factories in a full supply chain as efficiently as possible. This problem formulation differs from the previous formulations. Nonetheless, it integrates a supply chain network from input materials to end product in the formulation.

The second formulation is similar to the previous, but is able to deal with a growing or decreasing capacity for a product (Liu & Papageorgiou, 2013). Additionally, the flow time is considered in the objective function for a case in the process industry, similar to Rymoplast's approach of allocating capacity.

Supplier selection The biggest challenge according to Rymoplast is to deal with the uncertainty from the supplier side of the supply chain. The previously mentioned supply chain scheduling model (SCSM) methods focussed on the different levels i.a. suppliers to factories, and factories to customers. The next approach considers only the supplier side of the supply chain (Che & Wang, 2008), so from the supplier to a factory. And also aims to find the best supplier and supply quantity and does not consider the full scope of supply chain, including the factories and customers. The model minimises the total product costs and time and maximises quality of fullfilled orders form suppliers. It proposes to model the production configuration, supplier assessment and quantity allocating.

3.2.3 Blending problem

At the centre of Rymoplast's production process is the recipe, which connects the input materials to a certain end product. In recycling, blending and mixing different input streams via this recipe is key since it i.a. decreases supplier dependency and increases homogeneity of the end product, as mentioned in Section 2.2. The search for an optimal recipe or mix of input streams can be described as a blending problem. It minimises the costs of raw materials by finding a mix of various raw materials to produce one or more final products, based on input material characteristics (Djeumou Fomeni, 2018).

A second blending model takes into account the uncertainty in minimum and maximum procurement or input quantities, demand, and costs of material (Sakallı et al., 2010). A blend for a single end product or multiple blends for multiple end products can be considered.

As mentioned in Section 1.3, there is variability in the input, meaning that the right quality and quantity of input material might be up to the required standard needed in production. A blending problem is developed for the tea industry (Djeumou Fomeni, 2018), which has the objective to achieve a blend or recipe that is as "close as possible" to the desired quality. To achieve this, a trade-off between the minimisation of costs and the violation of quality requirements of a blend is considered. This modelling approach optimises the tea blend based on various characteristics, such as flavour and thickness, price and availability of input material.

A similar problem is developed for the coal industry (Shih & Frey, 1995) that is able to deal with uncertainty. Instead of violating quality requirements, it uses Chance Constraint Programming (CCP) to model variability in input material properties.

In Rymoplast"s production process, restrictions are put on which input material can be used for a certain end product. E.g. bont input material cannot be used to produce a natural end product pellet, but a natural input material can be used to produce a bont product end pellet. To solve this, a blending problem was developed the lowest cost blend using multiple inputs that are compatible, i.e. can be used in the same mixture in the case of a fertilizer company (Glen, 1988) (Ashayeri et al., 1994).

Similar to the blending problems, a network flow problem is developed (Ekşioğlu et al., 2006). The objectives and constraints have the same goals and cover the same aspects of the planning problem, but the mathematical formulation differs. The approach does cover a two-stage supply chain with multiple suppliers and multiple customers connected by multiple factories. This is similar to the network of Rymoplast.

3.2.4 Aggregated production planning

The sales, purchasing, and partly the production process are all covered by Rymoplast's general schedule. This schedule sets the aforementioned departments into motion. This is comparable to the Aggregate Production Planning (APP) found in the literature. The APP captures and optimises the operational activities of the company simultaneously, i.a. production and inventory, over a finite time horizon to meet the total demand (Nam & Logendran, 1992).

The role of the APP can be noticed as the coordinator between the different planning activities, in time ranging from short to long (Jamalnia, 2019). Figure 12 shows the relationship of the APP between the different planning levels considered in a production company. The APP is settled between the strategic (long-term) planning and the operational (short-term) planning, and has a medium-term time horizon between 3 and 18 months. Noticeable are the master production schedule (MPS) and the detailed production schedule, which show similarities to the operation production schedule mentioned in Chapter 2. The forecasted demand data is mentioned as the driving force behind the system.

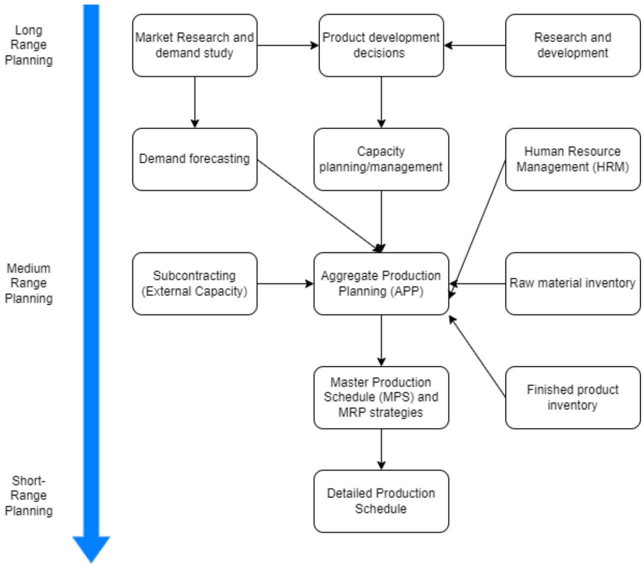


Figure 12: Diagram showing the relationship between short- and long-term planning activities, with a coordinating role for the Aggregate Production Planning (APP) (Jamalnia, 2019).

Noticeable is that the planning takes into account training and hiring of personnel and customer satisfaction. This is considered less relevant for this thesis, since Rymoplast aims for continuous production and customer satisfaction is not the focus of this thesis. The downside is that the supply chain including facilities, customers and suppliers is not directly modelled, but often does take transportation costs into account.

Optimisation models The models named below are optimisation methods that solve the APP. The focus is on uncertainty, as is considered a problem by Rymoplast.

In order to deal with uncertain economic scenarios and uncertain and noisy input data, a production planning problem is proposed to find an optimal production schedule that is less sensitive to these uncertainties (S. C. Leung et al., 2007). It is assumed that the future economic situation has a probability attached to it. A similar approach is used to solve a production planning problems with uncertain seasonal demand (Goli, 2019). A scenario tree is used to model the uncertainty, which is different from the earlier models.

To deal with the fluctuations in costs price of raw materials, an optimisation model APP is proposed (Kanyalkar & Adil, 2010). The objective is to minimise the mean and variance of the total costs. A similar approach for APP is developed that deals with uncertainty in the cost price and additional demand. The models cover most of the supply chain costs (Mirzapour Al-e-hashem et al., 2011).

Another strategy to deal with uncertainty is the rolling horizon strategy RHS scheduling method to schedule a batch plant (Cui & Engell, 2009a), similar to a factory of Rymoplast. This strategy includes the distant future to mitigate the short term gains and maximise the gains over the long period. The basis for this model is similar, but without the RHS (Till et al., 2007). Notably, is that the performance is not considerably impacted by the addition of RHS. The addition of RHS does not significantly affect the computational performance compared to the basis model.

Overview models The general schedule is the focus of the thesis and to address this, we have established the following characteristics. Certain characteristics can be found in the discussed models. In order to structure and keep an overview of the available models in the literature, Table 44 44 is created. This is used to find a model that best suits the company's needs, described in Chapter 4. First off, the need of the company is described with information from Chapters 1 and 2.

1. The objective of the general schedule is to optimise the margins between purchasing costs and the sales profit. Therefore, costs or profit related objective values are considered relevant objective functions. The costs considered most relevant by the company for this thesis are transportation costs, input material costs and end product revenue. Therefore, a description of the objective functions is given.
2. Both the production process and the supply chain of Rymoplast are restricted, as mentioned in Section 1.3 and Section 2.2. Therefore, constraints regarding production, supply and storage are considered relevant.
3. The supply chain of Rymoplast considers multiple suppliers, multiple factories and multiple customers. Therefore, the models should also consider them.
4. Multiple input materials are used in Rymoplasts recipe to created multiple end product. Therefore, the models should cover these aspects. The model needs to deal with matching multiple inputs to multiple outputs.
5. The general schedule currently covers a month, but the company wishes to plan further ahead to mitigate the bull-whip effect. Therefore, single-periods and multi-period models are reviewed.
6. The general schedule has a time horizon of 1 month. Therefore, a distinction between long-, mid- and short-term is made (Pereira et al., 2020):

    - Long-term or strategic: decisions that provide the groundwork for future development of the supply chain, affecting the future supply chain's layout. The planning horizon spans several years.
    - Mid-term or tactical: Establishes a rough plan for the multiple operations, which is often done at an aggregate level, similar to Aggregate Production Planning (APP). It evaluates an estimate of input quantities and their timing. The planning horizon spans between a few months and one year.
    - Short-term or operational planning: The focus of this planning level is on the day-to-day operations. A production schedule with detailed instructions is expected. The planning horizon spans a few days or a few weeks.

3.3 Solution Methods

As mentioned in Chapter 2, the general schedule is created two weeks before it is executed. After that, sales and purchasing are informed, and the general schedule is carried out. Therefore, the planning problem has to be solved with in a limited amount of time, in order for the solution to be relevant for the company.

However, APP and SCSM problems are classified as NP-hard, which means that the optimal solution cannot be found within a reasonable time or polynomial time. Medium or large size problems often take excessive time and sometimes run out of memory (Li et al., 2009). The use of conventional tools for solving the supply chain problem is therefore limited due to the complexity of the problem and the large number of variables and constraints, particularly for realistically sized problems supply chain problems.

Different algorithms can be used to find a high-quality solution within a reasonable amount of time, for problems that are considered to be NP-hard for large-size problems, as mentioned here.

The first algorithm, the Genetic Algorithm (GA) is used to obtain good-quality and efficient solutions for large-scale problems (Fahimnia et al., 2012; Ramezanian et al., 2012). The idea behind GA is mimicked from nature, more specifically natural selection, where the fittest members of a population are selected (Mallawaarachchi, 2017).

The GA is an iterative algorithm and alters the population of solutions. In each iteration, an individual from the population is selected to produce children for the next generations. The fittest of the population is preferred and passes his qualities to the next generation. The fitness of an individual is identical to the objective function. So, the individuals of a population are evaluated using the objective function of the model. The process is stopped when a certain criterion is met, for example a certain number of iterations. The general procedure is outlined in Figure 13.

GA seems to be quite good for finding generally good global solutions, but quite inefficient at locating the last few mutations to determine the absolute optimum (Ramezanian et al., 2012). Combining GA with other optimization methods can be quite effective. Examples are the NSGA-II and the multi-objective invasive weed optimisation algorithm (MOIWOA) (Goli, 2019). Both are able to deal with multi-objective optimisation problems.

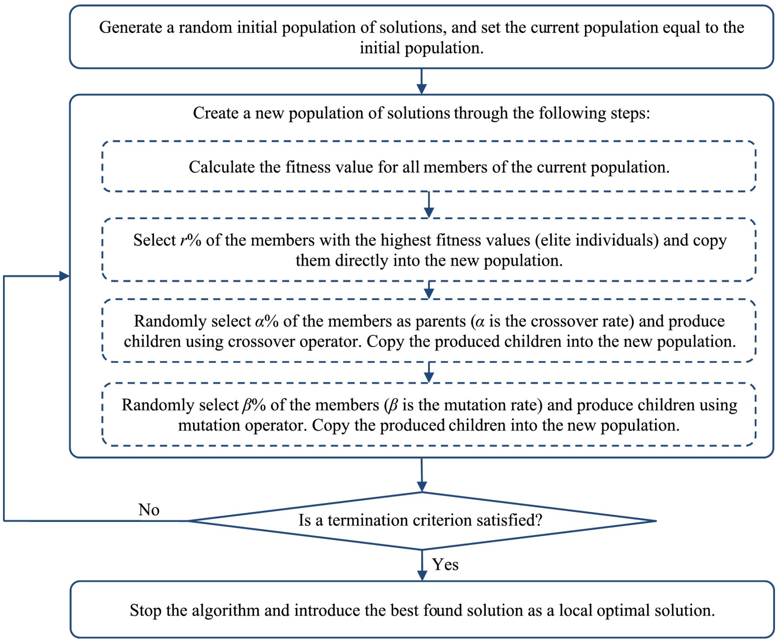


Figure 13: The practical GA procedure (Fahimnia et al., 2018).

The second algorithm, SA, is also inspired by nature, mimicking the process of annealing in metallurgy (Fahimnia et al., 2018). This involves heating and cooling of material in a controlled manner to increase the size of the crystals while reducing the energy levels.

The process is based around a temperature that mimics a heating and cooling down process. The initial temperature is set high, and decreases steadily with each iteration, while the algorithms runs. The process starts with an initial solution, then solutions in the neighbourhood of that initial solution are generated. A new solution is accepted, if the new objective value has improved compared to the previous solution. Or the new solution is accepted with a certain probability, if the new objective value is lower. The probability that a lower objective value is accepted allows for the algorithm to escape local minima. The algorithm ends when the temperature has reached its lowest point. The procedure applicable for most optimisation models is described in Figure 14.

Both SA and GA are referred to as meta-heuristics and mentioned as one of the most popular heuristics for optimising large-scale linear and non-linear optimization problems. They are fit to find a sufficient solution to an optimisation problem, with incomplete or imperfect information or limited computation capacity (Bianchi et al., 2009), as is the case for Rymoplast. Both heuristics stochastically find a potential solution. These meta-heuristics have been increasingly popular in the literature in the context of supply chain modelling and optimisation (Fahimnia, Zanjirani, et al., 2013).

Lastly, the Sample average approximation (SAA) with an accelerated Benders' decomposition al-

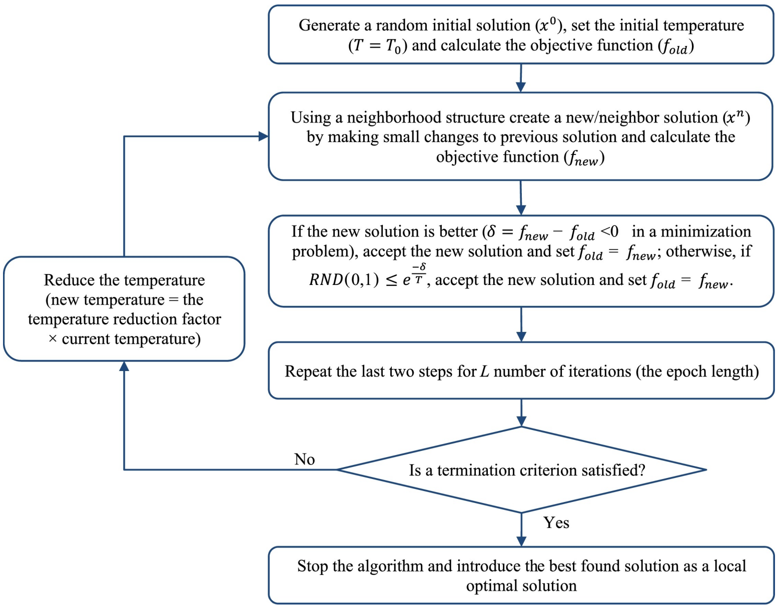


Figure 14: The practical SA procedure, where the RND(0,1) function generates numbers between 0 and 1 (Fahimnia et al., 2018).

gorithm handles supply chain problems with continuous distributions for the uncertain parameters, causing an infinite number of scenarios (Che & Wang, 2008). It provides high-quality solutions within a reasonable time, similar to the previous algorithm, but specifically accounts for the stochasticity in the models. The SAA scheme randomly samples a sufficiently large set of scenarios. The suggested methodology offers a practical framework for locating and statistically evaluating a wide range of potential candidate solutions.

3.4 KPIs

The efficacy of a general schedule is the main focus, which aims to deliver the right quality and quantity of end product to the customer in a timely manner. Monitoring the performance is necessary to determine whether we have addressed the core problem, which is described in Section 1.3. There currently is no system in place to monitor this. Next to that, the biggest bottleneck of Rymoplast is at the supplier side. The suppliers are essential to obtain the right quality and quantity of input materials to produce the right end product. Therefore, the focus is on the supplier side of the Rymoplast's supply chain.

Before the start of this subsection, it is important to note that performance measurements and performance measurement systems have different meanings in the literature. Performance measurements are described as the process of quantifying the efficacy and efficiency of action (Neely et al., 1995). Effectiveness in this context is the degree to which a customer's needs are met. Efficiency in this context assesses how efficiently a company uses its resources to provide a given level of customer satisfaction.

Performance measurement systems are referred to as the comprehensive collection of metrics that quantify the effectiveness and efficiency of various actions. The last one is left outside the scope of the thesis.

This section aims to find KPIs that are relevant to determine the effectiveness of the general schedule, thus answering sub-question of Section 1.5. Below, four different studies are mentioned from which relevant KPIs for Rymoplast are extracted, as shown in Table 4.

3.4.1 Performance measurements

In order to select and also monitor the "right" supplier, different metrics regarding supplier reliability, responsiveness, flexibility, costs, and asset management efficiency are proposed and sorted on the various hierarchical levels (Huang & Keskar, 2007). The levels take into account product type, supplier type, and supplier integration. The top three most popular performance metrics were quality, delivery and price or cost (Ho et al., 2010).

A similar study focussed also on the supplier side, and found a relationship between supplier management practices and firm operational performance (Prajogo et al., 2012). The focus is on the cause-effect relation between supplier management practices and operations performance. The management practises consist of long-term relationship, supplier assessment, and logistics integration. The operations performance measures are quality, delivery, flexibility, and cost. Rymoplast focuses on long-term relations with its suppliers, which is explicitly researched in this paper.

In order to evaluate the strategy used in a fully integrated supply chain, effective measures and metrics have to be integrated to gain insight in the applied strategy (Gunasekaran et al., 2001). Measure and metrics have to be balanced, to get a clear picture of the organisations performance. Six areas are identified that cover various aspects of the supply chain. Most notably are the supply chain finance and logistics cost, which cover i.a. partnership measures between buyer and supplier and production related measurements. The different metrics and measures are linked to each other, based on plan, source, production, delivery and customer service and satisfaction performance.

The most relevant and applicable metrics and measures for this thesis, related to the supplier performance and the general schedule performance, are collected in Table 4.

Metrics	**Term Level**
Total Stock incoming Level (Gunasekaran et al., 2001)	Operational
Scrap level (Gunasekaran et al., 2001)	Operational
Supplier rejection rate (Gunasekaran et al., 2001)	Operational
Quality of delivered goods (Gunasekaran et al., 2001)	Operational
Effectiveness of master production schedule (Gunasekaran et al., 2001)	Tatical
Conformance to specification (Prajogo et al., 2012)	Operational
Product quality performance (Prajogo et al., 2012)	Operational
Compliance with quality (Ho et al., 2010)	Operational
Net rejections (Ho et al., 2010)	Operational
Percentage of products or items not rejected upon inspection (Ho et al., 2010)	Operational
Quality assurance production (Ho et al., 2010)	Operational
Competitiveness of cost (Ho et al., 2010)	Operational
Cost reduction performance (Ho et al., 2010)	Operational
Orders received defect free (Huang & Keskar, 2007)	Operational
Incoming material quality control (Huang & Keskar, 2007)	Operational
% Errors during release of finished product (Huang & Keskar, 2007)	Operational
On time in Full (Davies et al., 2019)	Operational

Table 4: An overview of relevant KPIs as extracted from the literature.

3.5 Conclusion

In this chapter, the following research question is answered: **"What solutions found in the literature can be applied to solve the core problem experienced by Rymoplast?"**. To conclude this chapter and answer the RQ, an overview of the models and approaches that can be used to solve the RQ are given here. This chapter forms the basis of Chapter 4, in which the elements extracted from this chapter are used and also the decisions are discussed. But first off the knowledge gained from the literature, to further enhance my general understanding of the recycling business, is discussed and applied to the case at hand.

The business model of Rymoplast relies on the circular economy, which has the objective to close material cycles and keep up its value through value generation at different points in the product's life. In a RL, the materials flow from the end-users of the product are coordinated back to the manufacturer. The planning of RL deals with uncertainties in quantity and quality of input and output. A level of disassembly between participants in the reverse supply chain and high uncertainty in quantity, quality and timing of the return flow adds complexity to the supply chain scheduling (Fleischmann et al., 1997). Contaminations, availability of input material and end product make it hard to predict the quality, which limits the scale of economy and profitability. Therefore, specific knowledge is required to recycle and win back base materials.

As stated in this section, models are proposed that optimise the supply chains, which are similar to Rymoplast. These models are mostly based on MP, which optimise and solve decision-making problems. A decision problem can be formulated as supply chain problem, network flow problem or a capacity allocation problem. The objective to minimise the costs or maximise the profit, which can be translated to maximise the gap between purchasing costs and sales revenue.

As mentioned in Chapter 1, the supply chain deals with uncertainty. Therefore, approaches such as RO, SP, RHS, CCP and SA are discussed.

The problem experienced by Rymoplast can be characterized as a supply chain scheduling and planning problem. Howevers, these problems typically involve two stages. The second stage is particularly significant, as it revolves around scheduling the movement of products among suppliers, factories, and customers. The factory is at the centre of Rymoplast's supply chain. Here, input materials are blended for a certain end product. Therefore, a blending problem is used to find an optimal recipe or mix of input streams. The blending problem aims to minimise the costs of raw materials, by finding a mix of various raw materials with different characteristics to produce one or more final products.

The APP combines sales, purchasing and production schedules together, as is the case with the general schedule. This coordinating planning method captures the operational activities of the company simultaneously over a finite time horizon in the APP. This aims to optimise the production and inventory levels to meet the total demand. This planning has a similar scope as the general schedule.

The aforementioned formulation is referred to as NP-hard, where the complexity of the models causes high computational time for large problem instances. Therefore, solution methods are employed to find a high-quality solution in an adequate timeframe, such as SA, GA and SAA. The SA and GA are able to find a high-quality solution in an adequate amount of time. The SAA is similar, only focusses more on large-scale problems that deal with uncertainty directly.

In order to measure the effectiveness of the general schedule, measures and metrics are employed. These are presented in Table 4. Performance measurements are presented, with a focus on supplier-buyer relations, since the main bottleneck is on the supplier side.

In order to better understand the uncertainty and issue experienced in the supply chain, which assists us in the modelling choices, the literature is used to classify the supply chain. The CE, RL are recycling business models that aim to close the loops between materials streams, by up- or down cycling. Knowledge regarding product design and materials is required to deal with the different mechanical and chemical properties of different composite materials. Next to that, there is uncertainty in quality and purity of input materials, and the price and availability of input materials for recyclers. These challenges affect the quality of the material, give limitations to economies of scale and fluctuations in the price of recycled materials.

In Chapter 4, we incorporate several key elements from the current chapter. These elements include the supply chain planning method (Mirzapour Al-e-hashem et al., 2011), which is employed to model the supply chain of Rymoplast. Additionally, we utilize the Rolling Horizon Strategy (RHS) and the

Chance Constraint Programming (CCP) approach to effectively address uncertainties within the supply chain. Furthermore, the SA algorithm is employed to identify a suitable solution within a reasonable timeframe. The reasoning behind the selection of these elements is elaborated in Chapter 4.

4 Solution

In this chapter, a solution to the problems experienced by the company together with the motivation following is provided , extracted from the solutions mentioned in Chapter 3. This chapter answers the research question: **"What solutions found in the literature, be applied to solve the problem experienced by the company?"**.

In Section 4.1, the core problem encountered by the company are discussed, for which a solution is provided in this section. Section 4.2 gives the mathematical formulation. Section 4.4 gives the approach to include stochastisity in the model to account for the uncertainty. The algorithm to solve the MP is provided in Section 4.5. In Section 4.5.1, suggests alternative methods for finding an adequate solution within a reasonable time. Lastly, Section 4.6, the relevant KPIs to monitor the general schedule.

4.1 Encountered problems

A description of the problems with a solution is provided below without the adequate motivation. The motivation is mentioned separate in the subsections so that a more thorough and precise explanation can be provided.

As described in Section 1.3, the company has no fixed method or process to create their general schedule, since it misses a lack of overview and structure. The company relies on the experience, intuition and knowledge of the managers to make and execute the schedule in order to meet their demand. The company reacts to the mutations in the input materials inventory, which causes a bullwhip effect in quantity on the supply side and subsequently damages their relationship with the suppliers. A good relationship between Rymoplast and its suppliers is key to get the right input materials to their demand, according to the company.

According to existing literature, we have determined that a MP model, as described in prior research, is the most suitable approach to address the aforementioned supply chain managing issues. The selected model is able to model the entire supply chain of Rymoplast, including material flows among factories, suppliers, and customers, as well as modeling the production process. In contrast to alternative methods, such as blending problems and supplier selection approaches, mainly focus on specific parts of the supply chain.

The employed model provides a comprehensive understanding of the scheduling process by integrating the expertise and experience of decision-makers within a single model. By concentrating this knowledge, we are able to inform decision-making throughout the scheduling process and provide valuable insights. Additionally, the MP models possess the capacity to devise scheduling strategies spanning multiple time periods, thereby mitigating the detrimental effects of demand amplification. Further motivation is given in the next section.

Before the model can be implemented, it still has to be tailored specifically to Rymoplast's requirements, as will be discussed further in this chapter.

The size of the model is still unknown, therefore the meta-heuristic is only discussed and depending on whether the model can be solved in reasonable time to optimalilty implemented. This is to mitigate the fact that the model is NP-hard and therefore a meta-heuristic can give a high-quality solution in a reasonable amount of time.

Since the company deals with uncertainty, a RHS is applied and a constraint from CCP is added to solve this problem. The reasoning for this is provided in Section 4.4.

Finally, metrics are used to monitor the performance of the general schedule. This problem is addressed in Section 4.6.

4.2 Mathematical model

The mathematical model described is separated in two different sub sections, the main model in Section 4.2.1 and its additions in Section 4.2.2. The main model includes all indices, variables and constraint based on the notation found in the literature (Mirzapour Al-e-hashem et al., 2011). This internal supply chain model is closely related to the model described in Chapter 3.
The choice for this specific model is for the following reasons:

- The model uses multiple periods to optimize performance over the long term. To be more specific, the scheduling process captures not only the immediate planning period, but also extends to future planning periods. By considering future periods, the model ensures an adequate supply of input materials for subsequent periods. In contrast, a single-period model that solely focuses on maximizing short-term margins may result in insufficient input materials for future periods.

  Moreover, the multi-period approach allows the model to take advantage of fluctuating purchasing prices. It achieves this by purchasing larger quantities during periods of lower prices and reducing purchases during subsequent periods, while still maintaining sufficient material reserves.

  Therefore, a multi-period model is adapted to mitigate the pursuit of short-term gains, thereby avoiding situations where a solution is found for the immediate schedule but proves infeasible for the long-term schedule (Cui & Engell, 2009a).

- The model handles multiple factories, in which multiple inputs can be sourced from multiple suppliers in the factories, and combines them to produce multiple end products and distribute them to multiple customers (Li et al., 2009). This model uses multiple recipes as a decision variable to combine the inputs and outputs in the production process of Rymoplast.

- Sales, purchase and production schedules are integrated in an internal supply chain schedule, which copes with multiple suppliers, factories and customers. For the place of this internal supply chain in the global supply chain, a reference to Section 1.2.3 is made. The literature shows that it is beneficial to integrate both sales and purchase scheduling and production planning, as it produces more net profits when compared to models considering them seperately (Park, 2005). Rymoplast considers them separately in the current situation. However, the complexity increases, thus making it harder to solve within a reasonable amount of time (Fahimnia et al., 2012; Fahimnia, Zanjirani, et al., 2013; Park, 2005). This is addressed in Section 4.5.

- As extracted from the literature described in Chapter 3, both APP, SCSM, and blending models cover the overlapping aspects of the internal supply chain of Rymoplast. The SCSM covers the scope of the supply chain best, such as transportation between suppliers, factories and customers. Next to that, the SCSM is often simpler in formulation, such that certain constraints and rules from the blending and APP models can be applied more easily.

4.2.1 Main model

Below is a description of the model's indices, parameter variables, objective and constraints.

- **Indices**
  1. i, index on end product, where I is the number of types of products produced. $i = 1, ..., I$
  2. j, index on production lines, where J is the number of production lines. $j = 1, ..., J$. Each production line is assigned to a unique factory f.
  3. f, index on factory, where F is the number of factories. $f = 1, ..., F$
  4. k, index on customer, where K is the number of customers.$k = 1, ..., K$

5. l, index on supplier, where L is the number of suppliers. $l = 1, ..., L$
6. h, index on input material, where H is the number of types of input materials.$h = 1, ..., H$
7. t, index on the interval periods, where the chosen time frame spans a time period of T. $t = 1, ..., T$

- **Capacity parameters**
    1. $minCS_{lht}$ and $maxCS_{lht}$, minimum and maximum capacity of supplier l to deliver input material h in period t.
    2. $maxCP_{jt}$, maximum production capacity of production line j in period t (available production time).
- **Costs parameters**
    1. pk_{ikt}, the price of end product i in period t to customer k.
    2. pl_{hlt}, the price of input material h in period t from supplier l.
    3. cvv_{lhft}, purchasing cost per unit of input material h from supplier l delivered to factory f in period t.
    4. $cvtk_{if}$, cost of transportation a full freight of product i from factory f to customer k in period.
- **Other parameters**
    1. r_h, yield of input material h needed to produce one unit of product i.
    2. Z_{hi}, binary value that controls the input material h that can be used in end product i.
    3. pt_{ift}, processing time per unit of product i in factory f.
    4. IM_{hft}, inventory of input material h at factory f at time t. Where IM_{hft} at $t = 0$ is the starting inventory, and the IM_{hft} at $t = T$ is the end inventory.
    5. $maxIM_f$, maximum storage space available for all input materials at factory f.
- **Decision variables**
    1. x_{hijt}, amount of input product h used to produce i in production lines j in period t.
    2. y_{ifkt}, amount of product i delivered to customer k from factory f in period t.
    3. z_{lfht}, amount of the input material h supplied to factory f from supplier l in period t.
    4. $TrucksYifkt$, amount of trucks needed to deliver product i to customer k from factory f in period t.
    5. $TrucksZ_{lft}$, amount of trucks needed to deliver the input materials to factory f from supplier l in period t.
- Costs functions
    1. Sales Revenue $= V = \sum_{t=1}^{T}(\sum_{i=t}^{I}\sum_{k=1}^{K}\sum_{j=1}^{J}(y_{ijkt} * pk_{ikt}))$
    2. Transportation Costs Input $= \sum_{t=1}^{T}\sum_{i=t}^{I}\sum_{k=1}^{K}\sum_{f=1}^{F}(TrucksY_{ifkt} * cvtk_{fk})$
    3. Input Costs $= \sum_{h=1}^{H}\sum_{l=1}^{L}\sum_{f=1}^{F}(z_{lfht} * pl_{hlt})$

First, a MIP description of the deterministic main model is given:

P: max V = Sales Revenue - Transportation Costs Input - Input Costs

Subject to:

$$\text{Output constraints: } \sum_{j=1}^{J}\sum_{h=1}^{H} x_{hift} * r_h * Z_{ih} = \sum_{k=1}^{K} y_{ifkt}, \forall i, f, t \tag{1}$$

$$\text{Inventory constraint: } IM_{hft} = IM_{hf(t-1)} - \sum_{i=1}^{I}\sum_{f=1}^{f} x_{hjit} + \sum_{l=1}^{L} z_{lfht}, \forall h, j, t \tag{2}$$

$$\text{Start inventory constraint: } IM_{hf(t=-1)} = StartInv_{hf} \forall h, f \tag{3}$$

$$\text{Inventory capacity: } \sum_{h=1}^{H} IM_{hft} \leq maxIM_f, \forall f, t \tag{4}$$

$$\text{Supply constraint: } minCS_{lht} \leq \sum_{j=1}^{J} z_{ljht} \leq maxCS_{lht}, \forall t, h, t \tag{5}$$

$$\text{Production capacity: } \sum_{i=1}^{I} pt_{ijt} * \sum_{h=1}^{H} x_{hijt} * \frac{1}{r_h} \leq maxCP_{jt}, \forall j, t \tag{6}$$

Bounds

$$x_{hijt}, y_{ifkt}, z_{lfht}, TrucksY_{ifkt}, TrucksZ_{lfht} \geq 0, \forall l, h, i, j, k, t, f \tag{7}$$

As decided by the company, the objective aims to maximise the margin between the costs of acquiring the necessary input material, which consists of the purchasing and transportation costs, and the sales revenue. The costs part of the objective function consists of two parts, the transportation costs and the input costs, as defined in the literature. The costs part minimises the total losses of the supply chain. Compared to the objective function in the literature, it excludes the production costs, inventory costs and costs involved with workforce levels. The sales revenue part is added to calculate the margin.

Constraint (1) enforces the flow conservation of input material for an end product in the production process. Compared to the literature, this constraint does not account for the end product inventory. The inventory constraint (2) keeps track of the inventory balance between the outflow of input materials used in production, the inflow of input materials coming from suppliers, and the stock level of the previous period (Liu & Papageorgiou, 2013). The constraint (3) makes sure that the start inventory is used, which has an effect on the inventory levels of the subsequent months. Both constraints (1) and (2) have been slightly altered. In the literature, the inventory constraint account for the input materials required for an output. Since the company accounts for the yield per input material, this is changed in this formulation of constraint 1. The binary variable Z_{hi} makes sure that the allowed input material is used in an end product.

Constraint (4) makes sure that the storage capacity is not exceeded. Supply constraint (5) makes sure that sufficient input materials are sourced, and the production capacity constraint (6) makes sure that the production capacity for end product i won't be exceeded in factory f.

The model is considered to be a deterministic model. However, the general schedule has to account for the uncertainty as described in Section 1.3. Therefore, an additional constraint is added to the model, and a solution strategy is applied in Section 4.4.

In order to capture the full extent of the supply chain of Rymoplast, additional constraints and variables are required. The constraints that account for the demand, safety stock, the ingoing and outgoing trucks and the recipe for the end products. These are mentioned in the next section.

4.2.2 Additions to main model

In order to capture the full predefined scope of the supply chain of Rymoplast, constraints for the safety stock, the bound for the demand per customer, the specified MFI of an end product and the outgoing and incoming trucks are discussed in this section.

Minimum inventory

Parameter

1. $MinInvIM$, the minimal amount of stock required at the end of the month

Constraints

$$\text{Safety Stock: } MinInvIM_f \leq IM_{hft}, \forall h, f, t \tag{8}$$

Due to the uncertainty in supply of input materials, the company also expressed their wish to include a minimum safety stock for both end product and input materials. Therefore, the safety stock constraint (8) is added to make sure that the model adheres to the minimum inventory position of input materials.

Minimum and maximum demand

Parameter

1. $minD_{ikt}$ and $minD_{ikt}$, minimal and maximum amount that has to be delivered of product i to customer k at time t.

Constraints

$$\text{Demand min. and max. constraint: } minD_{ikt} \leq \sum_{j=1}^{J} y_{ijkt} \leq maxD_{ikt}, \forall i, k, t \tag{9}$$

The company has arrangements with their customers to deliver a certain amount of end products. Constraint (9) makes sure that their demand is fulfilled within a certain bound.

MFI constraint

Parameters

1. $minMFI_i$ and $maxMFI_i$, the minimum and maximum MFI required for product i.
2. MFI_h, the MFI index of input material h.

Constraints

$$\text{MFI constraint: } minMFI_i * \sum_{k=1}^{K} y_{ijkt} \leq \sum_{h=1}^{H} (Z_{ih} * r_h * x_{hijt} * MFI_h) \leq maxMFI_i * \sum_{k=1}^{K} * y_{ijkt} \tag{10}$$

The MFI constraint (10) makes sure that the produced end product is complying to the desired MFI (Djeumou Fomeni, 2018).

Truck Constraints Both decision variables $TrucksZ_{ljht}$ and $TrucksY_{ijkt}$ were mentioned earlier in Section 4.2.1.

Parameters

1. $Tonnage_l$ and $Tonnage_k$, the tonnage of end product a truck can transport from the supplier l to factory, and from the factory to customer k.

Constraints

$$\text{Incoming freight: } TrucksZ_{ljt} * Tonnage_l = \sum_{h=1}^{H} z_{ljht}, \forall l, j, t \tag{11}$$

$$\text{Outgoing freight: } TrucksY_{ijkt} * Tonnage_k = y_{ijkt}, \forall i, j, k, t \tag{12}$$

The incoming and outgoing freights are carried by truck in a fixed tonnage, therefore constraints (11) and (12) are added. The incoming freights are often in a mixture of both natural, pastel or bont input materials. Therefore, multiple input materials can be transported on a single truck. For the outgoing freights, only a single end product can be transported on one truck. Often these freights are often transported by bulk, which does not allow multiple end products. A combination of multiple end products on a single truck is therefore rarely the case.

Good to note, is that the model stated here, only considers the input material inventory and does not account for the end product inventory.

4.2.3 Modelling purchasing price

In reality, regular suppliers often receive a higher price as they deliver better quality input material, which is necessary to obtain the adequate quality and quantity of end product. The model may choose non-regular suppliers that deliver a lower quality input material due to the lower price over regular suppliers, since the model only aims to maximise the margin between purchase and sales and does not account for the quality of the delivered input material. To address this issue accordingly, the model must give preference to regular suppliers. This is achieved by handling a lower purchasing price for regular suppliers.

4.3 Solver

The optimization model can be effectively solved utilizing widely-used solvers, such as Gurobi or CPLEX, as discussed in Section 3.3. For this specific application, Gurobi in Python was selected because of its common use in the academic literature, rapid computation speed, and the author's expertise in the software. Additionally, Python has several useful libraries, that complement the use of the Gurobi API. Nevertheless, the problem under consideration is known to be NP-hard, as explained in Chapter 3.2, which implies that for medium and large-scale problems, an optimal solution might not be achievable within a reasonable time. The size of the fully incorporated model is currently unknown, but expected to be medium to large-scale upon comparing it to the models found in the literature. Hence, a heuristic approach is proposed in Section 4.5.1, which produces high-quality solutions in a practical amount of time.

4.4 Uncertainty

As mentioned in Chapter 1, at both the recycling market and at the company, there is a lack of data and the system to acquire data regarding the uncertainty in the supply chain. E.g. the ratio between accepted and rejected freight of input materials from the suppliers and the same ratio of end product at the customers, and the available amount of input material in the whole market. This makes it hard to extract necessary probability distributions. As mentioned in Chapter 3, in order to implement a SP model on e.g. price and quantity of input material, a known probability distribution is required.

Nevertheless, these uncertainties affect the general schedule, thus have to be accounted for. Therefore, the RHS is applied as a first measure to incoporate uncertainty, as mentioned in the first subsection 4.4.1, since it does not require a known probability distribution. The RHS includes the distant future to mitigate the short term margins and maximise the margins over the long period (Till et al., 2007). This is to mitigate the bullwhip effect experienced by the company on the supplier side.

If the scenario-based approach were chosen, such as RO or SP, then the company would rely mostly on managers expert opinion for input data. Relying on that knowledge is considered a risk of harm, as described in Chapter 1.3, therefore not an option for the company.

A second measure to combat uncertainty is with a CCP, as mentioned in the Section 4.4.2. The quality of the input material is relatively uncertain upfront, and can only be fully assessed during unloading and in production. Therefore, the input material can be rejected upon arrival due to quality concerns. The company needs sufficient input material in both quantity and quality to produce sufficient end products to satisfy their customers.

CCP helps to make the model robust against uncertain events. An advantage of this approach is flexible and allows decision makes to choose different risk profiles, given the likelihood of an uncertain event occurring. Next to that, it makes the decision-makers in the process aware of a certain risk and help them to act accordingly. For example, a decision-maker may be willing to take on more risk in exchange for a higher expected payoff, or may choose to minimize the risk even if it means a lower expected payoff.

4.4.1 Rolling horizon strategy

The RHS divides the solution space into two different intervals:

1. **Frozen interval:** covers the solutions in the first period and are implemented immediately. These are purchasing and sales decisions, e.g. the quantity input materials to source from the suppliers and the quantity of end products each factory has to produce and the customer to send it to. These decisions form the general schedule for the upcoming month, which include the sales and the production schedule.

   The frozen interval spans the same period as the general schedule, thus spanning the supply chain decisions for the upcoming month. This is the red block in cycle 1 as seen in Figure 15.

2. **Free interval:** covers the solutions in the periods after the frozen interval and are not necessarily implemented immediately. These decisions provide insight into future sales and purchase decisions, which can be used to inform the suppliers and manage their expectations for the periods

after the frozen interval. Therefore, the interval is more reliant on forecasting of demand and price developments or scenarios as the frozen interval.

The free interval spans the decisions for the successive months. These are the green blocks, representing month 2 until month 3, as shown in Figure 15. This is inline with the company's plans to include the subsequent period in their planning.

The RHS for the general scheduling process is illustrated in Figure 15, where the red square indicate the frozen interval and the green parts indicate the free interval. It is implemented as follows:

1. The start of the general scheduling process is at timestamp 1, before the general schedule is executed. Here the relevant data is gathered in order to calculate the schedule using the model from Section 4.2. The input data is described in Chapter 5.
2. At the start of month 1, the general schedule is executed, spanning the purchasing, sales and production decisions for month 1. This is considered to be the frozen period.
3. The free interval is considered to be month 2 and 3. For this interval, the forecast on the input price is used. This could result for example in purchasing more input materials for month 1 due to a dip in the costs price. Also used to inform supplier about the need for input materials in the successive month.

After the re-planning periodicity (RP) has passed, cycle 2 is executed and the timeline is moved forward, meaning the general scheduling process is reapplied with new data. After the RP of cycle 2 has ended, the timeline is moved forward again. This is done for all successive cycles.

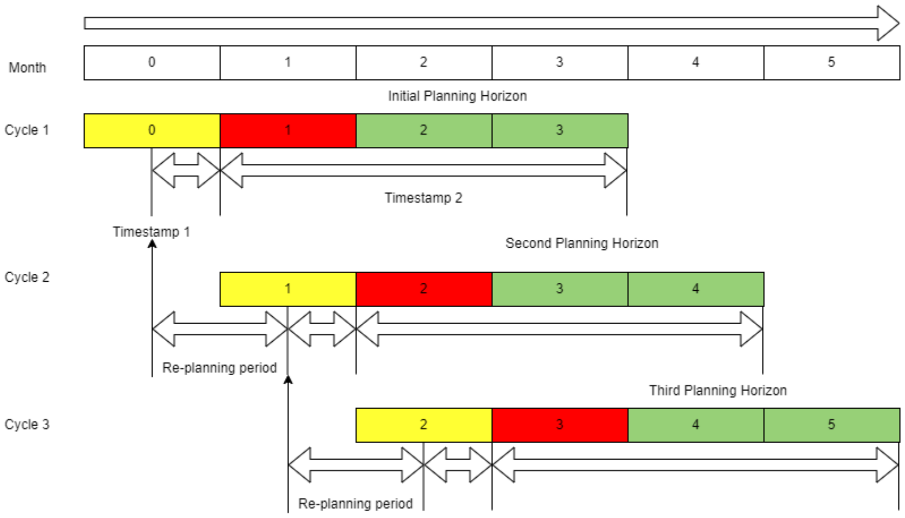


Figure 15: Overview of the rolling horizon strategy applied to Rymoplast.

4.4.2 Chance constraint programming

The primary source of variability arises from the supplier's end, as Rymoplast often rejects specific incoming shipments due to quality issues. However, a sufficient supply of input materials is crucial to fulfill the existing demand.

Therefore, the deterministic constraint (2) in the main model is altered to a stochastic constraint using CCP to account for this uncertainty (Shih & Frey, 1995). This approach is chosen as it requires a simple alteration to a single constraint. Next to that, it allows incorporating the risk preference of the purchasers.

The constraint aims to represent the probability that the total amount of input materials present at factory f at time t, due to the increase of input materials caused by incoming freights z_{ljht} and the decrease of input materials resulting by its use in production, is bigger than the input materials used in production x_{hjit}. The probability has to be bigger given an explicit reliability measure α, which can be altered in accordance to the risk preference of the decision maker. The rate at which input materials are accepted, is the AR_l and depends on the supplier. The variables used to determine if there is sufficient input material at a factory consist of a stochastic and deterministic values: the acceptance ratio AR_l is stochastic, while the reliability measure α, incoming input material z_{ljht}, used input material x_{hijt} and inventory position $IM_{hj(t-1)}$ are deterministic value. The amount of input material x_{hijt} that is used and the amount of incoming input material at a factory z_{ljht} are decision variables of the model. This can be summarised in the following constraint:

$$Pr\left[InputAccepted_{fht} \geq InputNeeded_{fht}\right] \geq \alpha, \forall f, h, t \tag{13}$$

Where $InputNeeded_{fht}$ is

$$InputNeeded_{fht} = \sum_{j=1}^{J} \sum_{i=1}^{I} x_{hijt} - IM_{hj(t-1)} \tag{14}$$

And the total amount of incoming materials that is accepted, depends on the amount of materials that is incoming z_{lfht} and the amount that is accepted AR_l. This results in the varaible:

$$InputAccepted_{fht} = \sum_{l=1}^{L} z_{lfht} * AR_l \tag{15}$$

There is insufficient data to determine μ_l and σ_l of the AR_l. Therefore, a data-gathering method and a stochastic formulation of the constraint model are given as recommendations. Next to that, it is not possible to write the intended constraint as a linear constraint due to a non-linearity in the probability distribution. This is further clarified in the Appendix. A simplified constraint is used instead in the form of a linear probability distribution is used, coming from expert opinion, to at least account for the supply uncertainty. Assumed then that the acceptance rate of incoming freight is the same across all months for all suppliers and all different types of input materials. This is in reality different. The constraint used for the model is:

$$\sum_{l=1}^{L} z_{lfht} * AR_l \geq \sum_{j=1}^{J} \sum_{i=1}^{I} x_{hijt} - IM_{hj(t-1)}, \forall f, h, t \tag{16}$$

4.5 Solution method

To begin, we explore an approach to determine whether it is necessary to employ a heuristic method, such as SA or GA, to achieve an optimal solution within a reasonable timeframe. Due to the unknown size of the model and the problem being NP-hard, it is unsure if the model can be solved in polynomial time, as mentioned in Chapter 3. Therefore, an algorithm is used to provide the company with a high-quality solution in a reasonable amount of time. This problem is addressed in Section 4.5.1.

The criterion for solving the model to optimality is set at a maximum time limit of 12 hours. If the model can be solved within this timeframe, there is no need to explore the sub-problem or implement any additional methods.

In the event that the time limit is exceeded, a smaller sized model is implemented. This involves reducing the model size and customizing it to handle each factory separately and solve it within the given 12-hour time frame. By doing so, an investigation can be conducted to determine the extent to which the model can be classified as NP-hard. This means separating the input data into smaller subsets and solving them individually to optimality. However, these sub-problems depend on each other. For example, if factory 1 satisfies the total demand of customer A, then factory 2 cannot satisfy the same demand. Vice versa on the supplier side, if factory 1 sources all input materials from supplier A, then factory 2 cannot source from the same supplier. Therefore, the sub-problems have to be solved in sequence of each other and the input data is altered depending on the previous sequence. This sequence is provided by the company.

4.5.1 Heuristic

If the solver fails to find an optimal solution within the specified 12-hour timeframe, a heuristic approach is taken into consideration. By employing a heuristic, the benefits of a fully integrated supply chain scheduling model are kept, while still achieving a high-quality solution within a reasonable time frame.

As mentioned in Chapter 3.3, SA and GA, are among other meta-heuristics which are considered popular for solving large-scale optimisation problems (Bianchi et al., 2009; Fahimnia et al., 2018). Moreover, both heuristics mentioned are part of a larger set of heuristics that have shown success in the realm of supply chain management (Arostegui Jr et al., 2006; Esmaeilikia et al., 2016; Fahimnia, Parkinson, et al., 2013).

The SA heuristic is chosen over the GA, as has shown a promising result in the literature paper of Fahimnia et al., where the SA shows faster convergence behaviour than GA when compared under a time restriction. This is beneficial for the limited time available for Rymoplast to solve the problem. Additionally, the best-found solutions differ only slightly.

Both SA and GA are considered good at finding adequate solutions near known solutions by searching the solutions space randomly. However, it is likely of being trapped into local optima too early, particularly when the solution space is regarded as larger and there are many local optima. This could pose a threat to the time at which the model is able to find an adequate solution, as there is a chance that the model gets trapped into an early local optimum, especially with large-scale problems. As these aspects have not been established yet, it is still good to keep them in mind.

Lastly, the author of this thesis is familiar with the use and implementation of SA.

Whether the meta-heuristic is applied in this thesis, including a discussion on the solving time of the model, is discussed in Chapter 5.

4.6 KPIs

As mentioned in Section 1.3, there are no metrics that monitor the performance of the general schedule. This is key to track whether the proposed model improves the general scheduling process of a month. In the literature of Chapter 3, a list of relevant KPIs are proposed. In collaboration with the company supervisors, a small selection of most relevant and applicable KPIs is made, as presented in Table 5.

The goal of the general schedule is to deliver the right quality and quantity of end products to the customers. As found in the literature, the on Time in Full (OTIF) is used. The metric keeps track of the number of deliveries accepted by the customers and compares them to the number of planned orders at the beginning of the month. The aim of this metric is to assess the effectiveness of the general schedule worked.

The main bottleneck of the process is on the supplier side, as mentioned in Section 1.3. In order to achieve a high score of the general scheduling process, Rymoplast depends on the right quality and quantity of input material from their suppliers to create a sufficient quality and quantity end product, in order to meet the demand of their customers. Therefore, it is important to track the performance of the suppliers. The following KPI focussing on the supplier side is chosen: Percentage Orders received defect free (Huang & Keskar, 2007). A score close to one is considered good, and a score close to zero is considered bad. Next to that, this metric is input for the CCP formulated in Section 4.4. The metric can also be altered to track the performance of a single supplier.

Lastly, the objective value of the general schedule model is used as a metric, which is the margin between purchasing costs and sales revenue per end product. The metric gives the business details about the top-performing final product. This affects both tactical and strategic choices, such as whether to expand a factory for a specific end product, shift production capacity to increase the output of a high-performing end product, or focus more on a specific end product to increase margins.

No.	**Metric**	**Definition**
1	General schedule performance	Number of deliveries accepted by the customers divided by the number of planned orders at the beginning of the month
2	% Orders received defect free	Number of orders received defect free by suppliers divided by total number of orders processed in measurement time
3	Production Margin	Total sales revenue / (Total costs of input materials + Total costs of transportation)

Table 5: Overview of the KPIs used in this research

4.7 Conclusion

The main goal of this chapter is to outline an approach to inprove the general scheduling process. Using forecasted input material prices, the advising model develops a three-month planning that affects decisions on movements of both input materials and end products managed by sales and purchases. The model maximise the margin between purchasing costs and sales revenue by optimising the movements between suppliers, factories and customers and the recipe of an end product.

RHS and a constraint derived from CCP is added to the main model to address the uncertainty. In RHS, only the decisions of the fixed interval made for the first month must be carried out; the remaining two months, the free interval only serves as guidance. CCP makes sure there is sufficient input material available at the factories.

The model is solved to optimality using an increasing scope of the company. First off, an optimal schedule for a single production line is given, then it increases to a single factory until the internal supply chain is included. Due to the NP-hardness and the unknown size of the model, we apply the meta-heurisitc SA to get a high-quality solution in an adequate amount of time.

In order to monitor the performance of the general schedule, we used three metrics. The first metric monitors the effect of the schedule, which monitors ratio of planned freights and delivered freights. This metric is partly affected by reliability of sufficient quality of input material accepted by the company. A second metric therefore tracks the amount of accepted incoming input freights. The last metric monitors the direct effect of the general schedule on the production margin of the company, which is the margin between the purchasing costs and sales price.

5 Input and results

In order to test the model's capabilities, an input data set is created to validate the model's outcome and eventually convince the decision-makers that the outcome is valid and can be put into practice. Therefore, the current situation is chosen as if it was implemented and used now, to engage the decision-makers in the scheduling process from the start and to experience the implementation of the RHS. To be more specific, the data set describes the situation as if the decision-makers were to start the planning process in January and plan for the period of February up to and including April.

A reconstruction of the past could not be made, and a comparison between the decisions taken by the model and those taken in the past could not be made. As we were unable to gather the data necessary to recreate a situation from the past, as certain data points were missing or hard to verify their accuracy.

This chapter covers the generation of input data for conducting an initial situation, as outlined in Section 5.1. Subsequently, the outcomes of the base scenario are examined in Section 5.2 to assess the model's validity, such that the managers can depend on the results and apply them in practice. Finally, Section 5.3 concludes the chapter, summarizing the key findings and implications.

5.1 Dataset

First off, the input data is introduced by outlining the manner in which it was generated. In particular, the process of data gathering involved collaboration with decision-makers from various departments, including production, sales, procurement, and logistics. The dataset used in this thesis is presented in Appendix Table 7 and provides a comprehensive description, including its size and average values.

Purchase The purchasing price for each type of input material was determined using a forecasted price based on the purchasers' expert opinion in assistance with a forecasting program, as shown in Figure 16.

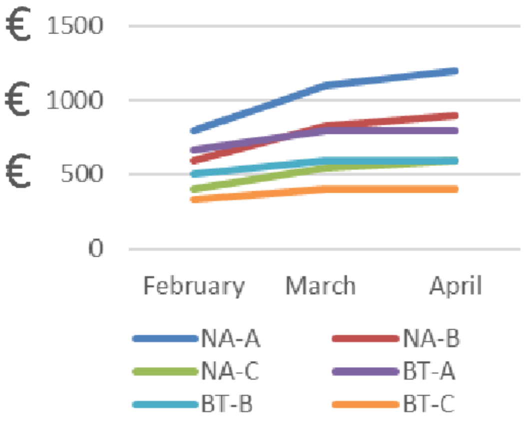


Figure 16: Purchasing price development of the planning period

The data used to determine the maximum supply quantity of each supplier is based on the dataset covering 2022. This data is the most recent dataset that covers an entire year. Next to that, this dataset has a good data quality when compared to other data sets that cover an entire year.

Sales The maximum and minimum sales volume is based on the forecasted demand for the year 2023. This forecast is mostly based on contracts for the entire year 2023, and contracts that were still in the making, when the data was gathered.

Similar to the purchasing price, the price of each end product was determined using a forecasted price based on the sales managers' expert opinion in assistance with a forecasting program. Depending on the base price, the customer and the application of the end product a final sales price is determined.

Production The data regarding e.g. the recipe and inventory capabilities were extracted based on their current product catalogue and factory configuration. Most notable is the production speed of each production line, which is determined by measuring the total produced output over the total available production time in the month of December 2023. Thus, the total available production time includes errors in production and maintenance. In the current scheduling, this data is used as this data for the scheduling process as is most up-to-date with the current performance of the factory and the production capabilities of the production lines and therefore most accurate.

Transport The most recent transportation costs were used for the dataset. At the time the data was collected, the oil prices were fluctuating considerably, and therefore only the most recent prices of January were accurate enough to represent the current situation. The fixed tonnage transport for the input is 25 tons.

5.1.1 Validation of input data

Ensuring the accuracy and reliability of the input data is crucial for obtaining quality and optimal results. The model's output depends on the quality of the input data, which makes validating the data an essential step in the modeling process. Inaccurate or incomplete input data can lead to wrong conclusions and suboptimal decisions, and therefore unreliable decisions in practice.

The data in question has been gathered and validated in collaboration with the relevant decision-makers. The transportation data has been reviewed and confirmed by both the logistic and production managers, while the production data has been validated by the production manager. The sales manager has validated the sales data, and the purchase manager has done so for the purchase data. All parties involved have deemed the input data to be feasible and valid.

The validation process itself involves taking the responsible employee through the data determination process. Depending on the size of the data set, a certain number of data points were randomly selected for examination, or alternatively, all data was subject to scrutiny. In the event of a mistake being detected, the corresponding data point was altered accordingly.

5.2 Results base situation

In this section, we present the outcomes of the base situation for each decision-maker involved. Additionally, we discuss the validity of the model to ensure that its outputs align with the expected outcomes. This step is crucial in confirming that the implementation of the model was successful and that it is performing according to the desired specifications. Furthermore, the practical applicability is commented on, with a focus on reliability for the managers.

The figures presented in this chapter and in consecutive Chapter 6 are depicted in units of 1,000 kilograms.

5.2.1 Solving time

Regarding the solving time, an experiment was conducted by running the base situation for 5 hours. The initial solution, achieved within 1 minute, had a gap of 0.16%. After 5 hours of computation, a slightly improved solution with a gap of 0.12% was obtained. Given that an adequate solution is found within a reasonable time frame, there was no need to implement the SA heuristic.

5.2.2 Objective

Initially, we discuss the objective value. In this section, we further elaborate on each component of the objective value in their respective subsections. This serves as a basis for comparing the objective values of different situations and understanding the impact of parameter changes on the objective value, as it represents the total margin of the company.

The base situation's objective value yields a total margin, the sales revenue, the purchasing costs and transportation costs are shown in Figure 17.

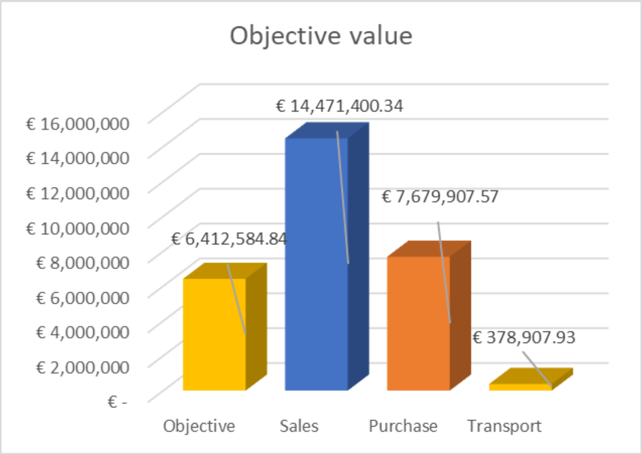


Figure 17: Objective values of the base situation

5.2.3 Sales

The sales revenue amounts to €14.471.400,34 over the course of three months. To achieve this, a total of 11,096 tons of end products have been sold. This can be split into three separate months and types of end products as depicted in Figure 18.

The sales revenue is computed using the numbers in Figure 18 with a stable average price per ton of €1,480, €1,378, €770 and €780 for Rymo21, Rymo22, Rymo51 and Rymo81 respectively. The reader can be assured that upon multiplying the sales volume with the sales price, the sales revenue is achieved.

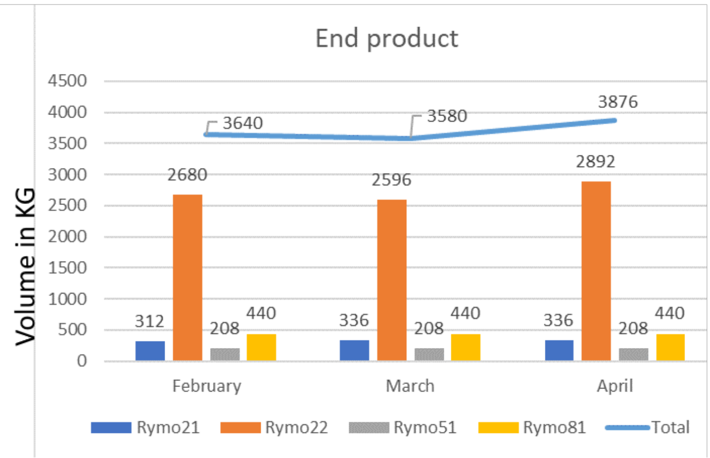
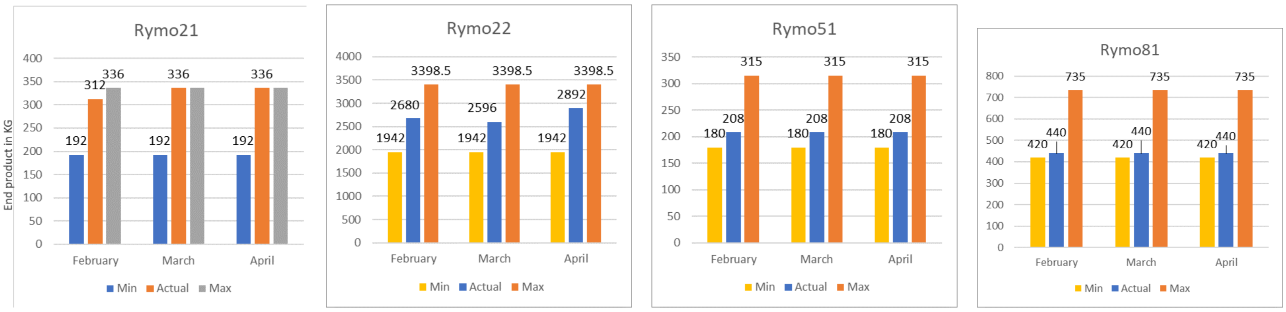


Figure 18: Sales volume per end product

A constraint that has to be fulfilled is the minimum and maximum demand per customer location.

As shown in Figure 19, the actually sold volume of end product stays within the set minimum and maximum demand. Notably is that the natural end products, in this figure Rymo21 and Rymo22, are towards their maximum, while the bont end products such as Rymo51 and Rymo81 are close to their minimum. This can be attributed to the higher margin of natural compared to bont. The margin for natural Rymo21 and Rymo22 is approximately €762 and €753, respectively, whereas the margin for Rymo51 and Rymo81 is around €203 and €287, respectively. This is in line with the expectation, as the model's objective is to seek the maximum margin, while still adhering to the demand constraint.



(a) Rymo21 **(b)** Rymo22 **(c)** Rymo51 **(d)** Rymo81

Figure 19: The amount of input material purchased over the first month of February from each individual supplier

Practice Together with the sales manager, each individual sales volume was checked per customer location per period to validate the model. Together with the previously mentioned data e.g. the maximum and minimum demand, the sales manager concludes that the results feasible and realistic.

5.2.4 Production

The sold end products have to match the factory's output as stated in the models' constraint. Therefore, the production data is discussed next and whether the results adhere to the model's constraints and can be put into practice. For this, the results regarding the production are used.

The first constraint is checked whether the output of the production lines' factories to the customer, match with its input. The input of the production lines can be seen in Figure 20, where the input times the yield of 0.9 for natural and 0.85 for bont input materials respectively, matches the output for the month of February. For the Rymo21 it means that the 312 tons produced matches its input of 96.7 and 250 tons NA-A and NA-C respectively, keeping in mind the 90% yield. The same logic can be applied to the Rymo22, Rymo51 and Rymo81 to verify the results. The method used to verify the constraints for the months of March and April is the same as for the previous months.

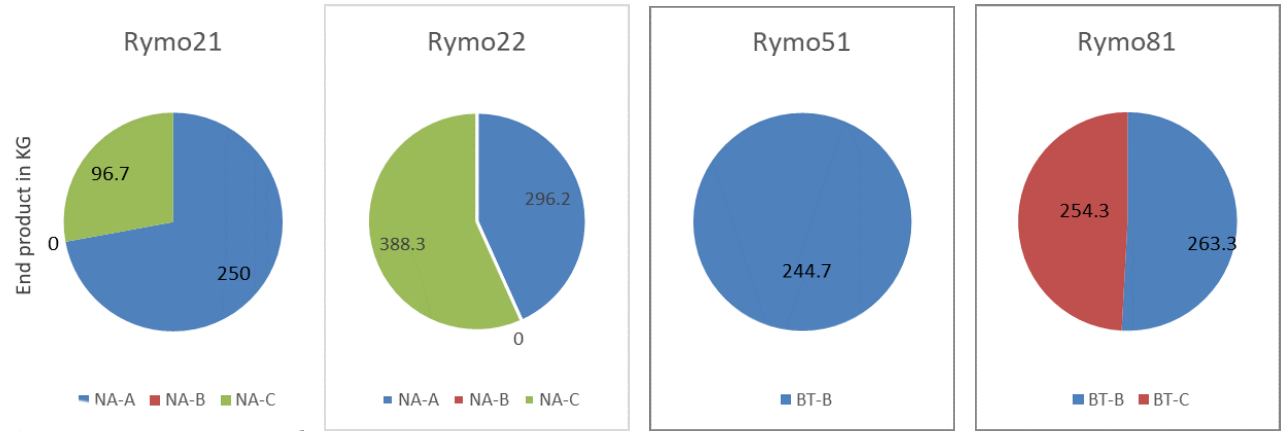
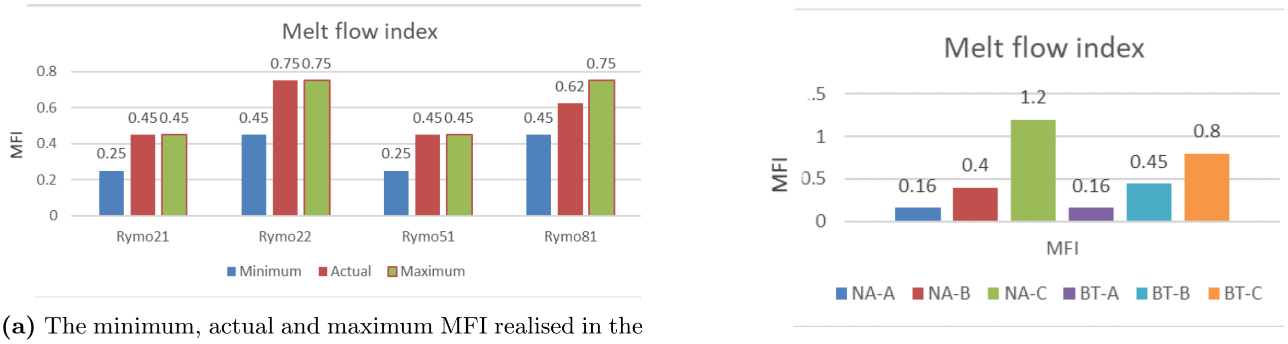


Figure 20: The input material used per end product in the month of January

Secondly, the MFI constraint is checked, where the realised MFI has to lie within the product specifications bound. This is achieved as shown in Figure 21a, where the actual realised MFI lies within minimum and maximum. It is worth noting that the MFI lies close to the maximum of the product specification. Since the objective of the model is to maximize the margin, the most cost-effective option is selected. Both the natural and black options have decreasing prices per ton for qualities A to C, while the MFI increases from qualities A to C, as indicated in Figure 21b. As a result, it is expected that the C qualities with the cheapest cost and highest MFI is preferred. This is discussed further in in the following section.

Rymo81 stands out as it is not close to its maximum MFI. One possible explanation for this is that the model has not found the global optimum yet. Therefore, it is still possible that Rymo81's MFI lies close to its maximum MFI.



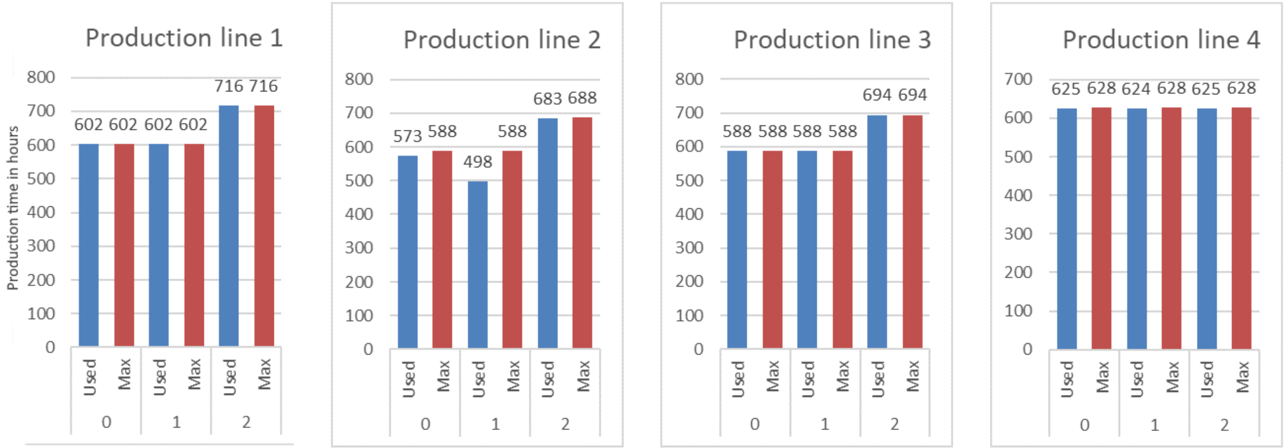
(a) The minimum, actual and maximum MFI realised in the month of February

(b) The MFI per input material

Figure 21: MFI graphs depicting the MFI per input material (a) and the realised MFI (b)

Another constraint that is checked is the production capacity constraint for each production line. The maximum production times available in red and the used production times per production in blue are plotted in Figure 22, where the number 0 to 2 represent the months February to April. This figure shows that the used capacity is kept under its maximum, thus the constraint is fulfilled.

Notably in the sales part was that the sales increase after a decrease, where the total tonnage sold went from 3,640 to 3,580 ending at 3,876 as shown in Figure 18. The last month has a higher production capacity for all production lines except 4, as shown in Figure 22, thus more end products can be produced and consequently sold. As previously mentioned, the model was not solved to optimality and therefore the unused production capacity can be explained for production line 3. In the unused production time of 90 hours, at least three full FTLs of end product could be produced.



(a) Rymo21 **(b)** Rymo22 **(c)** Rymo51 **(d)** Rymo81

Figure 22: The production capacity used per production line

Practice In order to validate the mix ratio and convince the production manager that these mixtures are realistic, the company's database is consulted, where the recipes including their mix ratio from previous orders can be found, which are similar to those seen in the results. Also, based on expert opinion, the mix ratio has been validated. Lastly, the output is checked to see if the used production capacity and the production output are realistic.

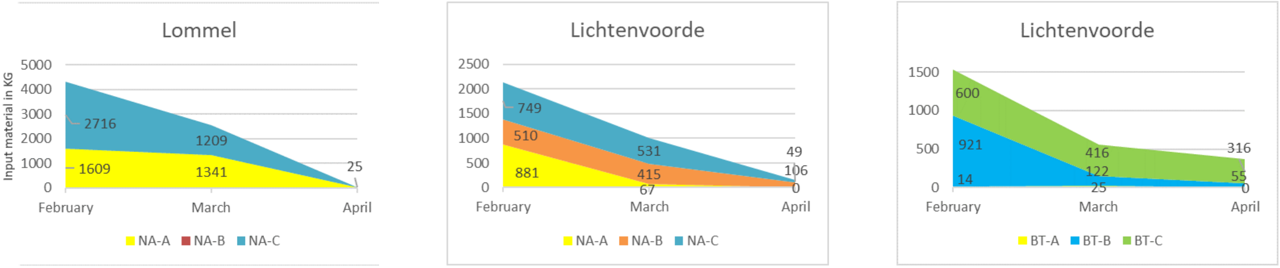
5.2.5 Purchase

To ensure that the production line operates smoothly, an adequate supply of raw materials is required. As a result, the purchasing department has to ensure that sufficient input materials are available in inventory and flow to the factories. This has been implemented in the model.

As stated by the inventory constraint, the input in the production lines, the inflow in purchased input material and the inventory position of the previous month has to equal the inventory position of the current month. In order to check the constraints, the usage of input material for production of each factory is depicted in Figure 24. The inflow of purchased input material is depicted in Figure 23. The inventory position for each month is show in Figure 25. Upon adding the inventory position of the previous month of Figure 25, the inflow of input material of Figure 23 and subtracting the usage in the production line of Figure 24 for all types of input material, time periods and factories, the result matches the inventory position stated in Figure 25. This validates the inventory position constraint.

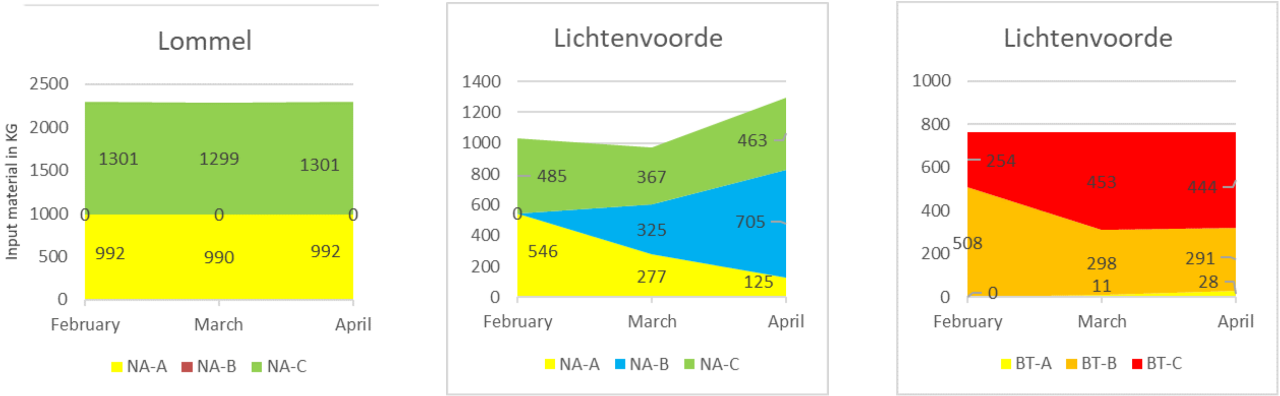
The purchasing results also have to adhere to the maximum supply constraint. The maximum supply availability per month constraint is presented in Figure 26 for each factory. The total input material purchased each month remains below the maximum represented in Figure 23. This explains the fact that not all input materials is bought in the first month for the entire planning period since the maximum supply available is reached, but also in the following month input material is purchased.

Since the inventory position is validated as mentioned previously, the constraints for the starting inventory and safety stock can be validated further. The starting inventory is for all types of input material and both factories is 100 tons, which can be seen in Figure 25. Next to that, the safety stock is set to be higher than 100 tons for all types of input material and both factories throughout the planning period, which can also be seen in the same figure.



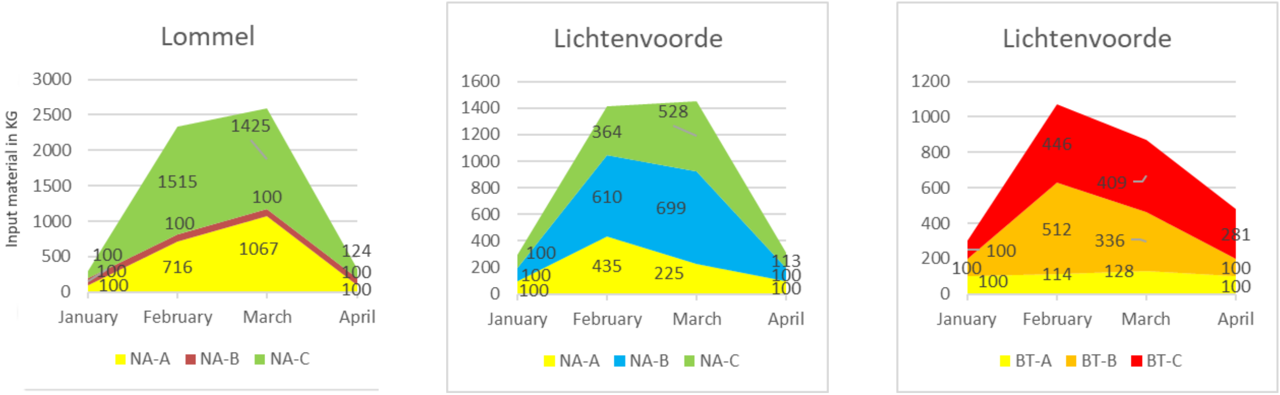
(a) Lommel (b) Lichtenvoorde (c) Lichtenvoorde

Figure 23: The inflow of input material



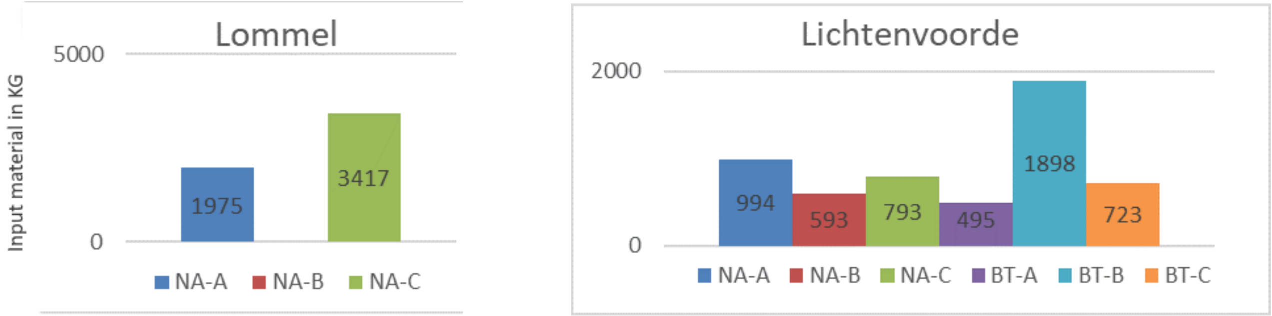
(a) Lommel (b) Lichtenvoorde (c) Lichtenvoorde

Figure 24: The usage of input materials per factory



(a) Lommel (b) Lichtenvoorde (c) Lichtenvoorde

Figure 25: The inventory position of input material



(a) Lommel **(b)** Lichtenvoorde

Figure 26: The maximum inflow of input material per location

Notably is the decline of purchased input materials throughout the planning period as shown in Figure 23 This is logical since the purchase price is slowly increasing as shown in Figure 16. As the model aims to create the biggest margin by minimising the purchasing costs, most input material is bought in the early months, given that there is supply maximum of input material and sufficient storage capacity.

To adhere to the MFI product specifications and still achieve the lowest costs as is the models' objective, the lowest costing and highest MFI having input material quality C is preferred. Referring back to the point made in the production part regarding the mixture of input material, Figure 16 shows that the C qualities are the cheapest, thus the resulting mixtures are as expected.

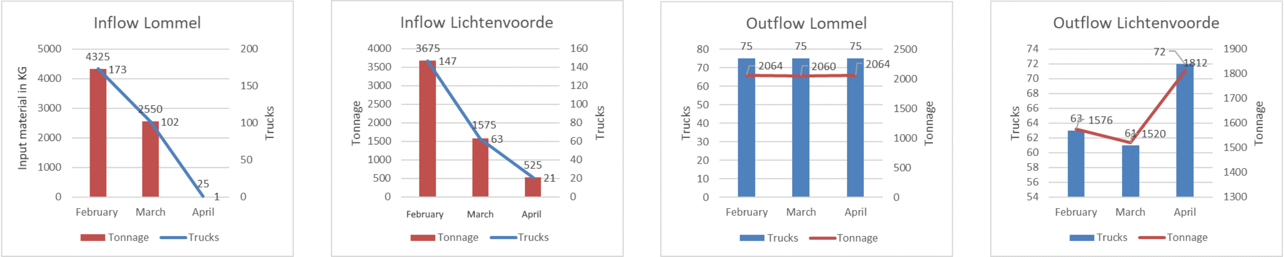
Practice Together with the purchase manager, each individual purchase volume was checked per supplier per period to validate the model. Together with the previously mentioned validation steps e.g. the maximum supply and price supply, the purchase manager concludes that the results are feasible and realistic.

5.2.6 Transport

The last constraint that has to be checked is the transportation constraint, where all inflows and outflows of product have to be transported on a truck with a fixed tonnage.

The amount of trucks times the truck load should match the tonnage input material received. Figure 27d representing Lichtenvoorde and 27c representing Lommel present the inflow of product in both the tonnage received and the amount of truckloads. As easily can be checked, the tonnage received divided by the truckload matches the 25 tons and therefore the trucks constraint for inflow is valid.

The same is done for the output as presented in Figures 27c for Lommel and 27d for Lichtenvoorde, the sold end products for both factories is presented. For the output, this can be 24 or 28 tons, depending on the customers' location. As easily can be checked, the tonnage sent out divided by the truckload matches a number that lies between 24 and 28 tons, and therefore the trucks constraint for outflow is valid. A more precise examination is done, where the tonnage per truckload per customer locations is checked, resulting in an exact match between the tonnage output and the truckloads sent out.



(a) Inflow Lommel **(b)** Inflow Lichtenvoorde **(c)** Outflow Lommel **(d)** Outflow Lichtenvoorde

Figure 27: The inflow and outflow of product for each factory

5.3 Conclusion

In this chapter, the process of generating the input data for the base situation is discussed, and how it was validated with the assistance of departmental managers. The data set was created to test the model's capabilities, and ultimately test and validate the model's outcome. The data set describes the situation as if the decision-makers were to start the planning process in January and plan for the period of February up to and including April. Important is the validation of the input data, as the accuracy and reliability of the model's output relies on the quality of the input, such that reliable supply chain decisions can be made.

Upon running the model for 5 minutes, the best-found solution yields a total objective value of €6.412.584, with sales revenue amounting to €14.471.400, and costs of purchasing and transport of €7.679.907 and €378.907, respectively. The sales volume of Rymo22, the most profitable end product, was maximized, resulting in 2,680 tons sold, followed by Rymo81 with 440 tons sold, Rymo51 with 208 tons sold, and Rymo21 with 312 tons sold. The production recipes used in the solution were close to the maximum MFI, which was the most cost-effective option. The results also revealed that the majority of the input materials were purchased in the first month when the price was the lowest, causing a surge in inflow and inventory in the initial months resembling a bull whip effect.

In this Chapter, it has been shown that the model complies with the formulated constraints, which further validates the model. Next to that, the results were validated with help of the managers.

6 Sensitivity analysis

The ability to adapt to the uncertainty in the recycling market situation is crucial for the company performance. To understand the effects of certain economic situations on the outcome of the model, various situations are considered. Therefore, the input data of Chapter 5 has been altered, such that the model can keep up with these changes in e.g. demands and supply. More practically, a sensitivity analysis is conducted for each situation to assess the impact of adjusting specific parameters on the model's results. The expected outcomes are discussed, and the model's results are presented and compared against these expectations. Finally, the insights gained from the analysis are discussed. Next to that, it demonstrates the functionality and efficacy of the model, as it shows that it can adapt to certain situations as was expected, and thereby validates its reliability.

First off, the approach for the sensitivity analysis is written, where the expected behaviour, insights and changes to the input data are discussed for the three different situations to further assure the model's validity and show efficacy. After that, an overview of the situations is given in Section 6.1. The minimal supply situation is discussed in Section 6.2, a lowered maximum demand is discussed in Section 6.3 and finally an insufficient stream of input material is discussed in Section 6.4. In each section, the results of situations are described, and checked is whether they match the expectations mentioned previously to further validate the model. After that, comments regarding the size, performance and robustness of the model are given in Section 6.5. At the end, the chapter is concluded in Section 6.6.

6.1 Overview situations

To start off, an overview of several distinct technical and economic situations is provided. These may include adjustments to production capacity, inventory capacity, starting inventory levels, and production capabilities. However, the company has identified the aforementioned situation as particularly crucial and will therefore be discussed in greater detail. In the subsequent sections, the description, expected outcomes, and objectives of each situation are highlighted, as well as the alterations made to the input data to reflect the various technical and economic circumstances. Finally, a comparison is made between the output generated by the model and the expected outcomes to evaluate their alignment. An overview of the situations is given in Table 6.

Nr.	**Section**	**Description**
1	Minimal Supply	50% of the maximum supply for the top 10 suppliers
2	Minimal Supply	25% of the maximum supply for the top 20 suppliers
3	Lower maximum demand	Total maximum demand is set to 75% of the original demand
4	Lower maximum demand	Total maximum demand is set to 50% of the original demand
5	Insufficient bont or natural available	The maximum supply of naturel available is set to 50% of the original supply
6	Insufficient bont or natural available	The maximum supply of naturel available is set to 25% of the original supply
7	Insufficient bont or natural available	The maximum supply of bont available is set to 50% of the original supply
8	Insufficient bont or natural available	The maximum supply of bont available is set to 25% of the original supply

Table 6: An overview of the situations

It is important to note that the solver in each situation runs for five minutes, and thus not all situations have been fully optimized. As is shown in Section 6.5.1, not more than 5 minutes is needed for the algorithm to find an adequate solution. Consequently, some of the results may show unexpected behavior that requires further investigation.

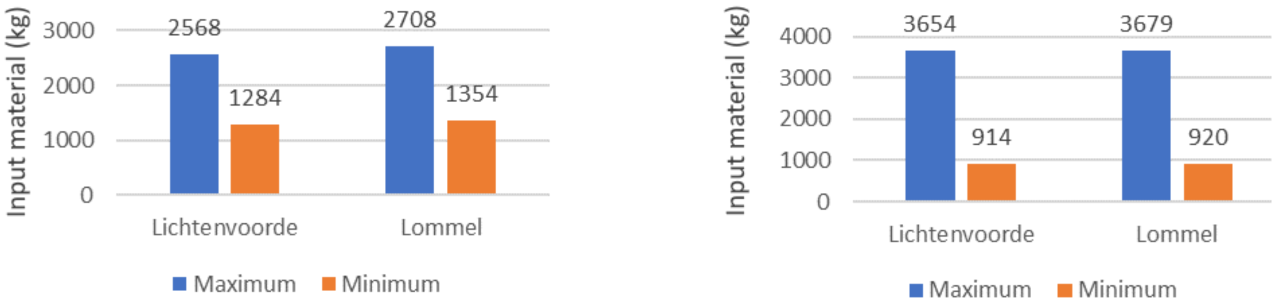
6.2 Minimal supply

As discussed earlier, the company has commercial interest to maintain a good relationship with its suppliers. Therefore, the company wants to implement a minimum supply quantity policy for its regular suppliers to force a stable supply of input material each month, regardless of the purchasing price. The expectation is that the implementation of the policy will result in a more consistent supply, with the supplied quantity remaining above the minimum set value, and overall supply fluctuations being reduced. It is anticipated that the objective values will experience a slight decrease for both the top 10 and top 20 supplier lists, as a result of the reduced total supply. The goal is to gain insight in the impact of implementing such a policy on the objective value and the inventory and supply quantity.

To achieve this, two separate policies have been created, for each factory, a list of the top 10 and top 20 suppliers has been compiled based on their total delivery amount in 2022.

6.2.1 Input

As mentioned previously, this situation knowns two instances, where for each factory a list of the top 10 and top 20 suppliers was created. The list consists of the top suppliers who delivered the most in 2022 for Lommel and Lichtenvoorde respectively, which account for a minimum and maximum amount of input material as shown in Figure 28. In this particular scenario, the minimum supply quantity is set to be at least 50% and 25% of the maximum supply quantity for the top 10 and top 20 suppliers, respectively.



(a) Top 10 **(b)** Top 20

Figure 28: The minimum and the maximum supply for each factory in the top 10 and top 20 situations.

6.2.2 Output

The objective values for the base situation, the top 10, and the top 20 suppliers, are illustrated in Figure 29. The results show a minor decrease in objective values of 10% and 5% for both the top 10 and top 20 situations.

The increase in purchasing costs is a notable finding, attributed to a more evenly spread purchasing throughout the planning period when the purchasing prices were higher. In contrast, the majority of the input materials are acquired in the base situation during the first month, leading to lower purchasing costs.

Figure 30 supports these findings, as it demonstrates a lower total volume purchased input materials at the start of the planning period and a higher amount towards the end. The minimum supply constraint, proves to be effective since at the end of the planning period the total input materials acquired for the top 20 and top 10 situations are 2,275 and 2,925 tons respectively, compared to below

100 tons in the base situation. These results contribute to the model's validation, highlighting the impact of the minimum supply constraint on the model's outcomes.

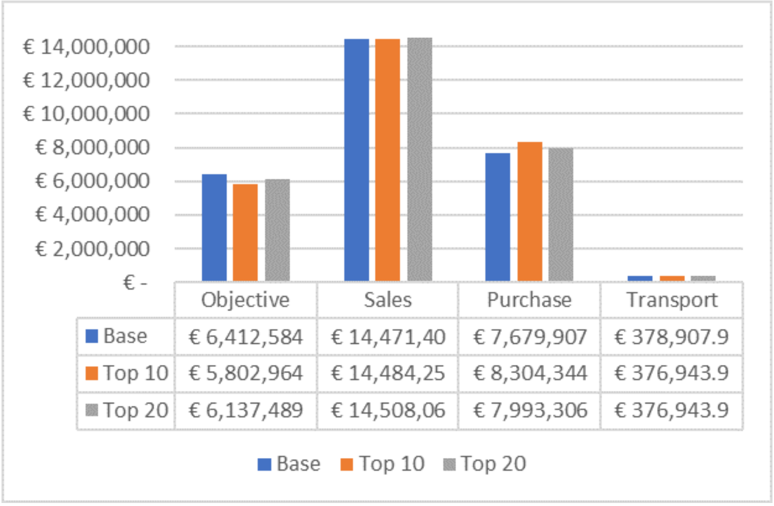
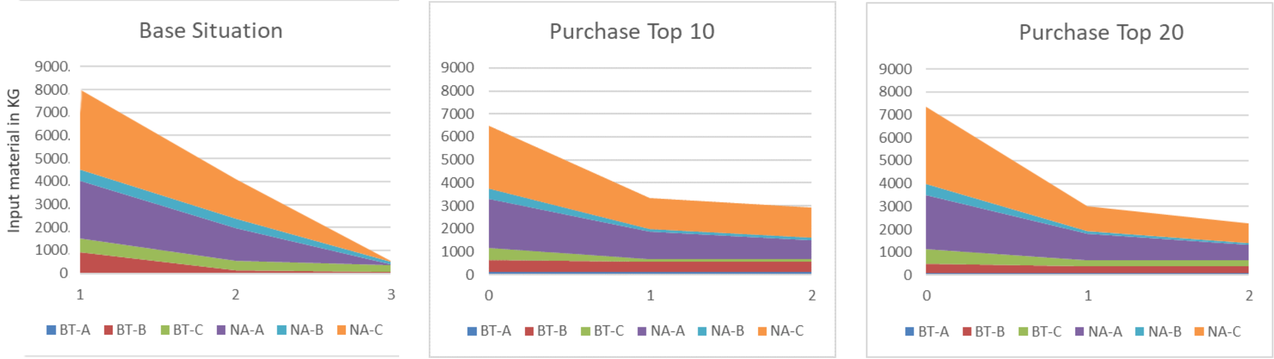


Figure 29: Objective value of the minimum supply situation



(a) Base **(b)** Top 10 **(c)** Top 20

Figure 30: The supply of input material in each situation

To conclude, the results provide valuable insight into the potential implementation of the model in real-world situations. The findings suggest that applying the model could lead to a decrease in the objective value of 10% or 5% for the top 10 and top 20 situations, respectively. Nevertheless, this trade-off could prove beneficial for the company, as it may improve the relationship with its supplier, which is challenging to quantify financially.

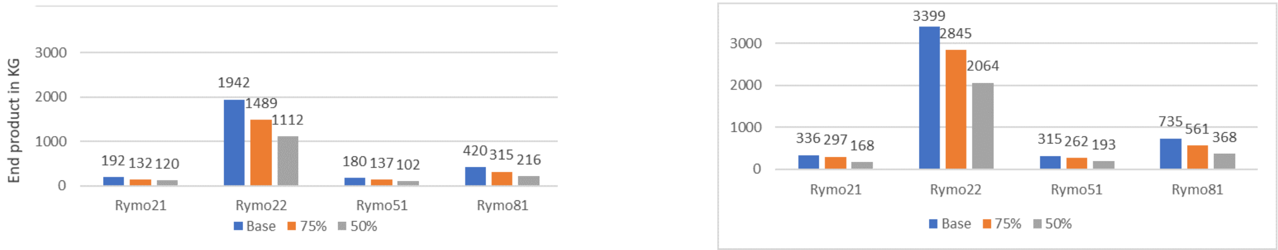
6.3 Lower maximum demand

This situation represents a scenario where the economy experiences a downturn and the company is unable to sell the projected volume of end products.

The expected outcome of this scenario is that the maximum sold amount of end product drops, leading to a decrease in the purchased input material. Moreover, a portion of the production capacity remains unused due to the decrease in the total sold end product. This ultimately results in a reduction in the objective values of the company. The objective is to gain insights into the effect of a decrease in sales on the overall performance of the company and shows the ability of the model to adapt.

6.3.1 Input

The situation involves two instances with a reduction in both the minimum and maximum demand of all customer locations to 75% or 50% of the originally expected demand, while maintaining one freight as the minimum. The minimum and maximum demand per type of end product are presented graphically in Figure 31.

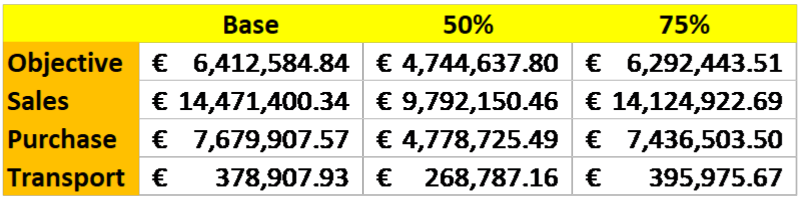


(a) Minimum (b) Maximum

Figure 31: The minimum and maximum demand represented for each situation

6.3.2 Output

The results show that the objective values significantly decreases for the 50% situation, while remaining relatively similar for the 75% situation compared to the base situation, as shown in Table 32 and Figure 33. As less end product can be sold, less input material is purchased, leading to a decrease in both purchasing costs and sales revenue.



	Base	50%	75%
Objective	€ 6,412,584.84	€ 4,744,637.80	€ 6,292,443.51
Sales	€ 14,471,400.34	€ 9,792,150.46	€ 14,124,922.69
Purchase	€ 7,679,907.57	€ 4,778,725.49	€ 7,436,503.50
Transport	€ 378,907.93	€ 268,787.16	€ 395,975.67

Figure 32: Objective values of the base, the 50% and 75% situations

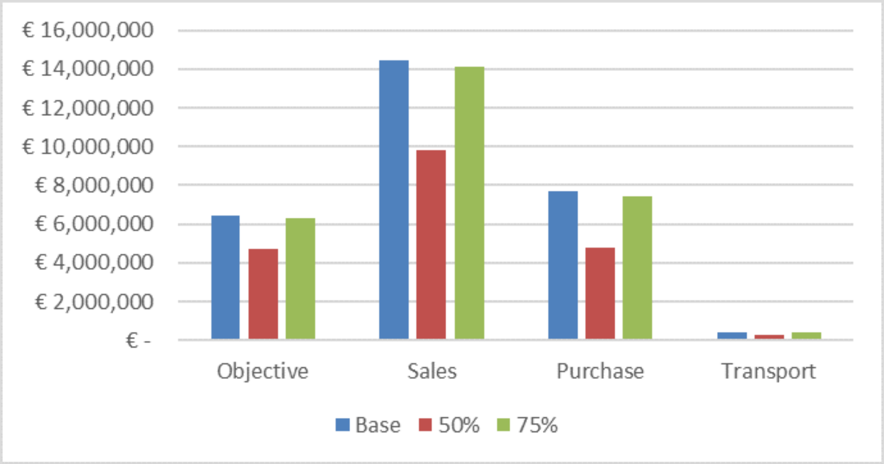


Figure 33: The graphical representation of the objective values in each situation

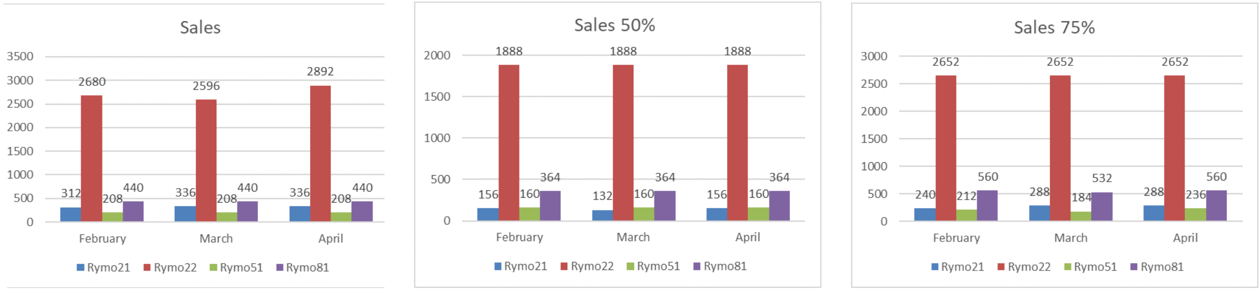
In the 75% situation, the maximum amount of natural end products is first reached, as the 2,652 tons remain unchanged throughout the planning period as seen in Figures 34c, even with an increase in production capacity towards the end of the planning period. Therefore, more bont Rymo81 is sold, going from 440 tons to 560 tons, filling the remaining production capacity.

More production capacity is available for production line 4, as shown in Tables 35b. But as production line 4 only processes natural and the demand for end products is at its maximum, consequently no additional end products are produced. The effect in the 75%-situation only has a minor effect on the company, but it demonstrates that the maximum demand of end product has been reached.

However, the effect is more present in the 50% situation, where the objective values decrease significantly as the maximum sales have decreased. The total volume of sold end products are on the maximum, as shown in 34b, since also production line 1 has production capacity left, which is able to produce both bont and natural end products.

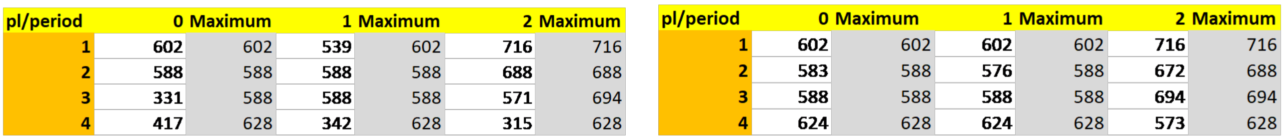
These findings give insight into the impact an economic situation has on objective value and production capacity. Most notable is the effect on Lommel's production line 4. Since the majority of the sold end products are natural, and Lommel produces only natural Rymo22, therefore the full production capacity of line 4 remains unutilized in both the 50% and 75% situations.

And as both situations provide results that were expected, the model's validation is enhanced further.



(a) Base (b) 50% (c) 75%

Figure 34: The quantity of sold end products in each situation



pl/period	0	Maximum	1	Maximum	2	Maximum
1	602	602	539	602	716	716
2	588	588	588	588	688	688
3	331	588	588	588	571	694
4	417	628	342	628	315	628

(a) 50%

pl/period	0	Maximum	1	Maximum	2	Maximum
1	602	602	602	602	716	716
2	583	588	576	588	672	688
3	588	588	588	588	694	694
4	624	628	624	628	573	628

(b) 75%

Figure 35: The production time used and the maximum production time per production line (pl) in hours

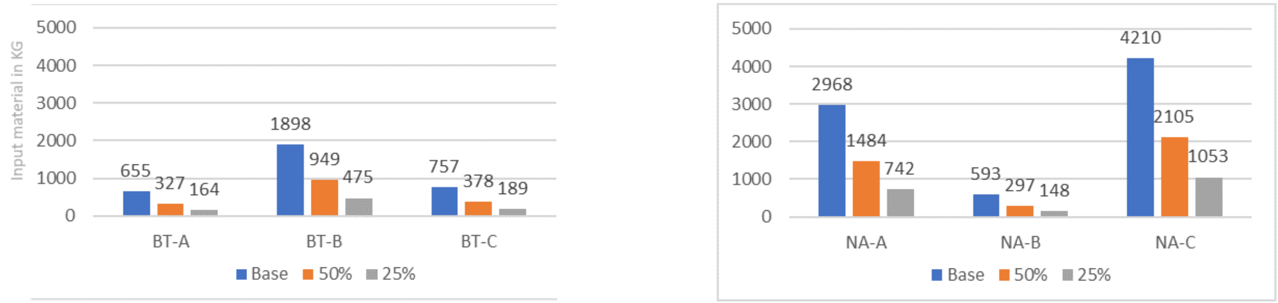
6.4 Insufficient bont or natural available

This situation pertains to an economic situation where the company is unable to source the adequate tonnage of input material in the market. The situation is split into two categories, namely natural and bont. Natural is the most frequently sold end product, and hence the decrease in objective value is expected to be most significant in this scenario. This is due to a decrease in the sales of end product caused by the limited supply of input material. Additionally, as the supply of natural input material reaches its limit, it remains stable each month. On the other hand, bont makes up only a small part of the total sold end product and is expected to experience none to a low impact on the objective value.

The aim is to gain insight into this situation on the objective value of the company, and consequently which factory is most affected in what manner.

6.4.1 Input

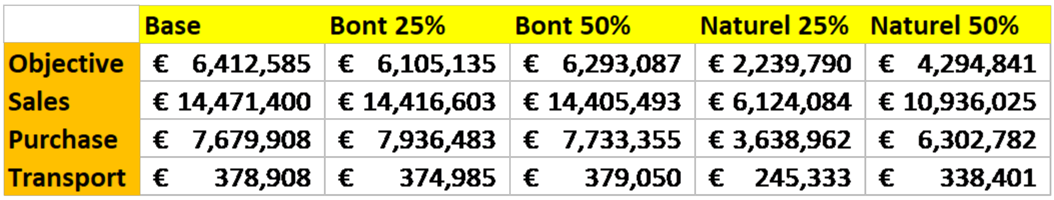
To simulate the situation, four datasets have been created to represent the total maximum supply of input material from all suppliers is reduced by 50% and 25%, respectively, for both natural and bont, as shown in Figure 36. In order to avoid infeasibility, the minimum demand of end product per customer location has also been lowered.



(a) Bont **(b)** Natural

Figure 36: The maximum supply represented for each situation

Output The impact of decreasing input material availability differs between the bont and natural situations. The objective value decreases by 5% and 2% in the former and by 65% and 33% in the latter situations respectively, as illustrated in Table 37 and in Figure 38. This result is as expected because natural end products Rymo21 and Rymo22 account for a significant portion (78%) of the maximum demand, while bont accounts for the remaining 22%, as can be seen in Figure 19.



	Base	Bont 25%	Bont 50%	Naturel 25%	Naturel 50%
Objective	€ 6,412,585	€ 6,105,135	€ 6,293,087	€ 2,239,790	€ 4,294,841
Sales	€ 14,471,400	€ 14,416,603	€ 14,405,493	€ 6,124,084	€ 10,936,025
Purchase	€ 7,679,908	€ 7,936,483	€ 7,733,355	€ 3,638,962	€ 6,302,782
Transport	€ 378,908	€ 374,985	€ 379,050	€ 245,333	€ 338,401

Figure 37: The objective values for each situation

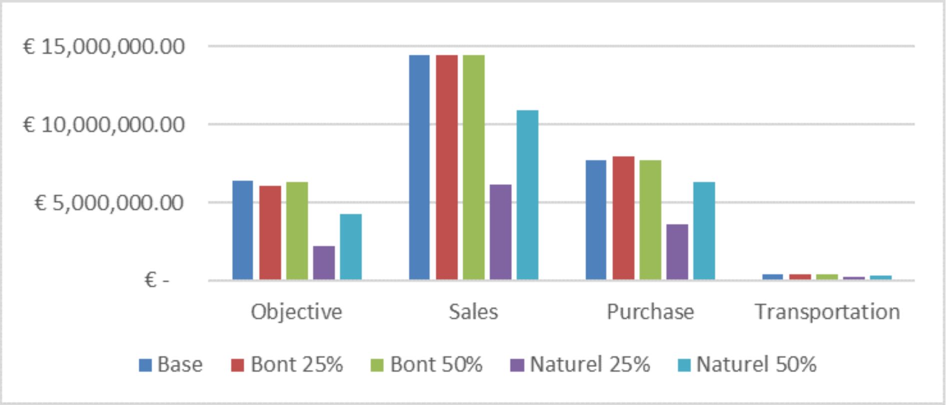


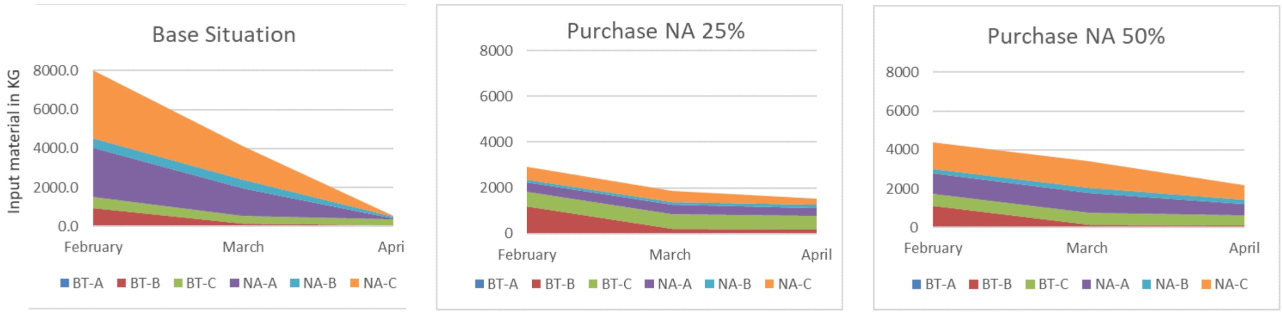
Figure 38: The objective values graphically represented for each situation

Natural As previously mentioned, the decrease in the total supply of natural input material for the 25% and 50% situations has resulted in a decrease in the volume of sold end products. A more detailed analysis reveals that the supply of natural input material is stable, indicating that the maximum supply of natural input material has been reached, as depicted in Figure 39. However, the sales volume is increasing throughout the planning period as more input material natural is acquired. Therefore, the output of Rymo22 has increased from 588 to 772 to 784 tons in the 25% situation and from 1,608 to 1,924 to 2,088 tons in the 50% situation, as seen in Figures 40.

However, as Lommel solely produces Rymo22, it suffers the most from the decrease in natural input materials, as shown in Figure 40. Only 21% of the available production capacity is used compared to an average of 87% production capacity used in Lichtenvoorde, which is capable of producing bont end products. This results in an increase in the production of bont end products, with the amount sold for Rymo81 increasing from 440 to 632 tons for the 50% situation and to 728 for the 25% situation, and for Rymo51 the sold end product increase from 208 tons to 260 for both situations.

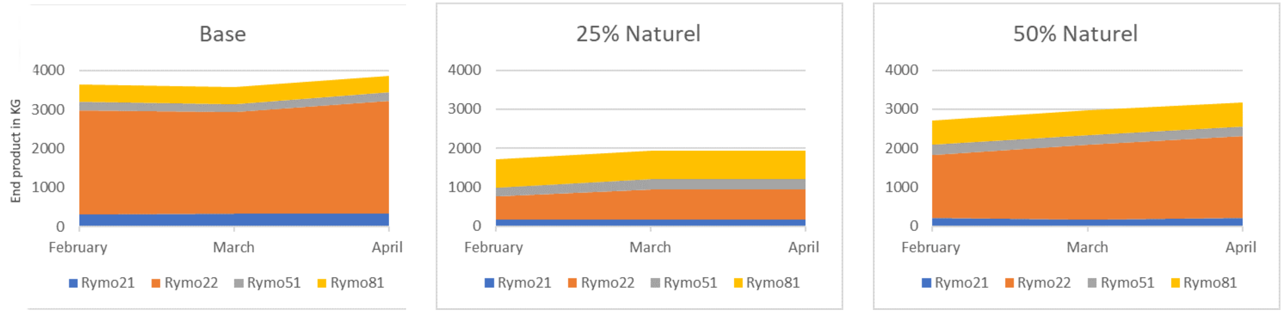
In the 25% scenario, the supply of natural input material to Lommel remains stable, which means that the maximum available amounts of NA-A and NA-C have been reached, as shown in Figure 39. However, it is worth noting that the maximum supply limit has not been reached yet, as the current steady supply of NA-A and NA-C to Lommel is only 210 tons and 360 tons, respectively, whereas the maximum available supply is 493 tons and 854 tons for NA-A and NA-C, respectively, according to the input data. The significant gap between the supplied input material and maximum can be attributed to the numerous small suppliers who are unable to deliver full freights and thus cannot deliver at all. A similar argument can be made for the 50% situation.

This gives insight into the dependency of Lommel on the supply of natural input material, while Lichtenvoorde still has to ability to switch to bont end products. Next to that, the model behaves in this situation as expected.



(a) Base **(b)** 25% **(c)** 50%

Figure 39: The purchased amount of input material in each situation



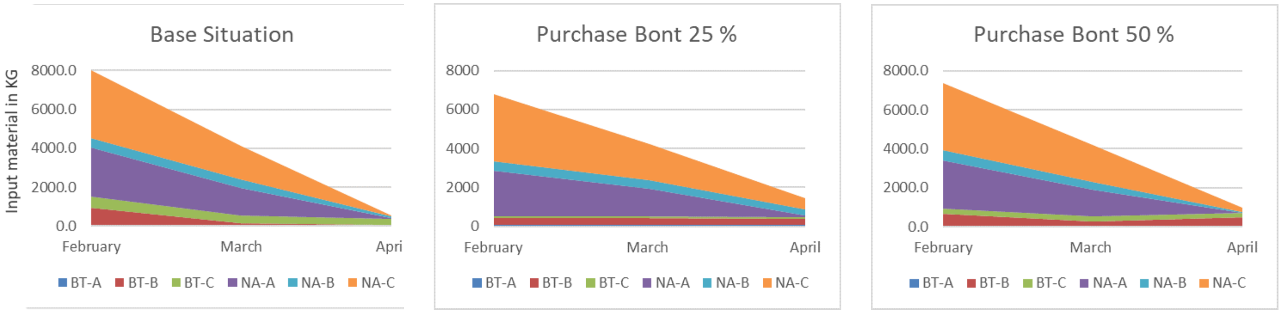
(a) Base **(b)** 25% **(c)** 50%

Figure 40: The sold amount of end product in each situation

Bont The impact of a reduction in bont input material is less significant than the decrease in natural input material. However, it is noteworthy that the supply of bont input material is stable in the 25% situation, as shown in Figure 41. In the 25% situation, more BT-A is sourced compared to the base situation, and the input of bont input material remains constant throughout the planning period. Both of these observations suggest that the maximum supply of bont input material is approaching. Meanwhile, the supply of input material in the 50% situation is similar to that in the base situation.

Fortunately, there is sufficient input material available since the quantity of sold bont end products remains the same in both the 25% and 50% situations as in the base situation. And as the model aims to maximize the total margin, which involves selling mainly natural input material with the highest margin and the minimum of bont end product with the lowest margin, the sales revenue a relatively unchanged.

These findings indicate that there is adequate bont input material available in the market to source from all suppliers and that a decrease in bont sales has a limited effect on the model's performance. Additionally, the model behaves as expected, which supports its validity, and further suggests that there is sufficient bont input material supply. The results suggest that there is enough bont input material available in the market for all suppliers to source from, therefore the decrease in bont only has a minor impact on the model's performance. Moreover, the model's behaviour aligns with the expected outcomes, which enhances its validity and reinforces the idea that there is sufficient supply of bont input material available.



(a) Base **(b)** 25% **(c)** 50%

Figure 41: The purchased amount of input material in each situation

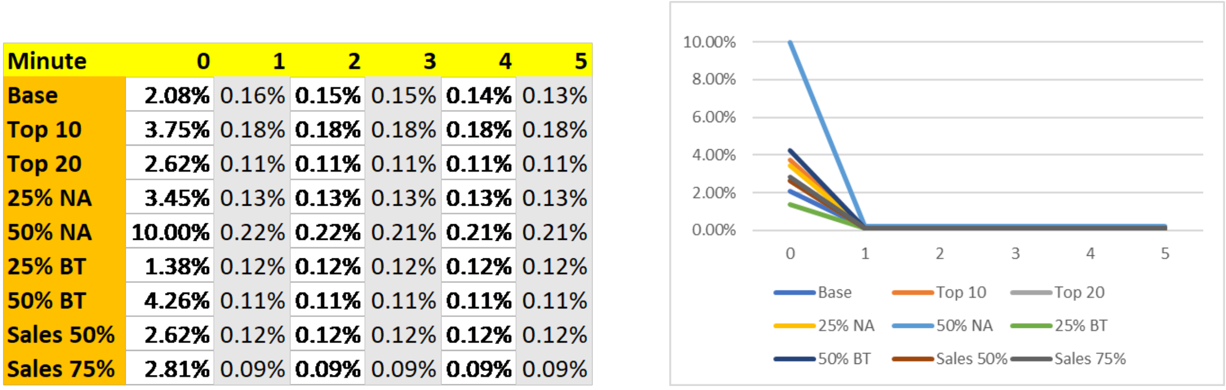
6.5 Model size

In this study, a dataset was utilized to optimize the supply chain for 25 customers and their 35 locations. The analysis took into account the supply chain of two factories, namely Lommel and Lichtenvoorde. Lommel has 100 suppliers and 1 production line, while Lichtenvoorde has 76 suppliers and 3 production lines. The planning period for the optimization process spanned 3 months, with intervals of 1 month being considered.

This results in a model that consists of 2,685 continuous variables and 711 integer variables, which are all non-binary. The model also includes 5,583 constraints, which capture the logical relationships between the variables. The total number of basic variables and non-basic variables in the model is 3,396.

6.5.1 Model performance

To assess its efficacy, the base situation was run for a maximum of 5 minutes, and a solution gap of 2.08% was achieved within one second, an improved gap of 0.17% was observed after 4 seconds with the best-found gap of 0.13% after 5 minutes, as shown in the Table 42a and Figure 42b. The model's computational performance was evaluated on a laptop equipped with an Intel i5-1035G4 processor and the Gurobi Optimizer version 10.0.1. This outcome is noteworthy because, as discussed in Section 4.5.1, the model's NP-hardness poses a challenge in finding the optimal solution within a reasonable timeframe. However, as the solver is able to find a near-optimal solution within a reasonable timeframe, it is deemed unnecessary to employ SA as a solution method.



Minute	0	1	2	3	4	5
Base	2.08%	0.16%	0.15%	0.15%	0.14%	0.13%
Top 10	3.75%	0.18%	0.18%	0.18%	0.18%	0.18%
Top 20	2.62%	0.11%	0.11%	0.11%	0.11%	0.11%
25% NA	3.45%	0.13%	0.13%	0.13%	0.13%	0.13%
50% NA	10.00%	0.22%	0.22%	0.21%	0.21%	0.21%
25% BT	1.38%	0.12%	0.12%	0.12%	0.12%	0.12%
50% BT	4.26%	0.11%	0.11%	0.11%	0.11%	0.11%
Sales 50%	2.62%	0.12%	0.12%	0.12%	0.12%	0.12%
Sales 75%	2.81%	0.09%	0.09%	0.09%	0.09%	0.09%

(a) Table **(b)** Graph

Figure 42: The gap (%) between the best-found solution and the theoretical upper bound for each situation

6.5.2 Robustness

The model was evaluated for robustness by solving all four situations as specified earlier, which resulted in a maximum of 0.22% within 1 minute and 0.21% within 5 minutes. This indicates that the solver is capable of finding an adequate solution within a reasonable time frame. However, the solver is able to find a good solution quickly but struggles to find the optimal solution. One reason for this is the presence of multiple local optima within the model, which causes the solver to and as there are many iterations that need to be solved, the gap between the upper bound and the best found solution lowers As an additional experiment, the base situation was run for 5 hours, resulting in a solution that was only marginally better with a gap of 0.12%. This emphasises the point made earlier.

6.6 Conclusion

In this chapter, sensitivity analysis is used to validate the model under changing economic circumstances and assess the behaviour of the model to changes in the input. The analysis consists of three different situations: the implementation of a minimum supply policy, a decrease in maximum demand, and an insufficient supply of input material.

The first scenario considers the implementation of a minimum supply quantity policy for regular suppliers, which is expected to result in more consistent supply and reduced overall supply fluctuations. This situation only affects the objective value by decreasing by 10% and 5% for the top 10 and 20, respectively.

The second scenario looks at the effect of a decrease in sales on the company's overall performance, with a reduction in the purchased input material and production capacity, and ultimately a lower objective value. The insight gained is that the used production capacity of Lommel's production line 4 is primarily affected, as it exclusively produces natural Rymo22.

Finally, the third scenario examines the impact of a limited supply of input material, where consequently less end product is produced, with natural end product expected to be more affected than bont. However, the model was hardly affected when 50% and 25% of the total bont supply were available. The insight gained from the natural situation reveals that Lommel is the most impacted by a shortage of natural materials, given its inability to produce bont. Moreover, in the scenario where the bont supply is reduced to 50% and 25% of the total, the objective value is marginally affected. The results from this situation underscore the ease of obtaining bont input material in the market. These situations provide insight into the impact of changes in the input data on the model's performance and highlight the importance of the availability of natural materials for the production of natural end products.

The model quickly found a solution with an optimality gap of 2.08% within 2 seconds for the base situation, and 0.16% after 1 minute and 0.13% after 5 minutes, with minor improvement after 5 hours. A possible explanation for the model's quick high-quality solution is its many local optima, which causes it to converge to a good but suboptimal solution quickly while struggling to find the globally optimal solution. The model shows comparable convergence behaviour for the optimality gap upon running different situations, which leads to the conclusion that the solving speed of the model remains robust to alterations to the input data.

7 Conclusion and recommendations

This chapter provides the conclusion to the thesis, with Section 7.1 summarizing the main findings. The limitations and assumptions made are outlined in Section 7.2, while Section 7.3 presents the recommendations for the company. Directions for further research are discussed in Section 7.4. Additionally, Section 7.5 highlights the contribution of this thesis to theory and practice. Finally, the tools used to implement the model are give in Section 7.6.

7.1 Conclusion

The impetus for this thesis stems from the challenges faced by the company with regard to supply chain scheduling. The aim was to provide insight into the general scheduling process and propose a more transparent method that offers more insight to enhance the efficiency of the supply chain scheduling process.

To address the aforementioned concerns, the primary research question is formulated as follows: *"How can Rymoplast improve their purchase and sales schedules, given the restrictions on production, while keeping in mind the commercial interest, cost-effectiveness and variability in supply and demand?"*. The research question was answered using multiple sub-questions. It was revealed that the scheduling process is complicated by uncertainties in the supply chain, as well as competing commercial interests towards customers and suppliers.

An approach is introduced to improving the scheduling process in the recycling industry through the development of a versatile and adaptable model. The model has been formulated in a general manner, enabling its applicability to other recycling companies and accommodating a range of different configurations. These configurations include the number of factories, production lines, suppliers, and customers, as well as the potential for varying products. Furthermore, the model is capable to accommodate different economic situations through customizable input data. This feature ensures the model's adaptability to changing economic conditions.

The proposed model in this study combines a supply chain scheduling problem with a blending problem to address the complexities of the recycling industry. The supply chain scheduling problem models the inflow of input materials and outflow of end products, while the blending problem approach is utilized to model the mixing process of production lines. The RHS approach is used to accommodate the constantly changing economic situations, with the model being solved on a monthly basis using overlapping planning periods. Additionally, a linear CCP method is developed to address the uncertainty surrounding the availability of input materials.

A base scenario was formulated to demonstrate the applicability and validate the model. A dataset was used that reflects the current situation and could be implemented instantly. An analysis of the results shows that naturel end products were sold at their maximum, which resulted in mostly natural input materials bought due to the substantial margin they yield. Noteworthy was the purchase of input materials in the early months, due to an increase in market prices. Importantly, the model adhered to all set constraints. The model has been shown to adhere to all constraints set.

In addition to the base scenario, the model was subjected to a sensitivity analysis by introducing other situations. This was done to assess the model's effectiveness and gain insight into the impact of different policies and economic situations on the model's results. Three distinct situations were evaluated, along with their corresponding expectations, with the aim of providing insight into the model's changes. The first situation involved implementing a minimum supply policy of input material for the regular suppliers, resulting in a more consistent supply across each month with only a marginal decrease in the objective value. The second situation involved an economic downturn, where the maximum forecasted volume of end products was decreased, resulting in a decline in the objective value and sales volume for the highest-margin product, Rymo22. The third situation involved a shortage of input material, which had a significant impact on the objective value for the natural situation as there were insufficient input materials to produce the required end products. Furthermore, the production capacity of production line 4 was observed to decrease at the fastest rate. The analysis results demonstrated that the model adhered to all the set constraints and provided valuable insight into the impact of different policies and economic situations on the supply chain.

7.2 Limitations

The model and the result's practicality in this thesis are subject to several limitations, primarily associated with the input data required for the model. This section aims to reflect upon the most critical assumptions made for the model and the resulting limitations on its practicality, and the approach to overcome these limitations.

One of the key assumptions that underlines the current model is the stability of the supply of input material over the planning period, with each supplier having a consistent supply capacity throughout. However, this assumption may not hold in practice, and the resulting variability in supply can significantly limit the practicality of the model as seen in Section 5.2. For instance, the model may suggest sourcing a smaller amount of input material based on a decreasing price trend. Insufficient availability of input material during months beyond the planning period's scope may result in the company being unable to procure an adequate supply of materials in the future. Due to the lack of data, it was challenging to estimate the maximum supply capacity of input material. Therefore, to approximate it, the highest amount delivered in a month throughout the year is used. To address this limitation in the current model, it is advised to develop a separate model that estimates the available supply of input material throughout the year to ensure an adequate supply during periods of insufficient supply. By accounting for the variability in input material supply, the model could provide more accurate and reliable recommendations to support decision-making. This limitation serves as a potential area for further research, as its implications may have a significant impact on the model's accuracy and effectiveness.

The current model assumes that the purchasing process determines the individual amounts of each type of input material to source from each supplier. However, this assumption is not realistic, as the company-wide known phrase of "waste is not made to order" suggests that the freight composition is largely influenced by the materials that the suppliers have on hand. While purchasers may control this process to a certain degree, the supplier is dependent on what is being supplied to them or what is available in the market. This assumption was made in order to obtain an approximation of the current situation. If the company calculates the total quantity of materials that must be sourced for a given period, purchasers can use this information to gain a better understanding of the amount that should be sourced each month.

Lastly, the current model is that the recycling company can acquire the required amount of input material at a pre-determined price during the purchasing process. However, in practice, the actual purchase price may deviate from this predetermined price, and suppliers may not always accept materials at the proposed price. Consequently, the model's results may prove impractical. While this assumption is based on the purchasers' experience, and given their knowledge of the market and their ability to perceive supplier relationships, it is assumed to be accurate. To address this limitation, a sensitivity analysis on the purchasing price may be necessary to assess the impact of changes in the purchase price on the outcomes. Similarly, the model supposes that the sales personnel can sell the end products at the predetermined price, which may not be achievable.

7.3 Recommendation

This section puts forward a set of essential recommendations resulting from the research conducted in this thesis. By implementing these recommendations, the company can enhance the workability and practicality of the model and improve its decision-making capabilities. These recommendations are provided in addition to those presented in Section 7.2.

It is recommended that the scheduling process is regularly updated to ensure the model's accurate and optimal performance. The effectiveness of the model relies on a significant amount of data that is unique to the company's business environment, which is vulnerable to constant changes in suppliers, customers, and shifts in economic conditions. As a result, it is crucial to periodically review and update the model's data inputs to ensure its accuracy and reliability.

To assist the company in the proper addition and maintenance of the input data, it is recommended that clear guidelines and a comprehensive manual are developed, which should be carried out in a manner that minimizes the potential for errors. Given the model's sensitivity to inaccuracies in the data, this step is crucial for ensuring the operationality and effectiveness of the model. Moreover, it is advised that the company maintain a base model as a backup in the event of a system malfunction. In order to further reduce the impact of data errors, it is also recommended that the company implements an automated workflow to ensure the consistent presence of accurate and correct input data. This would enhance the efficiency of the general scheduling process and reduce the time necessary to update the model.

Additionally, it is recommended that the company has established a contractual agreement with their supplier that outlines the frequency and volume of input material uptake. Additionally, these measures help the company to maintain a stable and reliable supply of input material or even improve it and gain knowledge on the supply capacity, ensuring a beneficial partnership with their regular suppliers. By implementing such measures, the company can mitigate the risks associated with supply chain disruptions and ensure a reliable supply of input material to meet production demands. This recommendation is a reaction to the situation discussed in Section 6, where the effects of a minimal supply policy were evaluated.

Moreover, the production speeds of each production line are not only dependent on the type of end product but also on the MFI of the input material. Investigating the effects of low and high MFI input material on production lines could yield valuable insights on how to optimize the factory's overall output. For example, by processing low MFI input material on line 1, and high MFI input material on line 2, could improve overall output of the factory. This topic could for developing a reliable measuring tool for to further improve a recycling companies output.

7.4 Further research

In this section, several research directions are proposed that have the potential to enhance the effectiveness of the proposed model for companies in the same industry. These directions are given in addition to Section 7.2.

An investigation into the development of sales and purchasing prices over time and their relationship with economic factors, such as the available supply and demand, constitutes a valuable research direction in the recycling market. This research could provide meaningful insights into the complex dynamics of supply and demand, shedding light on the factors that influence pricing trends.

Following this research, a predictive model that integrates these economic factors could be developed to improve the quality of input and output for the proposed model, enabling more informed decision-making regarding purchasing and sales activities. As a result, this model could enhance the efficacy of recycling company's operations. Overall, such research and modeling efforts have the potential to advance understanding of the recycling market and inform sustainable, profitable business practices.

Another area of further research that warrants consideration is the inclusion of supplier reliability as a critical factor in the recycling market. Although this study focuses on the relationship between sales and purchasing prices and their impact on the economic situation, the role of supplier quality and consistency in these dynamics is yet to be investigated. It is also worth noting that supplier reliability is a crucial aspect that is currently not considered in this study. Given the importance of purchasing and suppliers to the recycling company, it is recommended to get a better overview and criteria of what good suppliers are and what that entails for the input materials.

An area of further research is to research criteria for identifying and tracking "regular" suppliers. Given the significant influence of purchasing and suppliers on the recycling company's success, it is recommended that criteria for identifying and tracking "regular" suppliers are developed. Such an approach would allow for greater visibility and transparency into the supplier landscape, thereby facilitating informed decision-making and risk mitigation strategies. Such an approach can also help in mitigating the risk of harm to the company, as it enables a more centralised and insightful evaluation of the current suppliers.

7.5 Contribution to theory and practice

This study draws upon several modelling approaches, e.g. supply chain models and blending models to create a tailored approach to replicate the purchasing of input materials in the recycling industry, the production process and the sales process.

By combining individual components from different models, this approach presents a novel and valuable model that addresses the specific combination and customization requirements of the recycling industry. This practical modeling approach holds significance as it applies supply chain scheduling models to an industry that has not been explored in this manner before, thereby contributing to expanding the field of supply chain management and modeling. Next to that, the thesis comments on the importance of solving speed and model size in understanding NP-hardness, a well-known issue in supply chain scheduling problems.

The practical contribution of this thesis is the improvement of the general scheduling process for the supply chain of a recycling company. The proposed data-driven model offers a practical contribution by enhancing the scheduling process for the supply chain of a recycling company. It enables the company to make informed and effective decisions, thereby improving their profitability and operational efficiency while optimizing the balance between purchase and sales quantity. This shift from traditional intuition and common sense-based decision-making processes to data-driven approaches can lead to cost savings for the company.

Furthermore, the proposed approach combines and alines both the purchasing and sales schedule, enabling the company to address the challenges they have faced over time. Next to that, the thesis' sensitivity analysis sheds light on the impact of economic situations on the margin and potential weaknesses of factories, and dependencies on suppliers, providing a basis for future optimization efforts.

7.6 Verification

The scheduling program that was developed for the company, aims to assist in making informed sales and purchasing decisions. To ensure that the decision-makers have confidence in the results of the model, various programs have been utilized to provide the company with insight. This is in line with the objective, as it aims to provide Rymoplast insight into the whole general scheduling process, containing the sales, purchase, and production capacity schedule.

One of the primary criteria for the scheduling program was that it should be user-friendly and require minimal training, while also being easy to maintain, even for users who are not skilled with programs other than Excel. To create the general schedule, a combination of software programs is utilized, including Excel, Gurobi API in Python, Python, and Power BI.

Excel is widely used and familiar to decision makers, making it a suitable choice for the input stage of the scheduling process. The sheet is automated to enhance user-friendliness, using e.g. a base price in combination with indexes for the sales and purchase price part. Gurobi API in Python is used as it is an efficient tool for solving MPs. Python is used to ensure the Gurobi program is dynamic enough to accommodate changes in the data from Excel. Power BI presents the results visually, making it easy for users with limited knowledge of the program to verify the results.

All of these programs are linked to each other and can be operated using only Excel, increasing user-friendliness. However, a small mistake in the input data could cause Gurobi or Power BI to fail, rendering the entire scheduling program useless.

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Appendix: chance constraint programming

Assuming that there is sufficient data and that the AR_l is normally distributed, such that expected value of $\mu_{InputAccepted}$ and a standard deviation $\sigma_{InputAccepted}$ of the the stochastic variable $InputAccepted_{fht}$ can be determined.

$$\mu_{InputAccepted_{fht}} = \sum_{l=1}^{L} z_{lfht} * \mu_l \tag{17}$$

$$\sigma^2_{InputAccepted_{fht}} = \sum_{l=1}^{L} z^2_{lfht} * Var(AR_l) = \sum_{l=1}^{L} z^2_{lfht} * \sigma^2_l \tag{18}$$

$$\sigma_{InputAccepted_{fht}} = \sqrt{\sigma^2_{InputAccepted_{fht}}} = \sqrt{\sum_{l=1}^{L} z_{lfht} * \sigma_l} \tag{19}$$

The probability of $\mu_{InputAccepted_{fht}}$ and $\sigma_{InputAccepted_{fht}}$ do not depend on z_{lfht}.

To determine a level of reliability, it is essential to define the probability distribution of the random variable, $InputAccepted_{fht}$. Here is assumed that the variables AR_l follows a normal distribution. This results in the following cumulative normal distribution $\Phi(X)$.

$$Pr\left[\sum_{l=1}^{L} z_{lfht} * AR_l \leq InputNeeded_{fht}\right] \leq \alpha, \forall f, h, t \tag{20}$$

$$\Phi(\frac{X-\mu}{\sigma}) \leq \alpha, \forall f, h, t \tag{21}$$

$$\Phi(\frac{InputNeeded_{fht} - \sum_{l=1}^{L} \mu_l * Z_{lhft}}{\sqrt{\sum_{l=1}^{L} \sigma_l * Z_{lhft}}}) \leq \alpha, \forall f, h, t \tag{22}$$

Combining the normally distributed variable $InputAccepted_{fht}$ 15 and rewriting constraint 13 to 20, a deterministic variant of the constraint is made, that can be used in the mathematical programming model.

$$\sum_{l=1}^{L} \mu_l * z_{lhjt} + \sqrt{\sum_{l=1}^{L} \sigma_l * z_{lhjt}} \geq InputNeeded_{fht} * \Phi^{-1}(\alpha), \forall f, h, t \tag{23}$$

Since the $\sigma_{InputAccepted_{fht}}$ is non-linear, the constraint cannot be used in the MILP.

Changes to main model: end product inventory

The existing model assumes that the company sells and delivers all end products immediately, without keeping any end products in stock. However, historical data suggests that the company sometimes produces end products on stock. To account for this, a modification to the current model is proposed.

The proposed change introduces additional constraints and parameters to enable tracking of the inventory position of end products. A maximum inventory capacity for end products is also specified to prevent overproduction. By incorporating these updates, the modified model can assist in making informed decisions about inventory management by providing insights into which end products to put in inventory and how many to keep, based on factors such as input material price, end product price, available input material and production capacity.

In order to stimulate that the model chooses to deliver end products to customer over putting end products on stock, the model has an penalty incorporated in the objective value 30. The penalty is a price paid for each ton under the minimum set, as shown in constraint 27.

Inventory position for end product

- **Parameters**
- $minCP_{jt}$, minimum production capacity of factory f in period t (available production time).

$$\text{Inventory position per factory: } EP_{ijt} = EP_{ij(t-1)} - \sum_{k=1}^{L} y_{ijkt} + \sum_{h=1}^{H} x_{hijt} * r_h * Z_{ih}, \forall i, j, t \tag{24}$$

$$\text{Maximum inventory space: } \sum_{i=1}^{I} EP_{ijt} \leq max_Storage_Capacity_j, \forall j, t \tag{25}$$

$$\text{Maximum stock: } EP_{ijt} \leq MaxStock_EP_j, \forall i, j, t \tag{26}$$

$$\text{Minimum stock: } EP_{ijt} \geq MinStock_EP_j - StockBelowMinimum_{i,j,t}, \forall i, j, t \tag{27}$$

$$\text{Minimum production capacity: } \sum_{i=1}^{I} pt_{ijt} * \sum_{h=1}^{H} x_{hijt} * \frac{1}{r_h} \geq minCP_{jt}, \forall j, t \tag{28}$$

$$\text{Start Inventory: } IEP_{ij(t=-1)} = StartInvEP_{ij}, \forall i, j \tag{29}$$

$$\text{Addition to Objective value: } -\sum_{i}^{I} \sum_{j}^{J} \sum_{t}^{T} StockBelowMinimum_{i,j,t} * Penalty_{i,j} \tag{30}$$

Use Power BI dashboard

A concise workflow on how to use the same report for different Excel files:

1. Create a Power BI report with the graphs and charts that your bosses want to see.
2. Save the Excel file with a reusable name, such as "DasbhoardRymoplast.xlsx".

3. When you receive a new Excel file with updated data, save it with the same reusable name, overwriting the previous version of the file.
4. Open your Power BI report and refresh the data to update it with the new data from the updated Excel file.
5. If the new Excel file has a different format, use Power Query to adjust the data source to match the format of the original file.
6. If your bosses want additional charts or graphs based on the updated data, add them to the existing Power BI report.
7. Save the updated report and use it as a template for future reports.
8. By following this workflow, you can save time and effort by reusing the same report for multiple Excel files with updated data.

Change source of Power BI dashboard

Below, a concise workflow oh how to change the data source for the Power BI dashboard, such that the user can reuse the same report with different datasets.

1. Go to the "File".
2. Click on "Options and settings".
3. Click on "Data Source settings".
4. Click on the button "change source" in the data source settings tab.
5. Change to the source as desired.
6. Click on close.
7. Apply changes and wait for the changes to be made.

Cause and effect diagram

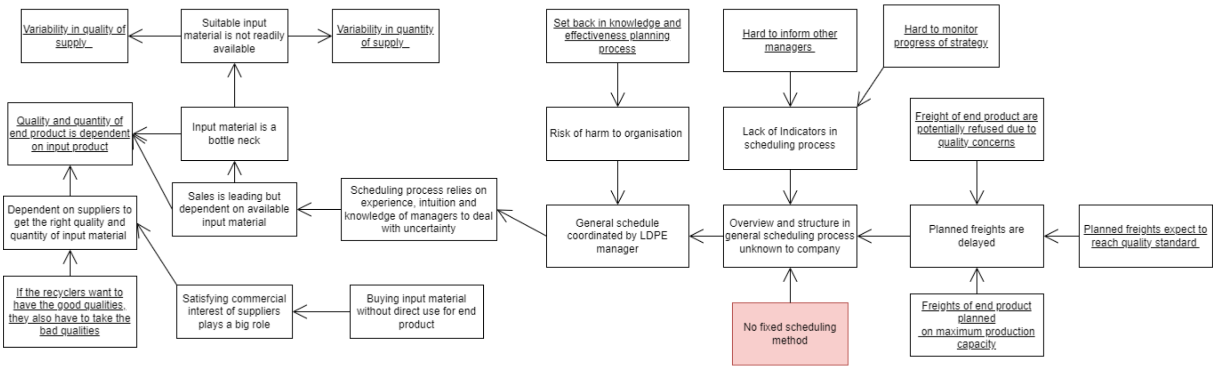

Figure 43: Cause-and-effect analysis diagram

Input data table

Department	Data	Average	Datapoints
Purchasing	Price	€386	3204
Purchasing	Minimum supply per type of input material	11.5 ton	1068
Purchasing	Maximum supply	0 ton	1068
Sales	Minimum demand	78 ton	35
Sales	Maximum demand	137 ton	35
Sales	Price	€1290	75
Production	Starting inventory	100 ton	12
Production	Processing times in hours	1.14	16
Production	Production capacity in hours	628 hour	12
Production	Safety Storage	100 ton	12
Production	Maximum storage	26,000 ton	2
Production	Yield	0.875 ton	6
Production	MFI per input material	0.5	6
Production	Minimum MFI	0.33	6
Production	Maximum MFI	0.55	6
Production	Recipe: E.g. in end product Rymo21, the input materials NA-A, NA-B, NA-C can be used.	x	21
Transportation	Transportation costs	€1,107	84
Transportation	Tonnage per truck outgoing freight	25 ton	2
Transportation	Tonnage per incoming freight	25 ton	2

Table 7: Input data used in the base situation

Changes to model including inventory stock costs

In this section, the last modification to the model, which is discussed in Section 4.2.2, is altered to incorporate the value for the starting inventory that each factory has. In the aforementioned model, the stock does not have any value, therefore the following additions have been made.

1. Input data is changed including the objective function.
2. Constraints are added.

Incorporating stocks as supplier

The following is altered to the input data of the model:

1. The starting inventory variables $StartInv_{hf}$ are set to zero of constraint 3.
2. Each factory is added to the list of suppliers of that particular factory as a supplier. Here, the starting inventory variables $StartInv_{hf}$ are set as the maximum supply constraint 5.
3. The value of the inventory is set to be the purchasing price for the input materials at t. It is then price multiplied by an index, such that the price is lower than that of the regular suppliers. This ensures that the model prefers the inventory already on hand. This also alters the objective function in the sense that the purchasing price of the inventory is added.
4. Good to note is that the inventory tracker variables are still used, and only the $StartInv_{hf}$ is set to zero.

Tracking Inventory

In addition to the input data changes, the following constraints are added:

$$\text{Inventory constraint :} IMIntern_{lfht} = MaxCS_{hf} - z_{lfht}, \forall lfh \text{ for period } t = 0 \tag{31}$$

$$\text{Inventory constraint :} IMIntern_{lfht} = IMInternlfh(t-1) - z_{lfht}, \forall lfh \text{ for period } t = 1, 2 \tag{32}$$

Constraint (31) incorporated the starting inventory at t=0. For the following periods, the inventory is tracked using constraint (32).

Title		Production	Transportation	Raw Material	End product	Inventory Supply	Uncertainty	Multi-product (single input to multi output)	Multi-blend or mix (Multi Input to single output)	Time	Production	Supply	Storage	Supplier	Factory or facility	Customer	Echolon	Single	Multi	Long	Mid	Short
Supply chain problem	**Objective**	Costs					Uncertainty	Production			Constraint			Supply chain				Period		Term		
Global reverse supply chain design for solid waste recycling under uncertainties and carbon emission constraint	Minimize costs and emissions		x				waste collection, currency exchange rate and transport costs	x			x	x		Multi	Multi	Multi	Multi		x	x		x
A strategic capacity allocation model for a complex supply chain: Formulation and solution approach comparison	Maximize profit	x	x	x	x		Price, capacity	x	x		x	x	x	Multi	Multi	Multi	Multi		x	x	x	x
Supplier selection and supply quantity allocation of common and non-common parts with multiple criteria under multiple products	Minimize costs	x	x	x			None	x	*1			x		Multi	Single	None	N.a.	x		x		
A stochastic programming approach for supply chain network design under uncertainty	Minimize investment and exp. future operation costs	x	x				processing, transportation costs, demands, supplies, and capacities, and the optimal value.	x			x			Multi	Multi	Multi	Multi	x			x	
Cost Optimization for the Allocation, Production, and Distribution of a Plastic Manufacturing Company Using Integer Linear Programming	Minimise costs	x	x	x			None	x	x	??	x	x	*3	Multi	Multi	Multi	Multi	x			x	
A Stochastic Programming Approach for Multi-Site Aggregate Production Planning	Minimise costs including production, subcontracting, labour, inventory and unrealized demand	x				x	Demand	x		x	x			None	Multi	None	N.a.		x		x	
Multiobjective optimisation of production, distribution and capacity planning of global supply chains in the process industry	Minimise total flow time, total costs and total lost sales	x	x	x			None	x		x	x		x	Single	Multi	Multi	Multi		x	x		
Multi-objective optimization of multi-echelon supply chain networks with uncertain product demands and prices	Optimise participant's profit, the average customer service level, and the average safe inventory level	x	x	*5	*5		Demand, product prices between actors	x		*4			x	Multi	Multi	Multi	Multi		x	Not mentioned		
Blending problem																						
A multi-objective optimization approach for the blending problem in the tea industry	Minimise costs and violating quality constraint			x			None	x	x			x		None	Single	None	N.a.	x	x	Not mentioned		
Coal blending optimization under uncertaint	Minimise mean and std. of costs and mean and std. of emissions	x		x			Coal properties, which influence costs	(Single)	x	x				None	Single	None	N.a.					
Aggregate Production Planning problem																						
A multi-objective robust optimization model for multi-product multi-site aggregate production planning in a supply chain under uncertainty	Minimise total costs	x	x	x		x	Costs and Demand	x	x	x			x	Multi	Multi	Multi	Multi		x		x	
A Robust optimization model for multi-site production planning problem in an uncertain environment	Minimise costs and maximise customer satisfaction	x				x	Market Demand		x	x	x			None	Multi	Multi	None		x		x	
A multi-objective invasive weed optimization algorithm for robust aggregate production planning under uncertain seasonal demand	Minimise costs and maximise customer satisfaction	x				x	Market Demand			x	x			None	Single	None	None		x		x	
Scheduling of a Multiproduct Batch Plant under Multiperiod Demand Uncertainties by Means of a Rolling Horizon Strategy	Maximise profit	x		x	x	x	Demand and capacity plant	x		x	x			None	Single	None	None		x		x	
Cross-facility management of production and transportation planning problem	Minimise costs	x	x			x	None							Single	Multi	Multi	Multi		x		x	
A robust optimisation model for aggregate and detailed planning of a multi-site procurement-production-distribution system	Minimise expected and variance of total costs	x				x	Demand			x	x		x	Multi	Multi	Multi	Multi		x		x	x

Figure 44: Literature overview