BACHELOR THESIS

Lot size calculation for purchasing materials

SVgroup | Schuitemaker & Veenhuis

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UNIVERSITY OF TWENTE.

SVgroup

Lot size calculation for the SKUs of slurry injector A

This thesis is part of the bachelor's program in Industrial Engineering and Management at the University of Twente. This should serve as input to optimize the lot sizing method at SVgroup to minimize the total expected costs of purchasing materials.

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Preface

This report indicates that the research that has been performed at SVgroup has been finished. This thesis is the last part of the bachelor's program Industrial Engineering and Management at the University of Twente. This thesis is about the optimization of the lot sizes of purchasing materials. At the end of this report, suggestions are given to improve the parameters that are used in the planning of the purchasing process.

I would like to thank my supervisors. First of all, I would like to thank the supervisor at the company, Janice van Benthem, for allowing me to conduct this research at SVgroup and for guiding me toward a solution that is built on scientific knowledge and can be implemented easily at the company itself. Besides, I would like to thank the master planner, Gerben Brakert, for making me understand the current working of the MRP and for dealing with the suggestions that were given by this research.

Finally, I would like to thank the supervisors, Matthieu van der Heijden and Leo van der Wegen, of the University. The feedback that was provided throughout the whole graduation process has been seen as valuable in creating the required models.

I hope that you will enjoy reading this bachelor's thesis.

Stijn Vennegoor
July, 2023

Management summary

This thesis serves as input for determining the lot sizes of purchasing materials at SVgroup, which should lead to a decrease in total expected costs, consisting of inventory holding and ordering costs. Two tools are made for SVgroup, one to calculate the total expected costs for stock-keeping units with a fixed price and one to calculate the costs when an incremental discount is given by a supplier.

SVgroup is a company that is located in Rijssen. It specializes in manufacturing agricultural machines. In this bachelor thesis, the purchasing materials of one specific finished product are reviewed. The company has a feeling that its ordering process is non-optimal. The input parameters of the MRP system that they use are not substantiated with knowledge. This led to the company setting these parameters the same way for roughly every SKU, no matter how expensive the SKU is and how much the SKU is used. The main parameter reviewed in this thesis is the so-called 'lot accumulation period'. This period has been set to 13 days for roughly 85% of all SKUs. All SKUs reviewed in this thesis have a lot-for-lot policy with an accumulation strategy. This parameter bundles the supply needs defined by the MRP for a given period (the lot accumulation period) for an individual SKU into one order. To be able to calculate whether the tool performs better than the current parameters of the MRP, the performance of the MRP itself is explained and analyzed in this thesis as well.

As stated above, this thesis focuses on the purchasing materials of one finished product only, as it counts for 63% of the total inventory value of the finished product over 2022. 129 SKUs of one finished product are reviewed. Besides, to be able to include lot size-based discounts as well, 10 SKUs of another finished product that already include different prices are being reviewed. The main research question answered throughout this thesis is stated as:

"How to optimize the lot sizes of the raw materials at SVgroup in such a way that it minimizes the total expected costs while storing sufficient raw materials to deliver the product on the due date?"

To be able to calculate the total expected costs, these costs should be divided into inventory holding and ordering costs. Three different inventory holding percentages are being used for the SKUs, namely 20%, 25%, and 30%. A distinguishment between the holding percentages is made for every SKU by defining the risk of holding the SKU and the space that it needs to be stored at Rijssen. Besides the inventory holding costs, the ordering costs are defined for every SKU. All SKUs have a fixed ordering cost of €14,68. The variable ordering costs relate to the transporting costs and thus are different for every SKU.

Literature has been used to find appropriate models that can be used at SVgroup. In a fixed horizon, the Wagner-Whitin model performs the best in comparison with other dynamic lot sizing heuristics. This method uses dynamic programming to calculate the optimal order frequencies and lot sizes. Other DP models have been reviewed that focus on this Wagner-Whitin model. Mizutani (2019) elaborates on this Wagner-Whitin model through the creation of a "shortest-path" dynamic programming approach.
The optimal policy stated in this source states that an order is only placed if the inventory is zero. The first model created in this thesis builds upon this optimal policy. The second model includes the restriction that a minimum amount has to be ordered (MOQ) and only a multiple of a certain value (IOQ) can be ordered.
For these two models, the assumption is made that only one fixed price holds for all SKUs. However, in reality, incremental quantity discounts might be given by the supplier. Therefore, two sources have been used to create a model that calculates the total expected costs with incremental quantity discounts.

Usage values of all SKUs of 2022 have been used to calculate the total expected costs of the suggestions made by the models with on fixed price. These suggestions have been compared to the suggestions made by the parameters that are currently implemented in the MRP. In total, €3872,15 could have been saved over 2022 for the 129 SKUs if the suggestions of the MRP are being replaced by the suggestions that the model makes. 10 SKUs that have different prices have been reviewed with model 3. The model (lot size-based discount model (model 3)) decreases the total expected costs (now consisting of inventory holding costs, ordering costs, and the price of the order) of these SKUs by 14.0% in comparison with the suggestion made by the MRP. Besides these numerical results, different lot accumulation periods are tested as well. The researcher found that the minimum number of periods between two consecutive orders suggested by the model is often the same period as the most optimal lot accumulation period.

Because of the long time to run the models individually (as a lot of input parameters should be given to the model), the models cannot be implemented in the ordering process for all SKUs. It simply takes too long to run the models in the way that they should be run. Therefore, the programming code has been changed a bit to be able to run the model over multiple items and extract the minimum number of periods between two consecutive orders. This minimum number of periods has been set as the new lot accumulation period. The new lot accumulation period has been calculated based on the usage data of 2022 and these new lot accumulation periods are tested on the usage data of 2021. Overall, the model decreases the total costs of 2021 by 15.06% in comparison with the suggestions given by the current MRP, as the newly suggested lot accumulation periods decrease the total costs by 10.55%. Therefore, the lot accumulation period suggestions made by the new model decrease the total costs by a decent amount.

The company is suggested to use the models for all SKUs individually (1). Nevertheless, the required time needed to run the models given in Chapter 4 is considered as too long (roughly two minutes per SKU, because the input variables should be implemented by someone). Therefore, if the company wants to improve the ordering parameters, it is recommended to set the value of the lot accumulation period through the newly programmed model that is suggested in Section 5.4 (2), as the small changes in the VBA codes of the models make sure that the models provided in Chapter 4 run over multiple SKUs at once. The last recommendation is that the company should review the new lot accumulation period once every 2 months, as a sudden increase in material requirements in comparison with the previous two years might be costly. Safety stock is not taken care of during this thesis. Therefore, future research might enlarge this research with the implementation of safety stock.

List of abbreviations

PTO	Purchase to order
MTO	Make to order
ETO	Engineer to order
MRP	Material requirements planning
ERP	Enterprise resource planning
SKU	Stock keeping unit
MOQ	Minimum order quantity
IOQ	Incremental order quantity
DP	Dynamic programming
LAP	Lot accumulation period

Table of contents

Readers guide

Chapter 1: Methodology

This Chapter covers 8 sections. First of all, the company is described. The problem context will be described and the motivation and goal for solving the main problem have been stated. These Sections are followed by the research questions and how the researcher aims to get answers to these questions. Inclusion and exclusion criteria are stated in this chapter as well. Finally, the intended deliverables of the thesis are elaborated.

Chapter 2: Current situation

The second chapter covers three main topics. First of all, the inventory problem of the researched product is discussed. The same problem is analyzed for the underlying SKUs of this product as well. Besides, the MRP usage is reviewed. Certain problems regarding the MRP system arise when analyzing it. Lastly, the current manner of determining the different costs associated with ordering is discussed. This Chapter serves as input for Chapter 3.

Chapter 3: Literature Review

Chapter 3 elaborates on the knowledge about lot-sizing heuristics that we don't know yet. This systematic literature review should help us with implementing a new lot-sizing heuristic at SVgroup. Different heuristics are discussed in this chapter. Afterward, the performance measurements of these heuristics are discussed.

Chapter 4: Model Creation

The fourth chapter focuses on the models that are built that should help SVgroup with determining their lot sizes. Chapter 4 makes a distinction between three different kinds of models. First of all, a model is made for SKUs without a MOQ and/or IOQ. The second model is created for SKUs that do have these parameters. The last model focuses on lot size-based discounts, as it might be an important topic for the reviewed SKUs soon.

Chapter 5: Model Validation

In Chapter 5, data from 2022 has been used to evaluate the current suggestions made by the MRP system. The suggestions made by the first two models created in Chapter 4 are compared to these suggestions given by the MRP. Complexities about the models are stated in this chapter and solutions to these complexities are given. Lastly, model 3 is compared to the current MRP suggestions in this chapter.

Chapter 6: Implementation

After the model has been validated in Chapter 5, some suggestions should be provided regarding how to use the models. Because of the findings in Chapter 5, the models should give other outputs than what was first assumed. This Chapter indicates what changes are made by the researcher even as what should be done by the company to make sure that the model is used correctly.

Chapter 7: Conclusion

The last Chapter gives the main conclusions that could be extracted from the research that is performed in this thesis. Besides, certain recommendations for the company are stated. Finally, a future research is stated, to even further improve the ordering and planning process at the company.

1. Methodology

This section introduces the research on the inventory management of the raw materials needed for the production of a certain product group that will be performed at SVgroup in Rijssen. In Section 1.1, the company is introduced. Section 1.2 focuses on the reason why we performed this research. Section 1.3 addresses certain problems that influence the main action problem. Afterward, this chapter dives into the main aim of this research, followed by the questions that make sure that the goal is reached. Section 1.6 elaborates on the inclusion and exclusion criteria of this research. The next section focuses on the approach of every research question and finally, an estimate will be given about the durations and timing of every activity.

1.1 Company description

SVgroup is a company that focuses on manufacturing agricultural machines. The company was formed after the two companies called Schuitemaker and Veenhuis merged. This merger was formed a couple of years ago. Besides providing agricultural machines, the company also focuses on providing winter services to its customers. The agricultural machines section can be divided into three subcategories:

- Forage harvesting
- Feeding
- Manure

The first category focuses on the growing season in which farmers need to harvest their grass or maize. This category includes silage wagons (for maize) and dual-purpose wagons (for maize and grass). Quality and ease of use are the main takeaways that the company is aiming for.

The second group of products is the feeding category. Feeding is a daily activity for farmers, which should be performed fast and easily. Therefore, the focus of SVgroup is to deliver feeding machines that are easy and fast to use, while taking the reliability of the distribution of the food into account. The feeding category consists of two main machines: the feed dosing wagon and the block dosing wagon.

The last category elaborates on the manure activities of the farmers. The company produces manure tanks and slurry injectors. The most important aim of this section is to make agriculture more sustainable and close an efficient soil-plant-animal cycle. The input of the chemical fertilizer is minimized as much as possible to maintain sustainability while maximizing the nutrients available to the crops. This leads to an optimal yield level. Examples of products that form this category are slurry injector A and slurry injector B.

To conclude this subsection, the main takeaway during the production of the machines at the factory in Rijssen is to make products that are reliable and easy to use, while taking sustainability into account.

1.2 Motivation for research

The main problem that initiate this thesis is stated as follows: “The parameters of the ordering process are not substantiated with any knowledge”. The main parameters where the company faces trouble are the ordering frequencies, order points, the corresponding lot sizes, and the lot accumulation period. The last parameter mentioned is used to bundle multiple supply needs of one

SKU into one order. This is one of the reasons why the value of the inventory available in the warehouse is way too high. The inventory value that is too high is mostly formed by raw materials that need to be purchased for the products. The ERP system of the company consists of roughly 49.000 SKUs. This thesis is therefore based on the need of designing a tool to give the company more insight into one of the stated parameters.

1.3 Problem statement

As mentioned above, Schuitemaker and Veenhuis merged a couple of years ago. After the two companies merged, cost efficiency was not taken into consideration properly. The main goal for the company was to sell a lot of products to increase their revenue and so reduce their losses. Because of this objective that was set by the company, it didn't matter how often purchasing materials were ordered. Therefore, to make sure that all products were in stock, the company uses a small LAP for a lot of products. This indicates that one order would be placed for a single item once every couple of weeks (often once every 2 weeks), no matter how expensive the item is. The main goal that the company set led to a reduction in losses and eventually turned into gaining profit. However, the board suggests that the inventory should be managed in a better way.

Currently, most of the raw materials are ordered with a purchase-to-order (PTO) strategy, as the MRP calculates the material requirements. For 314 raw material SKUs, the materials cannot be ordered through a PTO strategy, because the lead times of these SKUs are longer than 3 months. These SKUs are ordered based on a forecast. All other purchasing SKUs, which are ten thousand of SKUs, are ordered with the MRP. This means that the requirement is stated and this material requirement is ordered for a certain cycle that is defined through the input parameters of the MRP. The finished products are made following a make-to-order (MTO) strategy and an engineer-to-order (ETO) strategy.

Before a year starts, the company calculates how many finished products they are planning to sell in the upcoming year. They set these orders in their ERP system (Navision) as "verkooporder eigen" (=sales order own). When setting this order, no customer has been attached to it. The customer is attached to the order 2 to 3 months before the planned selling moment on average. When this happens, the sales order own transforms into a regular sales order.

Currently, when a sales order own is set, a production order is set directly too. This production order triggers the material requirements. When a production order is set, the date when the product should be finished is given. The MRP gives the master planner of the company suggestions regarding the ordering moment of the materials based on the input parameters that are set (for example, the number of accumulation days).

The problem that often occurs at the company is that the start of the production of the finished product is delayed a couple of weeks before it goes into production. This problem occurs because there is no frozen period present before the start of the production process. What this means for the inventory is that the raw materials are already ordered and will be delivered on the first start date and the production starts a month later. Therefore, the bought materials for the finished products have to be stored in the warehouse for the time between the old and new start date.

To be able to get this as input for the MRP runs, the values of the parameters should be substantiated with knowledge. The main parameters that have to be set are the lot sizes, the order frequencies, and thus the lot accumulation period. Currently, there is no safety stock and reorder point set for most SKUs, as the lot-for-lot policy is used to buy every lot. The other parameters are set on intuition and 'experience'. Those parameters are set in this way because the company doesn't know how to set these parameters correctly.

Another problem where the company faces problems is that the finished products have seasonal demand. The production of the products only happens in a part of the year. One product is produced from October until May. For June, July, August, and September, the company does not produce any unit of this product. The company doesn't know how to take this seasonality into account during the ordering process. The seasonality and the lack of a frozen period lead to uncertainty. This indicates that safety stock should be calculated. However, currently, the safety inventory and reorder points are not calculated. Besides, the optimal order quantity for every raw material is not calculated as well. Therefore, the problems lie in both the safety and the cycle stock.

Currently, the ordering policy for all SKUs that are not finished products is set on a lot-for-lot strategy, even though roughly a third of all SKUs have lead times of 3 weeks or longer. Besides, the parameters corresponding to a lot-for-lot strategy (LAP & rescheduling period) are set on intuition, which means that these values are not optimal. This leads to the lot-for-lot strategy not functioning optimally. All this leads to high inventory costs.

A problem cluster could be made for this problem description. This problem cluster is stated below:

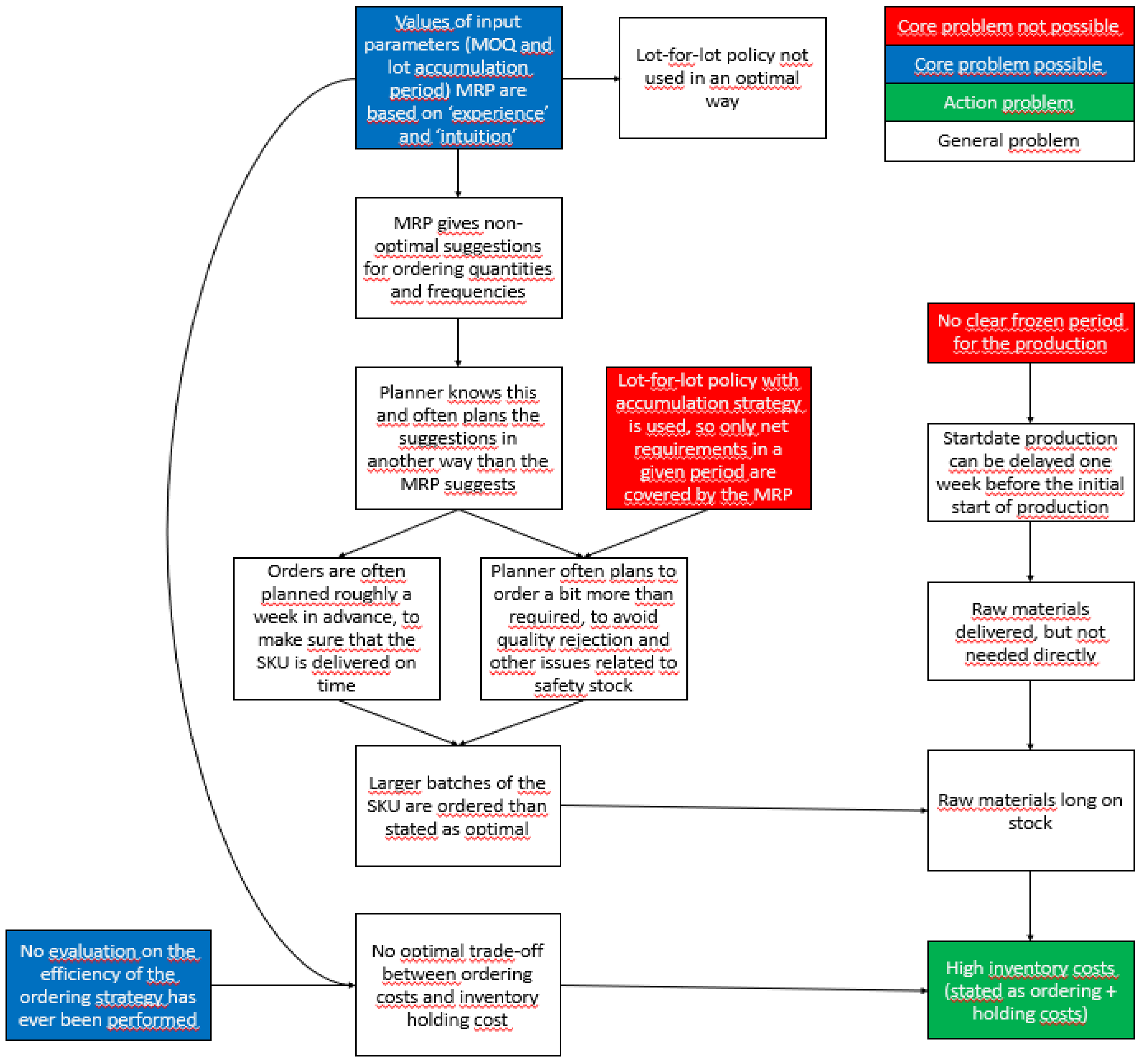

Figure 1 Problem cluster

The blue squares can be seen as possible core problems. These two core problems can be solved together because if the values of the input parameters of the MRP are substantiated with knowledge, the evaluation of the efficiency of the corresponding ordering strategy shouldn't be too hard to perform. Therefore, the main goal of this thesis is to solve the firstly stated core problem: "The values of the input parameters (LAP & MOQ) are based on 'experience and intuition'". The action problem (the inventory costs are considered too high) should be solved by optimizing the input parameters of the MRP.

1.4 Research goal

The company wants to restructure the inventory management policies for all commodities. Nevertheless, improving inventory control as a whole might be too broad to aim for during the 10 weeks in which the research is performed. Therefore, the research goal of this thesis is to provide SVgroup with a tool in Excel that optimizes the lot sizes and corresponding ordering moments only. Therefore, the main goal of the research is to suggest a method that optimizes these lot sizes and reordering moments. The optimization should help the company with improving a part of its inventory management. The company wants to use this model after this thesis is completed. Therefore, a recommendation section will be provided in this thesis to make sure that the company uses the model correctly. In the next sections, it is stated what will be included and what will be excluded during this thesis.

1.5 Scope

As stated above, an optimization of inventory management is needed at the company. Because of only having 10 weeks to perform the research at the company, it is important to state what requirements should be included in the research and what should be excluded. In an ideal situation, the company wants to review the inventory management of all SKUs (raw materials, semi-finished products, and finished products) of all 25 finished products. However, because of having ten thousand SKUs, this is impossible to perform in 10 weeks. Therefore, one product will be focused on; slurry injector A. This is a slurry injector that has a very seasonal pattern, which is why this product is representative of all products at SVgroup. This finished product consists of 184 SKUs, of which 55 are semi-finished products and 129 are raw materials. The inventory value of the raw materials of the product is 63% on average of the total inventory over the last year (2022) of the finished product. The semi-finished products account for 15% of the total inventory of the whole product and the finished product counts for 22% of the total inventory value of slurry injector A. This is why the focus during this research will be on the raw materials of slurry injector A only, because the most profit could be made for this type. Table 1 illustrates the average value of the three product groups of slurry injector A in 2022.

Table 1 Inventory value as a percentage of total

Product category	Index value	Percentage of total
The finished product (slurry injector A)	100	22.3%
Semi-finished products	67.84	15.1%
Purchasing/raw materials	280.89	62.6%

1.6 Research design

During this thesis, the main focus will be on the optimization of the lot sizes of the raw materials of slurry injector A. After analyzing the problems at the company, the main research question can be formulated as:

How to optimize the lot sizes of the raw materials at SVgroup in such a way that it minimizes the total expected costs while storing sufficient raw materials to deliver the product on the due date?

To be able to achieve the goal of the research, it is key to get a certain flow in the research. This flow is taken care of using sub-questions. These sub-questions guide us toward the desired outcome for the main research question. The questions could be linked to the managerial problem-solving method stated by Heerkens & van Winden (2021), which is the problem-solving approach that will be used throughout the research. Every chapter in this thesis could be linked to one of the steps of this method. The following 5 main research questions help us guide towards an answer for the main research question:

1. *What is the current situation at SVgroup with respect to determining the lot sizes and what causes the inventory problem?*
    a. *How does SVgroup currently determine the lot sizes of the raw materials of slurry injector A?*
    b. *What nature does the demand for slurry injector A (and the raw materials of it) have?*
    c. *How is the MRP currently used?*
    d. *What methods does SVgroup use to manage its inventory?*
    e. *How is the total expected cost currently calculated?*
2. *Which methods known in the literature about the optimization of lot sizes could be used for the SKUs in the scope of the research?*
    a. *To what extent can static lot-sizing heuristics be used at SVgroup?*
    b. *What dynamic lot-sizing heuristics are known in the literature?*
    c. *How can the performance of the different lot-sizing heuristics be measured to select the best heuristic for SVgroup?*
    d. *What complexity brings the dynamic lot-sizing heuristics?*
    e. *How to calculate the inventory costs?*
3. *How can the lot sizes of the raw materials of slurry injector A be optimized?*
    a. *What heuristic could be used to determine the lot sizes for this specific product?*
    b. *What changes should be made to the heuristic to make it applicable to the situation at SVgroup?*
    c. *What assumptions are necessary to make?*
4. *How does the proposed model perform?*
    a. *How can the model be validated?*
    b. *How do the lot sizes of the proposed model perform compared to the current LAPs set for the SKUs?*
5. *How can the proposed model be implemented in the ordering process of the raw materials at SVgroup?*
    a. *How should SVgroup use the developed model?*
    b. *How can the model be used for other products as well?*
    c. *What are the implications of applying the improvements?*
    d. *How can the model be used to improve the current input parameters?*
    e. *What further research goals are recommended?*

1.7 Research approach

This Section states what activities need to be performed per research question. All these activities should lead to an answer for the main research question.

Chapter 2: Current situation
Firstly, we need to analyze the current situation at SVgroup regarding the calculation of the lot sizes during a given period. The usage of the MRP will be analyzed in this chapter. This analysis will include the extent to which seasonality is taken into account as well. Besides, the inventory problem is analyzed in this chapter, to gain insights into what the factors are that form this problem and how the inventory costs currently are calculated.

Several actions need to be performed to develop this chapter. To get the required information, we need to interview the master planner. He knows exactly how he currently sets the lot sizes and why he sets them this way. Furthermore, the interview gives an overview of how the MRP works and how it is used at the moment. To analyze the demand for slurry injector A, data analysis needs to be performed. Besides, the average inventory value of slurry injector A and four SKUs (chosen based on different lead times) will be analyzed through data analysis. These actions give knowledge about the seasonality question and the inventory questions.

Chapter 3: Literature Review
After analyzing the current state of ordering, literature should be used to generate solutions for this research. We need to analyze the different kinds of heuristics used for calculating lot sizes. These heuristics will be used later on for every SKU relating to the raw materials of slurry injector A. Besides, the complexity that the heuristics bring will be evaluated. Finally, this Section reflects on defining the inventory costs related to the heuristics.

Chapter 4: Model Creation
The knowledge gained from the previous chapter will be used to develop a model/prototype that integrates two new heuristics and the ordering policy that the company uses right now. At first, the heuristic that suits the situation at the company best will be selected. Possible changes to the heuristic might be made to adapt the model to the situation at the company. Lastly, possible assumptions should be stated in this chapter to know what is based on data and what is based on these assumptions. To conclude, data analysis needs to be performed to determine what heuristics suit slurry injector A best.

Chapter 5: Model Validation and Results
After building the model, validation of it needs to be performed to conclude whether or not the prototype works. The performance of the model will be addressed by comparing the outcomes of the new methods with the outcomes of the current reordering policy.

Chapter 6: Implementation
The SKUs of slurry injector A are only a small fraction of all SKUs stated in the ERP system. Therefore, the model might be used easily for the SKUs of slurry injector A only, but to use it for all products, the time required to run the model might be too long. Chapter 6 should answer questions regarding how to use/change the model to make sure that all SKUs can be reviewed through this model.

Chapter 7: Conclusion and Recommendation
After completing the model, a conclusion of it should be stated. Furthermore, possible recommendations about the usage of the model should be stated as well. Finally, recommendations about possible following research will be given to the company.

1.8 Deliverables

Every chapter serves as input for the next chapter. This indicates that every chapter provides a deliverable for the next chapter. Chapter 2 describes the current situation at the company. We perform an analysis of the inventory problem, as well as of the MRP usage and the production process. This descriptive deliverable will be used as input to define the key concepts of the literature review, which is indicated in Chapter 3. This chapter reviews different lot sizing heuristics/methods and selects lot sizing methods that could be feasible in the case of SVgroup. We use the literature to create a prototype in Excel that minimizes the total inventory costs. The creation of the prototype is used as input for the validation chapter. After validating the model, an analysis of the results could be made. These results form a basis for the implementation that is provided in Chapter 6. Chapter 6 focuses on the extent to which the model should be changed to make sure that the model can be used for all SKUs. Finally, Chapter 7 concludes this thesis. It also states recommendations for the company.

2. Current situation

In this Chapter, we discuss the current situation at SVgroup concerning determining the lot sizes of raw materials. The first Section elaborates on the inventory problem at SVgroup. The purchasing materials are analyzed in this Section. Section 2.2 focuses on the way that the MRP is used at the company. Possible bottlenecks during the ordering process are identified in this Section as well. Section 2.3 elaborates on the costs of ordering. The inventory costs are elaborated, as well as the setup costs. Afterward, the extent to which these costs are currently used is explained. The last Section provides a conclusion that is used as input for Chapter 3.

2.1 Inventory problem raw materials

As stated in Chapter 1, the main problem stated by the company is that their inventory costs are too high and that the ordering process is not substantiated with knowledge. Therefore, the inventory problem should be researched. In this section, the inventory problem with respect to the raw materials is evaluated.

First of all, the inventory value for all raw materials of slurry injector A over the last year needs to be calculated. The finished product consists of 129 raw material SKUs. From these 129 raw materials, for 47 SKUs, the average amount of inventory over the last year is more than €1.000,-. Of these 47 SKUs, a total of 17 SKUs face an average amount of more than €5.000,-. The raw materials have lead times ranging from only 3 days to 120 days. These lead times are stated in the planning tab of the corresponding SKU in Navision. The lead times stated in a MRP are considered as deterministic (Silver et al., 2016). However, in reality, this lead time will not always be the stated time period (it will depend on how busy the supplier is). A lot of SKUs of slurry injector A have either an 'incremental order quantity' or a 'minimum order quantity' or both stated in the planning tab. This indicates that the company often cannot order all quantities that they want to order. The inventory value of the last two and a half years of different SKUs with different lead times needs to be analyzed to extract some conclusions about how the inventory is managed. Figures 2, 3, and 4 show the inventory value of three SKUs with 3 days, 20 days, and 50 days lead time respectively.

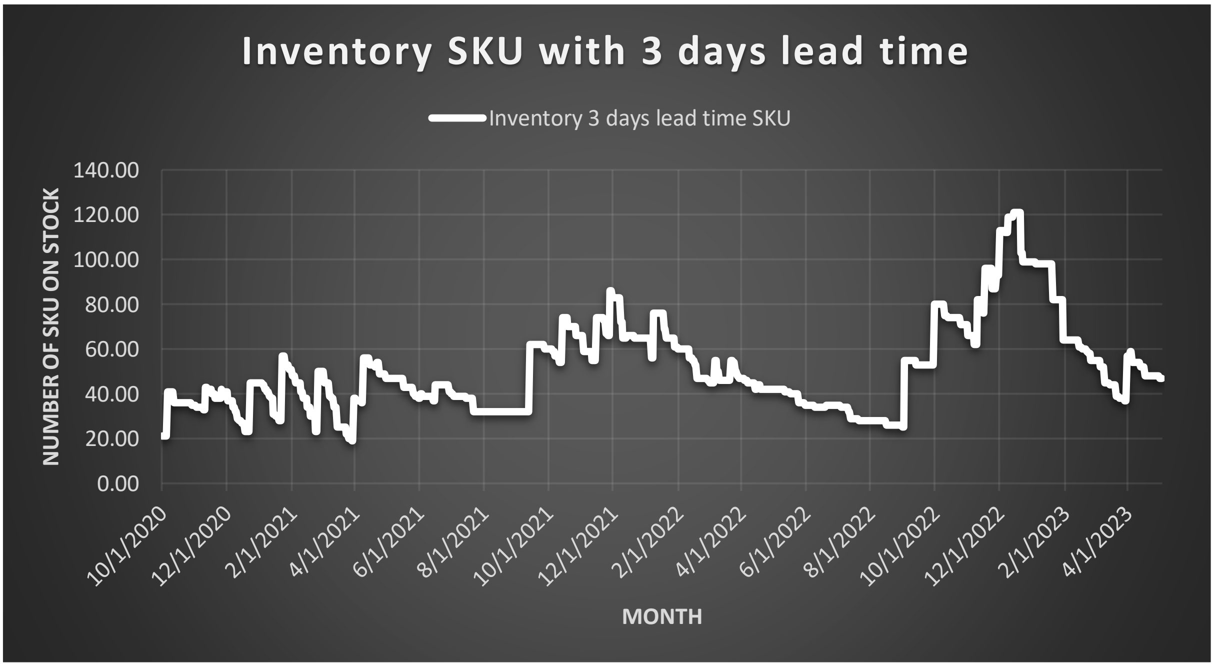

Figure 2 Height inventory 3 days lead time

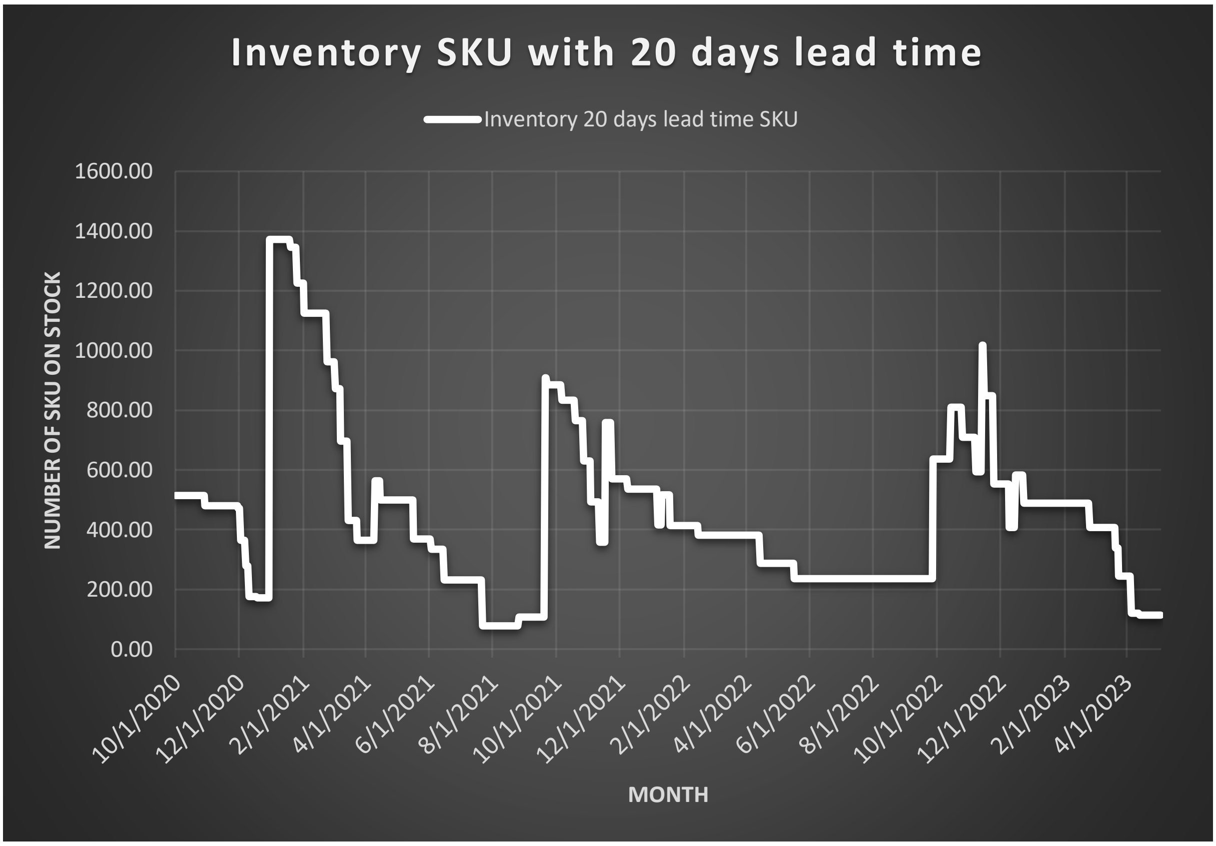

Figure 3 Height inventory 20 days lead time

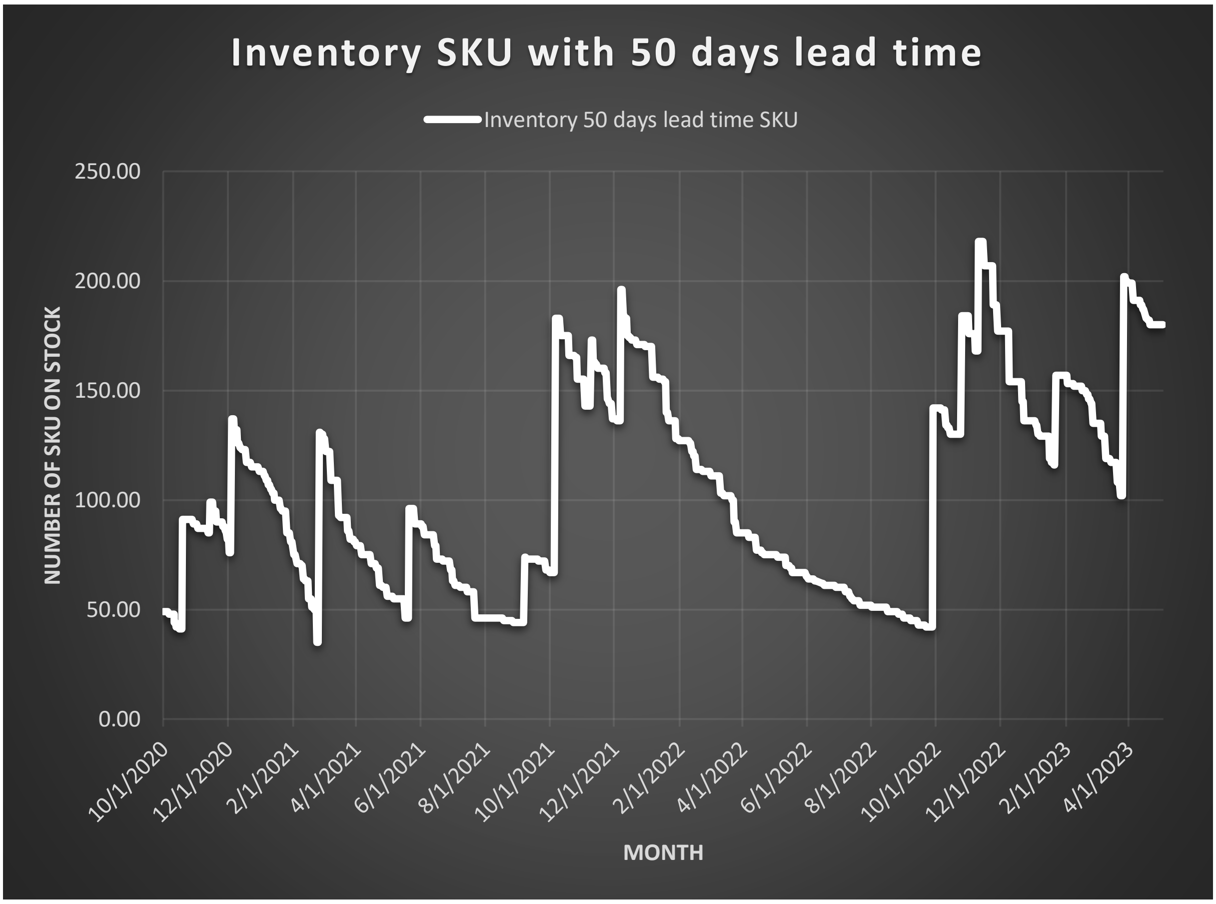

Figure 4 Height inventory 50 days lead time

Some conclusions can be extracted from the figures individually and from the three figures as a whole.

First of all, the inventory of none of the SKUs has been zero in the last two and a half years. The company doesn't define a clear safety stock for these SKUs, as they produce these SKUs on order. Following this fact, if the company produces on order correctly, the inventory should go up and go back to zero at a certain point. In Section 2.2, an elaboration on this statement is made.

Secondly, the SKU with a lead time of 20 days has an IOQ of 200. One can see this IOQ in Figure 5, as the vertical lines that go upwards are equal to steps of 200 (quantities of 200, 400, 600, etc.). This leads to the company having to purchase a large quantity at once, which leads to a huge increase in inventory on hand at once.

Besides, all three graphs show that the product faces a seasonal production plan that starts in October. For the 20 days and 50 days lead time SKUs, the largest batches of the purchasing materials are ordered for the first of October and cover a large portion of the demand of the whole production season. The company doesn't know whether ordering this large batch at once is economically optimal or not, as they do not evaluate their way of ordering. This statement is elaborated on in Section 2.3.

Finally, the line of the 20 days lead time SKU is way more horizontally straight than the lines of the 3 days lead time SKU and the 50 days lead time. This can be explained easily, as the 3D and 50D SKUs are part of different finished products. The finished products where these exist are all slurry injectors (the family group), namely slurry injector A, slurry injector B, slurry injector C, and slurry injector D. All these finished products face a seasonal demand pattern roughly at the same period of time. This explains why the graphs above all show seasonal demand. Nevertheless, the current ordering process does not change, as this process focuses on the material requirements, which are given by their MRP system.

2.2 Planning

Before the usage of the MRP can be analyzed, an elaboration on how the MRP is triggered should be made. Section 2.2.1 elaborates on the ordering strategy that is used by the company. Section 2.2.2 explains how the MRP system works.

2.2.1 Ordering strategy

The company has a certain strategy that they use for ordering their raw materials. Figure 5 illustrates the planning tab of one purchasing SKU in Navision. Below the figure, it is explained how these parameters that are set influence the ordering strategy.

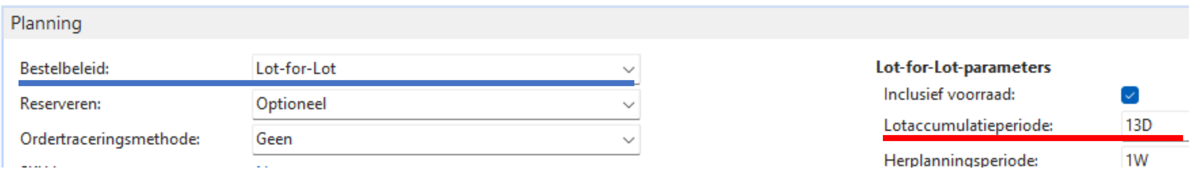

Figure 5 Planning tab per SKU in Navision

The two main parameters to understand the ordering strategy at SVgroup are underlined in blue and red. The blue line indicates the general ordering policy of this SKU. For all raw materials, this is set on lot-for-lot. This would mean that whenever a production order is planned for a certain date, a purchasing order is set too. This would lead to no inventory costs, as the policy suggests buying the material requirement per lot.

Nevertheless, the second parameter set in this planning tab relates to the actual ordering strategy that the company uses. The second parameter is stated as the "lot accumulation period", which is set on 13 days for this SKU. This parameter is used to bundle multiple supply needs of that SKU into one order. So for this SKU, if there is a difference of 12 days between two different supply needs, the LAP states that the two different supply needs should be bundled (as 12 days is less than the 13 days stated in Figure 5)

For most purchasing materials of slurry injector A, the LAP is set on 13 days. So if the order amount of one product is 1 for every week, the MRP suggests ordering two in week 1, zero in week 2, two in week 3, zero in week 4, etcetera. Of the 129 SKUs, for 106 SKUs the LAP has been set on 13 days (82.2%). The other 23 SKUs (17.8%) have LAPs of 28 days, 7 days or 0 days. Why these values have been set in a different way and with these values is unknown to the company. The LAP of 13 days is set for all of these 229 SKUs no matter how much it is used and how expensive the SKU is. As stated above, for two SKUs, the LAP has been set on 0 days. A LAP of 0 days indicates that if there consist a supply need on a certain day, a purchasing order is set that consists of only the supply need of that certain day. The conclusion that can be subtracted from a LAP of 0 days is that it is similar to the normal lot-for-lot policy.

2.2.2 MRP usage

The MRP is used to generate ordering amounts and corresponding moments to cover all material requirements that are formed out of the production orders. The MRP gives the planner suggestions regarding the ordering quantities and moments per SKU. Figure 6 visualizes an example of order suggestions that the MRP generates. The orange part of the figure shows the height of the inventory if the planner does nothing related to ordering the product. The green parts of the figure show the suggestions made by the MRP. The x-axis consists of the days and months in which the MRP gives order suggestions. The y-axis relates to the number of this SKU on stock.

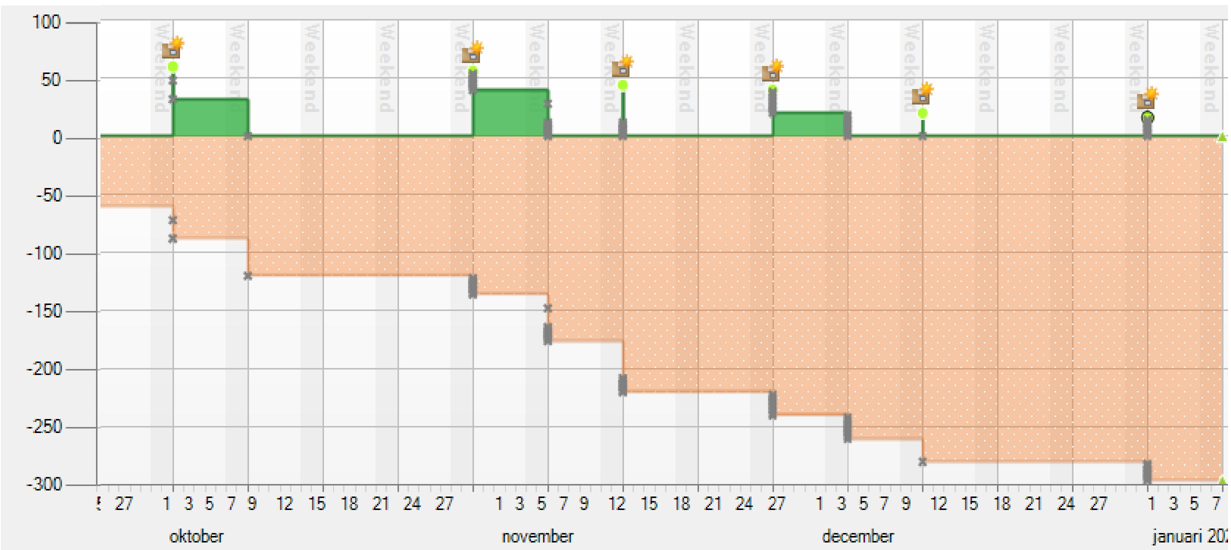

Figure 6 Example suggestion MRP

In this example, the MRP suggests ordering six times from October to January. The LAP of 13 days could be seen pretty quickly once looking at this figure. The MRP suggests ordering 50 of this SKU on the first of October. This suggested order covers the material requirements of the upcoming 2 weeks

(=ordering day + 13 days accumulation), meaning that a part of the suggested order will be stored in inventory for one week, as it is used in the week after the suggested order should be placed.

2.3 Costs of ordering

To calculate whether the ordering moments and quantities are chosen optimally, the total inventory costs should be minimized. The average total costs could be defined as a tradeoff between the inventory holding costs and the setup costs. As the focus of this thesis is on the raw materials of slurry injector A only, the setup costs can be stated as the costs of placing an order.

2.3.1 Inventory cost

Currently, the company uses an inventory cost percentage of 25%. Durlinger (2015) states that the term "inventory costs" can be divided into 3 different categories: capital costs, storage space costs, and inventory risk costs. The weighted average cost of capital relates to the capital costs. This percentage is not known yet for 2022-2023 at SVgroup, but they estimate this value to be between 3.5% and 4.5%. Therefore, the capital costs will be estimated to be 4%. The source analyzes the different costs and states that the storage and inventory risk costs should be calculated per SKU, as these costs should be variable. A differentiation between the storage and risk costs should be made to get different percentages. Two key variables are important for the calculation of the percentage, namely the risk of becoming obsolete and the value density. With value density, the researcher should elaborate on the value of the product on one pallet.

There are two warehouses at SVgroup, one warehouse for small materials and one for big materials. Therefore, to come up with limit values for the value density, it is important to use the same volumes for both warehouses (namely, a pallet of 110 cm by 75 cm by 38 cm). The limit values with corresponding inventory percentages are as follows:

$$Value\ density:\ < €1.500\ per\ pallet \rightarrow High\ percentage$$

$$€1.500 < Value\ density < €10.000 \rightarrow Medium\ percentage$$

$$Value\ density:\ > €10.000 \rightarrow Low\ percentage$$

To determine the risk percentage of the inventory, all reviewed SKUs need to be clustered. The 11 clusters (with corresponding risk index) that are considered are screws (1), metal (1), electronics (3), air (2), hydraulics (3), stickers (1), rubber (2), locking rings (1), lights (2), plastic (2) and engines (2). As one can conclude, none of the clusters consist of deteriorating SKUs. One needs to consider what might happen when SKUs are in stock in the warehouse. The SKUs might be damaged, they might get stolen, metal might get rusted, and most importantly, the clusters all have a different chance of getting obsolete after a certain period. In the electronics industry, changes to products happen a lot, because of the technologies getting better (Durlinger, 2013). Therefore, the "electronics" cluster has the highest risk index. The percentages of the risk of holding inventory related to the index numbers are as follows:

$$Low\ risk\ percentage\ for\ clusters\ with\ index\ value\ 1$$

$$Medium\ risk\ percentage\ for\ clusters\ with\ index\ value\ 2$$

$$High\ risk\ percentage\ for\ clusters\ with\ index\ value\ 3$$

All SKUs that are in the scope of this thesis are reviewed on the value density and risk index. The following table can be made after the analysis:

Table 2 Groups with different inventory percentages

	Low risk	Medium risk	High risk
High density value	1. 20 SKUs	4. 3 SKUs	7. 14 SKUs
Medium density value	2. 50 SKUs	5. 8 SKUs	8. 18 SKUs
Low density value	3. 13 SKUs	6. 2 SKUs	9. 1 SKU

As the risks of holding inventory are not as high as they would be for deteriorating SKUs, only 3 percentages will be chosen for this table. For the SKUs in groups 1 and 4, a storing + risk percentage of 16 will be used. For the SKUs of groups 2, 3, 5, 7, and 8, a storing + risk percentage of 21 will be used. For the SKUs in groups 6 and 9, a storing + risk percentage of 26 will be used in this thesis.

Overall, three different inventory holding cost percentages will be used throughout this thesis; 20%, 25%, and 30%.

2.3.2 Setup cost

As the setup cost of setting the lot sizes for purchasing materials is stated as the cost related to placing an order, the total amount of orders set over a given time period should be calculated. The ordering cost can be divided into 4 subsections: costs to place an order, to transport the products, to receive the order, and to store the order (Durlinger, 2015).

First of all, an order placement comes with costs. From the first of January 2022 until 31 December 2022, the company set a total of 26151 purchasing orders. This amount is equivalent to 545 orders per week on average (based on 48 weeks a year; 52 weeks minus holiday weeks). Two full-time operational purchasers are busy buying the suggested orders that are planned by the MRP. Furthermore, they have to plan some orders themselves. Finally, they have to make sure that the SKU tab in the ERP system is up to date. All this leads to the buyers being busy with ordering for 80 hours per week. Furthermore, half of the week of the MRP planner consists of planning the purchasing orders. This means that a total of 100 hours are spent on placing the 545 orders every week.

Besides placing an order, costs should be included to be able to receive the order. The administrative employee is responsible for all administrative checks. Half of his week, he is busy with administrative things to receive an order. Besides the administrative employee, one employee checks the quality of the incoming products. This takes 20 hours of his week as well.

Thirdly, the supplier can deliver the product franco or might state that the buyer has to pay for the transport of the raw materials. The 129 SKUs reviewed for determining the inventory costs are bought by 35 different suppliers. 21 suppliers deliver their products without charging any costs to SVgroup. For 6 suppliers, the company has to pay a fixed price for transport once they order any amount. 8 suppliers state that they deliver their products for free if the value of the order set by SVgroup is higher than a certain amount. To make sure that this variable component is taken into account in the ordering costs, the invoices of the last 10 orders of these 14 suppliers are analyzed. For the 6 suppliers that charge a fixed price for transport, the number of SKUs on these 10 invoices is used to calculate the average number of SKUs on one invoice. The freight costs included for a SKU are the fixed price divided by the average number of SKUs. For the other 8 suppliers, the same analysis has been performed. Besides, a certain number of these 10 invoices are delivered without any freight costs included, because the value of the order is above the stated amount. Therefore, we need to divide the freight costs by the average number of SKUs on the invoices and by the fraction of invoices that had a lower total value than the stated amount. Table X illustrates the freight costs that are included for the suppliers that do not always deliver the freight without charging the company for it. Suppliers 1 until 6 are the suppliers that charge a fixed amount no matter how much is ordered. Suppliers 7 until 14 state that they charge SVgroup a certain amount for freight costs if the total value of the order is lower than the stated amount. Suppliers 15 to 35 deliver their products without charging SVgroup anything. Therefore, these suppliers have not been put into Table 3.

Table 3 Freight costs suppliers 1 until 14

Supplier	SKU nr. in scope	# of invoices delivered without charge out of last 10 invoices	The average number of SKUs per invoice	Freight cost included
1	126	None	IOQ is too high, so delivered without charge	None
2	36	None	1 per order	€ 1.669,00
3	122, 123, 124 & 125	None	1.9 per order	€ 7,89
4	98, 99, 100 & 102	None	2.3 per order	€ 80,87
5	44	None	1.5 per order	€ 6,67
6	93	None	2 per order	€ 6,25
7	81	10	IOQ is too high, so delivered without charge	None
8	79 & 80	5	1,8 per order	€ 3,47
9	42, 43, 45, 46 & 82	3	2,1 per order	€ 10,00
10	129	3	IOQ is too high, so delivered without charge	None
11	47 & 48	3	1,1 per order	€ 5,41
12	41	4	2 per order	€ 4,50
13	60 & 72	4	2 per order	€ 3,75
14	4, 28, 29 & 30	10	All previous invoices (last 10) were stated to be delivered without charge	None

Finally, handling costs should be included. Two full-time employees are working on storing the incoming purchasing materials. This means that 80 hours of storing should be included in the ordering costs. In these 80 working hours, the storing of the materials is included, as well as taking samples of orders to measure the quality of the order.

To conclude, 200 hours a week are used to make sure that an average of 545 orders are placed, received, and handled. With an hourly wage of €40,-, a fixed ordering cost of €14,68 should be used, consisting of the order placement costs, order receiving costs, and handling costs. Besides this, all SKUs have a different way in which they are delivered. This variable cost is added up to the €14,68 for the SKUs that are delivered by suppliers 1 until 14.

2.3.3 Usage of the costs

Currently, the tradeoff between inventory and setup costs is not calculated at the company. This results in the master planner often having to accept the suggestions made by the MRP without him knowing for sure whether the suggestions have an optimal tradeoff between these costs. This also results in the company not ever having evaluated its inventory policy. A comparison of their inventory policy with other lot sizing methods couldn't be performed because of this. Therefore, a model that calculates the optimal tradeoff between these costs is desired.

2.4 Conclusion

After analyzing the inventory problem, the MRP system that is used at the company, and the current way of setting the lot sizes, we can conclude a couple of things. First of all, the height of the inventory of slurry injector A corresponds with the seasonal pattern of the demand. The height of the purchasing materials is in accordance with the inventory of slurry injector A as well, no matter what the lead time of the supplier is. Besides, the raw materials count for more than 60% of the total value of the inventory of the product group slurry injector A (finished product, semi-finished products, and raw materials). This is why the focus will be on the raw materials only. Furthermore, a lot-for-lot policy is used for all raw materials, with a LAP of 13 days for 88.8% of these raw materials. This LAP is once set on intuition and no calculation has been performed to make sure that it forms an optimal tradeoff between inventory and setup costs, to reduce the total costs related to the ordering process. The inventory costs and ordering costs have been determined for all SKUs in the scope and can be used as input in Chapter 5.

3. Literature review

This chapter focuses on the following question: "Which methods and heuristics are discussed in the literature and how to select the right heuristic to dynamically calculate lot-sizes?" This question will be answered through a systematic literature review. The first section of this chapter states what kind of heuristics should be evaluated in terms of the context of the research environment. Section 3.2 elaborates on 2 single-item heuristics that could be used in the context of the company. In Section 3.3, another method is explained to make sure that all SKUs can be reviewed in Chapters 4, 5, and 6. Section 3.4 concludes this chapter and states what heuristics could be used best for the SKUs of slurry injector A.

3.1 Methods Selection

This Section explains the variation in lot-sizing heuristics and what kinds of heuristics are chosen to analyze throughout this systematic literature review. At the end of this Section, a conclusion is given based on the situation at the company.

Models that elaborate on the optimal timing of orders and define the optimal order quantity are considered as dynamic lot-sizing models. These lot-sizing models are considered ways to prevent cases where the material is out of stock and cases where there is too much material present at the company (Djunaidi, 2019). To select what heuristic suits the company best, multiple criteria need to be evaluated. Silver (1981) states some criteria that need to be evaluated. The most important criteria are stated below:

The first consideration that needs to be evaluated is the number of items that will be reviewed. Some heuristics focus on single-item lot-sizing heuristics, while others focus on multiple items (Silver, 1981).

The demand distribution is another factor that influences the selection of the heuristic. Demand can be known with certainty, which leads to using a deterministic approach. If the demand is not known with certainty, a probabilistic approach needs to be considered (Silver, 1981).

The amount of periods taken into account in the model is another parameter that influences the selection of the heuristic. When implementing a single period in the model, the inventory level of the previous period will not be considered. However, when implementing multiple periods, the model becomes more complex (Silver, 1981).

As stated above, the main objective of this Section is to select the right heuristic in the case of SVgroup. Currently, the company uses a MRP that uses the material requirements of the purchasing materials to set replenishment orders. Silver et al. (2016) elaborate on the usage of the MRP. They state that implementing multi-stage methods might be too complex in manufacturing environments, because of the large variety of components that are often required for a single assembly component. The material requirements that are stated by the MRP for a purchasing item are related to the planning of the finished and semi-finished products in the lower-level codes. Two main questions should be considered when a MRP is implemented in a company: what should be made and what does it need to be made? (forecast and material requirements) (Silver et al., 2016).

When looking at the raw materials of the finished product at the company, the conclusion can be made that a heuristic or method is needed that focuses on the following things:

- As the MRP calculates the right number of products of item i to order in a given time interval, a single-item heuristic should be used, as it is easy to compare the selected heuristic/method with the suggestions that the MRP gives for a single SKU.

- The demand for a single SKU is derived from the materials requirements for that SKU.
- 16 SKUs do not have a MOQ and/or IOQ. For the other 113 SKUs, either an IOQ or a MOQ, or both are included. Therefore, a heuristic/method should be extended to be able to use it for these 113 items as well.
- It is stated in Navision that all of the 129 SKUs reviewed in this thesis have a fixed price per unit. Therefore, lot size-based discounts are not given for these products. That's why the final method does not have to comply with different prices. Nevertheless, in reality, quantity discounts are often included in the price that has to be paid for an order. As a matter of fact, in a study performed by Muson and Rosenblatt, it is stated that 83% of consumers receive quantity discounts. Therefore, Section 3.4 and Section 4.3 give an elaboration on the implementation of lot size-based discounts.

3.2 Single-item lot-sizing heuristics

As concluded above, the situation with respect to the determination of the lot sizes at SVgroup can be seen as a single-item lot sizing problem, as well as a multi-item lot sizing problem. This is because the lot sizes of the raw materials are not dependent on one another. Nevertheless, the raw materials do face a complementary demand pattern, because the demand for those materials is derived from the demand for the finished product. In this section, the Wagner-Whitin method is explained and evaluated.

3.2.1 Wagner-Whitin

One of the first lot-sizing heuristics that improves the standard EOQ calculation. The EOQ formula does not calculate the minimum cost once the demands during certain periods are different and inventory costs differ over time (Wagner and Whitin, 1958). The algorithm that is provided in the article of Wagner (1958) is a DP model that obtains the optimal solution for order sizes in finite-time planning. This time planning is divided into multiple time buckets/periods. At the end of the time planning, the total demand during the time buckets has to be met (Asmal, 2019). One of the assumptions made in this model is that the demand during the time horizon is time-varying, but known with certainty. Multiple steps are involved in calculating the optimal solution (Asmal, 2019)(Ernawati, 2021)(Djunaidi, 2019):

1. Firstly, the cumulative total demand (Qce) over the time horizon has to be calculated. This is the demand of previous time periods (Qci) + the demand in period e (current period, Qe).
   $Q_{ce} = Q_{ci} + Q_e$
2. Calculate the total variable cost in periods c to e (Zce), when placing an order in period c to cover demand for the periods c up to e. The following calculation is used for this:
   $Z_{ce} = C + h * P * \sum_{k=c}^{e}(Q_{ce} - Q_{ci})\ for\ 1 < c < e < N$
   With:
   C = Ordering cost per order
   h = Holding cost
   P = price per unit
   N = last time bucket
3. Next, the minimum cost per period needs to be calculated. This minimum cost is denoted as fe and uses a starting inventory level of zero. The corresponding formula is denoted as:
   $f_e = \min(Z_{ce} + f_{c-1})\ \ for\ c = 1, 2 \ldots e$
4. Multiple constraints need to be taken into account:

a. The last order that is set in the time interval should cover all demand for the remaining time buckets: $f_N = Z_{ce} + f_{c-1}$
b. If the last order sequence covered demand up till v-1, a new order has to be set in time bucket v to cover demand for periods v up till c-1: $f_{c-1} = Z_{vc-1} + f_{v-1}$
c. Because of the assumption that starting inventory is zero, the first order has to be set in the first time bucket. This order needs to cover the demand from the first period up till period w-1: $f_{w-1} = Z_{w-1} + f_0 \; with \; f_0 = 0$

The Wagner-Whitin model gives the best solution with respect to the total inventory cost in comparison with other single-item lot sizing heuristics (Samak-Kulkarni, 2013). This is because this method uses DP to come to the most optimal solution. The Wagner-Whitin model can be used for SKUs without a MOQ or IOQ. For SKUs that do have these parameters, another method is needed.

3.3 Extended lot sizing methods

As stated in Section 3.1, a lot sizing method should be extended to be able to include SKUs with MOQ and IOQ as well. The single-item lot sizing methods stated above can be used for SKUs that do not have these parameters (MOQ & IOQ) included in their planning template in the ERP system. These heuristics cannot be used for SKUs with these parameters, because the heuristics simply cover the material requirements. When the ordering amounts can only be a fraction of a fixed amount, it can be possible that one has to order, even though a couple of products of item i are in stock at the beginning of the period.

Other approaches regarding the calculation of optimal lot sizes are needed. Throughout the bachelor's program, multiple courses are given that might be able to solve the lot sizing problem. As Wagner and Whitin (1958) have created their model through DP, it is known that DP could be used for solving lot-sizing problems. Therefore, the focus from Chapter 4 and onwards will be on a model that simplifies the Wagner-Whitin model and thus uses DP to be able to calculate optimal ordering moments and corresponding lot sizes.

Mizutani and Trista (2019) evaluate different DP models related to inventory management. A differentiation is made through the number of state variables. The first model states that the current period is the only variable that is important for the determination of optimal lot sizes. This model relates to the Wagner-Whitin model that is elaborated above. Because of not always ordering a cumulative of the requirements (as a multiple of the IOQ should be ordered), the inventory should be a state variable as well. Mizutani et al. (2019) state a generation-point forward DP model that can be changed easily to be able to implement restrictions regarding the MOQ and IOQ. The optimal value function is stated as follows:

$F(k) =$ minimum cost so far from period 1 up till k when the inventory level at the start of period k is equal to 0. The regeneration point DP model sums over multiple stage costs to get the total minimum cost at the last period in the horizon. Mizutani et al. (2019) state this recurrence relation as $F(k) = min\{F(j) + c(j,k)\}$, with j being the previous regeneration point. The decision that has to be made is whether to include the demand of the current period k in the order that has been set in period j. An important condition that is given is that the inventory at the first and the last periods should be equal to zero. The lowest cost is given by the minimum expected total cost related to the period after the planning horizon. The set of options regarding the order quantity can be stated as:

$$\begin{Bmatrix} z_n = 0 & if \; v_n > 0 \\ z_n \in \{d_n, d_{n,n+1}, d_{n,n+2}, \dots, d_{n,N}\}, & if \; v_n = 0 \end{Bmatrix},$$

with z_n being the number of products of item i to order at each period n,
and v_n being the inventory on hand at the start of period n (Mizutani et al., 2019).

When implementing restrictions regarding the order quantity (based on the IOQ), the assumption that the ending inventory is equal to zero doesn't hold anymore, because it can happen that a fraction of the IOQ will still be in inventory. Furthermore, because of the order quantity that might not be equal to a cumulative of the upcoming demand, the inventory might be greater than zero at period n, but less than the demand in period n. In this situation, the purchaser has to set an order, because the inventory will be less than zero in period $n + 1$ if we do not buy anything. Therefore, the set of options stated above cannot be used directly for SKUs with an IOQ. Section 4.2 elaborates on the change that should be made to this optimal policy.

3.4 Lot size-based discount

For the SKUs of slurry injector A, the company assumes that there is one fixed prize for every SKU. Nevertheless, in reality, this is not the case for all of the 129 SKUs reviewed. The company knows this as well and currently implements multiple prizes for different lot sizes in their ERP system for all purchasing SKUs of a newly implemented finished product. They are currently experimenting with these lot size-based prizes for the new product. If they experience that purchasing bigger batches yield more profit, they want to implement this for the SKUs of slurry injector A as well. Nevertheless, because the company not being able to determine the optimal tradeoff between holding and ordering costs, they do not know whether it is economically optimal to buy bigger batches of the SKUs or not.

To be able to calculate whether lot size-based discounts should be used in the ordering process, several constraints should be implemented on the different prizes. Xu et al. (2000) and Zhang et al. (2012) implement constraints on prices in a DP approach. The first main model stated by Xu et al. (2000) states the objective and constraints that should be implemented for SVgroup as well. Nevertheless, the article states a model that elaborates on a fractional discount of the fixed price (called ∝). In the context of SVgroup, the lot size-based discounts are not stated as fractional discounts of the price of ordering one unit. SVgroup states that there are different prices for different lot sizes. Therefore, this fractional discount should be changed to restrictions that suit the SKUs at SVgroup. Zhang et al. (2012) elaborates on incremental quantity discounts. The unit price relates to the number of units that are purchased at once. The following unit price structure is given:

$$\begin{aligned}
&p_{t,1} \ \rightarrow For\ the\ first\ Q_{t,1}\ units,\\
&p_{t,2} \ \rightarrow For\ the\ next\ Q_{t,2} - Q_{t,1}\ units,\\
&\vdots \quad \rightarrow \vdots\\
&p_{t,x} \ \rightarrow For\ each\ unit\ that\ exceeds\ Q_{t,x-1}\ units,
\end{aligned}$$

An important note for this structure is that $Q_{t,0} = 0\ and\ Q_{t,x} = +\infty$. Besides, the corresponding prices decrease ($p_{t,y} > p_{t,y+1}, with\ y < x\ and\ y \geq 1$). This structure indicates that the units ordered in one order can have different prices (unit 1 in order X might cost more than unit 100 ordered in order X). However, the multiple prizes stated in the ERP system of SVgroup relate to the prize $p_{t,y}$ for all units in one order if the order amount lies between the interval $Q_{t,y} - Q_{t,y-1}$. Therefore, the unit price structure stated above should be changed a bit to use such restrictions.

The ordering cost corresponding to the unit price structure given above can be stated as follows (Zhang et al., 2012):

$$f_t(x_t) = \begin{cases} p_{t,1}x_t, & if\ Q_{t,0} \le x_t < Q_{t,1} \\ \sum_{j=1}^{k-1}\{(p_{t,j} - p_{t,j+1})Q_{t,j}\} + p_{t,k}x_{t,} & if\ Q_{t,k-1} \le x_t < Q_{t,k}\ with\ k = 2, \dots, K_t \end{cases}$$

Because of the unit price that should be changed to make sure that the model can be used in the case of SVgroup, the unit price structure stated above should be changed as well. As one can conclude from the function stated above, if the ordered quantity is more than the second discount quantity, the total price that has to be paid to the supplier is not directly equal to one fixed price for the whole ordered quantity. The price of the total order stated above consists of fractions of the complete order times the corresponding price. In the case of SVgroup, the price that should be paid to the supplier for an order is equal to one price (depending on the order quantity) times the quantity of the whole order. In Section 4.3, the new unit price structure and order cost formulation are given.

3.5 Conclusion

When selecting heuristics that might help with determining lot sizes and corresponding order moments, one needs to decide whether to focus on multiple items at once or on one single item. The MRP at the company calculates the ordering moments and lot sizes based on the LAP, MOQ, and IOQ for every single SKU. If we want to implement the newly designed model in the context of the company, a single-item approach needs to be chosen. The Wagner-Whitin model can be used for normal SKUs that do not have a MOQ or IOQ. The model stated by Mizutani et al. (2019) can be used for both SKUs that do not have an IOQ & MOQ and for SKUs that do have these parameters stated in Navision. However, for SKUs with these parameters, the model suggested by Mizutani et al. (2019) cannot be implemented directly without creating some restrictions. For SKUs that have different prices depending on order quantities, other models should be used. Two sources have been stated in Section 3.4. The model stated by Zhang et al. (2012) can be used for calculating lot size-based discounts. However, because of a different situation at SVgroup in comparison with the situation in which Zhang et al. (2012) perform their research, a change in the cost and unit price function is needed. Therefore, the main models can be used as input for the models that will be created in Chapter 4. Nevertheless, some changes in these models should be made to make them applicable for use at SVgroup. These changes will be made in Chapter 4. The following table can be made to state what models can be used for what criteria:

Which model for what criteria?	No lot size-based discount	Lot size-based discount
No MOQ/IOQ	DP model stated by Mizutani et al., which relates to the Wagner-Whitin method.	The main model of Mizutani et al. + new unit price structure given by Zhang et al.
MOQ&IOQ	Mizutani et al. + some restrictions related to MOQ & IOQ that will be made in Section 4.2	The main model of Mizutani et al. + the restrictions related to MOQ & IOQ + new unit price structure of Zhang et al.

4. Model creation

To be able to illustrate whether the current manner of ordering and holding inventory is done optimally, some lot sizing models should be made. In total, two sorts of lot sizing models have been created. The first model has been created for SKUs that do not have a MOQ or an IOQ. The method stated by Wagner and Within is used for these SKUs. The second lot sizing model expands model two so that the company can use a lot-sizing model for SKUs that do have a MOQ and/or an IOQ. The third section illustrates the final model that has been made. This model can be used for SKUs that have lot size-based discounts. Section 4.4 concludes Chapter 4 and can be used as input for Chapter 5.

4.1 Model 1: A dynamic programming approach

As stated in the introduction of Chapter 4, this model could be used to find the optimal order quantity and the optimal ordering moment. The DP model stated in Section 3.3, based on Mizutani et al. (2019), can be used to formulate a model that suits the case of SVgroup. This model stated by Mizutani et al. (2019) is based on the Wagner-Whitin model. The set of options stated in this same Section can be used for SKUs without an IOQ. Therefore, the quantity ordered relates to this set of options. The model is created in the following way:

Stage: Beginning of week n. ($n \in \{1,\ldots,N_i\}$)

State: $V_{i,n}$= inventory on hand of item i at the beginning of week n. ($V_n \in \{0, 1, \ldots, TD_i\}$)

Decision: Choose the previous regeneration point j. Decide the optimal quantity x_{in} of item i to order for week n when in state $V_{i,n}$, with $x_{i,n} \in \{0; D_{i,n}; (D_{i,n} + D_{i,n+1});\ldots;(D_{i,n} + D_{i,n+1}+\ldots+D_{i,N_i})\}$

Optimal value function: $F(n) =$ The minimum expected total costs so far for the first n weeks if $V_{i,n} = 0$.

Constants:

$\boldsymbol{D_{i,n}}$: Material requirements of item i in week n
$\boldsymbol{TD_i}$: Total demand in the reviewed period $\left(D_1 + \cdots + D_{i,N_i}\right)$
$\boldsymbol{N_i}$: Planning horizon of item i
$\boldsymbol{O_i}$: Cost of setting an order for item i
$\boldsymbol{p_i}$: Price of ordering 1 item of item i
$\boldsymbol{h_i}$: Holding cost per period of item i

Variables:

$\boldsymbol{x_{i,n}}$: Quantity of item i ordered in period n
$\boldsymbol{\delta_{i,n}}$: Binary variable indicating whether an order is placed or not ($\delta_{i,n} \in \{0,1\}, 1\ if\ x_{in} > 0$)

DP model:

Minimize: $$F(n) = \underset{j\, =\, 1, \ldots, k-1}{Minimum}\{F(j) + c(j,n)\} \qquad (1)$$

With: $$c(j,n) = \delta_{i,n} * O_i + \sum_{s=j}^{n-2} V_{i,s+1} * h_i \qquad (2)$$

$j =$ previous regeneration point before the current period k

Subject to:

$$x_{i,n} + V_{i,n} - D_{i,n} = V_{i,n+1}, \qquad (3)$$
$$x_{i,n} \leq M\delta_{i,n}, \qquad (4)$$
$$V_{i,0} = V_{i,N_i} = 0, \qquad (5)$$
$$V_{i,n}, D_{i,n}, x_{i,n} \geq 0, \qquad (6)$$
$$N_i \geq 1. \qquad (7)$$

The main objective is to find the minimum expected total cost so far for the first n periods. The decision is to choose the previous regeneration point, which is indicated as period j (1). $c(j,n)$ relates to the cumulative stage cost between periods j and n. Therefore, $j \leq n-1$ (2) (Mizutani et al., 2019). To determine whether it is needed to order at week n, the demand balance (3) is stated to make sure that the inventory will never be negative. Winston and Goldberg (2004) state that one of the characteristics of DP applications is that the decision chosen at stage n transforms the current state in stage n into a certain state in stage $n+1$. This characteristic can be applied to the demand balance, as $x_{i,n}$ relates to the decision that needs to be made. To make sure that the order costs are included in the total cost statement, it is important to include a sufficiently big number M (4). If $x_{i,n} > 0$, then the ordering costs should be included for week n. Besides, the beginning and ending inventory should be equal to zero (5). Finally, the non-negativity constraints are stated (6&7).

Assumptions:

1) The first assumption that is made is that the material requirements are known with certainty. In reality, sometimes the beginning date of the production of finished products, and thus the material requirements of this production order, is delayed or set earlier. This means that the material requirements have some small fluctuations over time.
2) All ordered products are used in the corresponding weeks and none of these products go to waste. Quality issues and safety stock of the items are not considered. Therefore, if we order $x_{i,n}$, a total quantity of $x_{i,n}$ is completely used to cover demand in the periods that the order should cover.
3) The inventory at the end of the reviewed period is stated as zero, to make sure that the optimal value is given for a fixed time horizon. However, in a rolling horizon, this model might not give the optimal value for the expected total cost.

Procedure:
Several steps need to be taken to make sure that the model performs in a good way. These steps are related to the Wagner-Whitin method and are elaborated below:

1) The total costs of the states in the last stage need to be calculated. In the last stage, the height of the inventory on hand can be either zero or the demand in the last week (because of assumption 2). This means that we either order the exact demand in the last period or that we cover the demand with the inventory on hand that is equal to that demand. The corresponding total cost is either equal to only the order cost (if in the first state) or equal to the holding cost (if in the second state). The inventory at the end of the planning horizon is equal to zero.
2) For periods 2 up to $N_i - 1$, the total costs related to the holding cost or the order cost. The order cost is included if and only if the inventory at the beginning of the corresponding stage is equal to zero. The number of products that have to be bought when the inventory is equal to zero relates to the minimum total costs in stage $n+1$. If the inventory is greater than the demand in period n**,** the expected total cost consists of only holding costs, as the inventory can cover at least the demand of period n. Therefore, it is unnecessary to place an order.
3) For the first period, we only include order costs, as the inventory is stated to be equal to zero. This indicates that an order of at least the demand in the first period should be placed.

Because of assumption 2, the inventory can only be equal to zero or be equal to a cumulative of the upcoming demand (demand of period n, the demand of period n + period $n+1$, …, the demand of periods $n, n+1, \ldots, N_i$).

4.2 Model 2: MOQ and IOQ implementation

The first model can only be used for SKUs for which any order amount is possible. However, in reality, this is often not the case. Suppliers often deliver their products in boxes or containers that consist of a certain number of products of item i (IOQ). This indicates that orders cannot always be a cumulative of the upcoming demand. A restriction on the height of the order needs to be included. In the case of SVgroup, the researcher concludes that 4 of all reviewed SKUs have a MOQ that is higher than the IOQ, and 109 SKUs have a MOQ that is stated as either equal to the IOQ or less than the IOQ. In reality, the MOQ cannot be less than the IOQ, as one IOQ is the minimum that the company should order if they decide to place an order at a certain stage. For the other 16 SKUs reviewed, the model stated in Section 4.1 can be used, as these SKUs do not have an IOQ and MOQ. The optimal policy for these SKUs without an IOQ can be stated as follows (Mizutani et al., 2019):

$$\begin{cases} x_{i,n} = 0, & if\ V_{i,n} > 0 \\ x_{i,n} \in \{D_{i,n};\ (D_{i,n} + D_{i,n+1}); \dots; (D_{i,n} + D_{i,n+1} + \dots + D_{i,N_i})\}, & if\ V_{i,n} = 0 \end{cases},$$

However, the assumption that the inventory at the end of the whole horizon should be equal to zero doesn't hold anymore. Therefore, restrictions on the height of the order placed should be included. Two instances will be reviewed: the $MOQ_i \leq IOQ_i$ (Section 4.2.1) and $MOQ_i > IOQ_i$ (Section 4.2.2).

4.2.1 Model 2a: MOQ ≤ IOQ

As stated above, the ending inventory doesn't have to be zero at any time anymore. A fixed number of IOQs should be ordered. Therefore, the ending inventory can be determined beforehand and lies in the interval $0 \leq V_{i,N_i} < IOQ_i$. The exact calculation of the ending inventory is stated below. The optimal policy stated above can be changed to the following policy:

$$\begin{cases} x_{i,n} = 0, & if\ V_{i,n} - D_{i,n} \geq 0 \\ x_{i,n} \in \{IOQ_i, IOQ_i * 2, \dots, IOQ_i * k\}, & if\ V_{i,n} - D_{i,n} < 0 \end{cases},$$

with k being the maximum number of IOQs that can be ordered throughout the entire horizon. k is calculated as follows: $k = \frac{TD_i - V_{i,0}}{IOQ_i}$. The calculated number should be rounded up to the next integer. This maximum number of IOQs that should be ordered throughout the entire horizon, k, can be used to calculate the ending inventory, namely $V_{i,N_i} = V_{i,0} + k * IOQ_i - TD_i$.

In the model stated below, this optimal policy is elaborated. Only the key changes compared to the first model are stated below (the elements not stated below can be seen as the same as the previous model (stage, optimal value function, and variables):

State: $V_{i,n}$= inventory on hand of item i at the beginning of week n. ($V_{i,n} \in$ {0, 1, …, $IOQ_i * k$})

Decision: Choose the previous regeneration point j. Decide the optimal quantity x_{in} of item i to order for week n when in state $V_{i,n}$, with $x_{i,n} \in \{0, IOQ_i, IOQ_i * 2, \dots, IOQ_i * k\}$

The constants, variables, and optimal value function are considered the same as the model stated in Section 4.1. Restriction (5) stated in Section 4.1 does not hold anymore, as the beginning and ending inventory can be different than zero for this model. The sufficiently big number M in restriction (4) in Section 4.1 should be greater than $TD_i + MOQ_i - 1$. Both assumptions 1 and 2 stated in the previous Section still hold for this model as well. Nevertheless, as stated at the beginning of this Section, the inventory on hand at the end of the horizon might not be equal to zero anymore. Therefore, assumption 3 doesn't hold for this model.

Procedure:
To make sure that this model works well, the involved steps taken should be stated:

1) After period N_i, we have a fixed remaining inventory that lies in the interval $0 \leq V_{i,N_i} < IOQ_i$.
2) The optimal solution is given by the end of the last period. This relates to the beginning of the period $N_i + 1$.
3) The decision that needs to be made is what the optimal previous regeneration point ($period\ j$) should be, through calculating $F(n)$
4) In the first period, only the order cost and the cost to the corresponding state in the next stage should be included.

4.2.2 Model 2b: MOQ > IOQ

For 4 of the reviewed SKUs, the MOQ is higher than the IOQ. For this instance, different numbers of ending inventories can be possible. The main model stated in Section 4.2.1 can be used for this case. However, the optimal policy should be changed to the following:

$$\begin{Bmatrix} x_{i,n} = 0, & if\ V_{i,n} - D_{i,n} \geq 0 \\ x_{i,n} \in \{MOQ_i, IOQ_i * r, \ldots, IOQ_i * k\}, & if\ V_{i,n} - D_{i,n} < 0 \end{Bmatrix},$$

with r being $\frac{MOQ_i}{IOQ_i}$ rounded up to the next integer and k being the same as in Section 4.2.1. The maximum number of orders that can be set (M_i) is equal to $\frac{TD_i - V_{i,0}}{MOQ_i}$ rounded up to the next integer. The ending inventory depends on the number of orders set. Therefore, $X_i(m) = \frac{TD_i - V_{i,0} - m * MOQ_i}{IOQ_i}$, with m being the total number of orders set throughout the entire planning horizon, lying in the interval $1 \leq m \leq M_i$. As one can conclude, the ending inventory depends on the number of orders set throughout the entire horizon. The ending inventory, V_{i,N_i}, is equal to $V_{i,0} + m * MOQ_i + X_i(m) * IOQ_i - TD_i$.

The ending inventory calculation is the only thing that is different for this instance in comparison with the model explained in Section 4.2.1. Therefore, all other elements of model 2a apply to this model as well.

4.3 Model 3: Lot size-based discount

To determine whether it is economically optimal to include incremental quantity discounts in the ordering process, some restrictions on the unit price should be implemented. The unit price structure stated by Zhang et al. (2012) (stated in Section 3.4) can partly be used for incremental quantity discounts at SVgroup. In the case of SVgroup, the structure in which the different prices are stated does not correspond with the unit price structure stated by Zhang et al. (2012). At SVgroup, if a SKU has different prices, the price $p_{n,x}$ with the quantity $Q_{n,x}$ counts for the whole order if the ordered quantity lies in the interval $Q_{n,x} - Q_{n,x-1}$. The unit price structure can be stated as follows:

$$\begin{aligned} &p_{n,1} \rightarrow If\ x_{i,n} \geq Q_{n,1} \wedge x_{i,n} < Q_{n,2}, \\ &p_{n,2} \rightarrow If\ x_{i,n} \geq Q_{n,2} \wedge x_{i,n} < Q_{n,3}, \\ &\vdots \quad \rightarrow \vdots \\ &p_{n,y-1} \rightarrow If\ x_{i,n} \geq Q_{n,y-1} \wedge x_{in} < Q_{n,y}, \\ &p_{n,y} \rightarrow For\ each\ unit\ that\ exceeds\ Q_{n,y}\ units, \end{aligned}$$

As one can conclude from this unit price structure, the minimum number of products of item i that needs to be bought is $Q_{n,1}$. Therefore, if a MOQ_i is stated, $Q_{n,1} = MOQ_i$. If there is no minimum order quantity, the company can buy any amount, so $Q_{n,1} = 1$. If a SKU has a $MOQ_i\ or\ IOQ_i$, the same elements of model 2 should be considered, with restrictions on the unit price. When there is no MOQ_i or IOQ_i, then the elements of model 1 should be used.

The main objective function for the lot size-based discounts should be changed a bit compared to the models stated in Sections 4.1, 4.2.1, and 4.2.2:

Minimize: $$F(n) = \underset{j=1,\dots,k-1}{Minimum}\{F(j) + c(j,n)\} \quad (1)$$

With: $$c(j,n) = \delta_{i,n} * O_i + \sum_{s=j}^{n-2} V_{i,s+1} * h_i + x_{i,j} * p_{n,t} \quad (3)$$

$j =$ previous regeneration point before the current period k

$p_{n,t} =$ the corresponding price per unit when $x_{i,j}$ items are ordered to cover the demand for periods j to k.

All restrictions and elements included in the first two models hold for this model as well. Finally, the procedure in which this model should be performed is the same in comparison with the other two models. The only change that has to be made is that the function should include the total price of the order as well.

4.4 Conclusion

Three models have been built in Excel with the usage of VBA. These different models all have their purpose. The first model gives the optimal ordering quantities and moments for SKUs without a MOQ or IOQ applied to it. The second model expands the first model, for it to be able to calculate the optimal quantities and moments for SKUs with an IOQ and/or MOQ as well. This second model makes a distinction between two instances, namely when the IOQ is equal to the MOQ and when the IOQ is less than the MOQ. The main differences between models 1 and 2 are that the ending inventory could be something else than zero and there are limitations for the amount that has to be ordered. The main cost function ($F(n)$) of the DP model does not change. The last model (model 3) focuses on different prizes that are put in the ERP system for a new product. Because the company putting multiple lot size-based prizes on the purchasing materials of slurry injector A as well shortly, this model can be easily implemented in the ordering process of the company. The main difference between models 1 and 2 on the one hand and model 3 on the other hand is that the price of the total order should be considered in the cost function ($F(n)$), as different prizes could be paid for the total order. An elaboration on the prize of the order amount is given in Section 4.3 as well. All the programmed models will be validated and evaluated in Chapter 5.

5. Model validation and results

The models stated in Chapter 4 have been implemented in VBA. To be able to evaluate the efficiency of the current manner of setting the lot sizes and the proposed model, the models need to be validated. To be able to state whether or not a model can be stated as valid, one needs to compare the model with an existing system (Law, 2014). The existing system with which the models can be compared is the MRP system in Navision. The MRP has certain input parameters (LAP, MOQ, and IOQ) that influence the actual order suggestions that the MRP suggests. The different models can be validated by comparing the MRP suggestions for the usage data of the SKUs in 2022 with the suggestions made by the model. Nevertheless, one might doubt the validity of the proposed models if this would be the only validity check that would have been performed. This hesitation to state whether the model is valid is because of the rolling horizon in which the models might not give the optimal suggestions. After a period has gone by, one can say with certainty what the usage values of SKUs were for that period. However, to say with certainty what the material requirements of a SKU for the upcoming periods are is impossible. This indicates that other validation techniques should be performed as well. Law (2014) states two other validation checks. First of all, the results from the proposed models could be reviewed with the opinion of an expert. Besides, a comparison of different models might be considered. Section 5.1 elaborates on the comparison of the order process given by the current parameters (LAP, MOQ, and IOQ) of the MRP. Besides, Section 5.2 gives an insight into what the stakeholders at the company think about the suggestions made by the models. Section 5.3 relates to a comparison of the models with the implementation of different LAPs. Section 5.4 concludes Chapter 5.

5.1 Comparison of MRP and models

As stated in the introduction of this chapter, data from 2022 has been used to check whether or not the models create an optimal tradeoff between ordering and holding costs. The input variables that are needed for the model to work properly are the price, the holding cost percentage, the ordering cost, and the demand. Table 5 shows the differences in total costs of 16 SKUs between the suggestions that the MRP would have given and the suggestions given by model 1.

Table 4 Comparison Model 1 and MRP

SKU NR.	Holding %	LAP in days	MOQ	IOQ	Model	MRP	Difference	Difference %
SKU 5	0.25	13	0	0	€0	€0	€0	0.00%
SKU 38	0.25	13	0	0	€38.33	€146.99	€108.66	73.92%
SKU 60	0.25	13	0	0	€29.43	€190.95	€161.52	84.59%
SKU 63	0.25	13	0	0	€48.00	€147.54	€99.54	67.47%
SKU 67	0.25	13	0	0	€15.43	€29.36	€13.93	47.45%
SKU 71	0.25	13	0	0	€75.36	€75.36	€0	0.00%
SKU 87	0.2	13	0	0	€36.79	€146.97	€110.18	74.97%
SKU 92	0.25	13	0	0	€105.60	€111.06	€5.46	4.92%
SKU 93	0.25	13	0	0	€101.28	€109.54	€8.26	7.54%
SKU 94	0.25	13	0	0	€81.04	€94.74	€13.70	14.46%
SKU 98	0.25	13	0	0	€152.82	€251.33	€98.51	39.20%
SKU 104	0.25	13	0	0	€110.59	€177.49	€66.90	37.69%
SKU 108	0.25	13	0	0	€75.09	€117.44	€42.35	36.06%
SKU 109	0.25	13	0	0	€140.32	€319.33	€179.01	56.06%
SKU 110	0.25	13	0	0	€193.34	€259.30	€65.96	25.44%

SKU 111	0.25	13	0	0	€56.33	€88.08	€31.75	36.05%
Total					**€1259.75**	**€2265.48**	**€1005.73**	**44.39%**

As one can conclude from the table stated above, model 1 gives a better tradeoff between holding cost and ordering cost per SKU. In total, 16 SKUs have been reviewed for this model. On average, €1005.73/16 = +-€63 can be saved per SKU that does not have an IOQ or MOQ.

The same validation as for model 1 has been made for model 2. 109 SKUs have been reviewed by Model 2. Table 6 points out the difference between the proposed model and the MRP suggestions of these 109 SKUs.

Table 5 Comparison Model 2 and MRP

SKU NR.	Holding%	LAP	MOQ	IOQ	Model	MRP	Difference	Difference%
SKU 1	0.25	13	0	6	€0	€0	0	0%
SKU 2	0.25	28	0	6	€21.80	€47.83	€26.03	54.42%
…								
SKU 64	0.2	13	0	10	€195.12	€239.22	€44.10	18.43%
SKU 65	0.25	13	0	5	€110.52	€329.90	€219.38	66.50%
…								
SKU 128	0.2	13	0	25	€20.14	€30.64	€10.50	34.27%
SKU 129	0.2	13	0	25	€25.91	€61.25	€35.34	57.70%
Total					**€20576.14**	**€23442.57**	**€2866.42**	**12.23%**

109 SKUs have been reviewed for this model. That means that on average, €2866.42/109 = +-€26.30 can be saved through implementing this model into the ordering process. When analyzing Tables 5 and 6, one can conclude that the most profit can be made while addressing the SKUs without the IOQ and MOQ parameters. For these SKUs, the MRP states that an order should be made once every 2 weeks. For most of these SKUs, these 2 weeks of LAP do not even come close to the average time between two consecutive orders that Model 1 suggests. When a MOQ or IOQ is implemented in the planning tab of the SKU in Navision, the LAP often gets 'overruled' by the quantity that is still in stock because the company had to order a larger amount than the cumulative demand of the periods inside the LAP.

As stated above, an elaboration for SKUs with multiple prizes has been made. To check whether this model works, other SKUs need to be tested, as the SKUs of slurry injector A do not have multiple prizes per SKU implemented in Navision yet. A newly implemented product does have these multiple prizes stated in Navision. This product (slurry injector B) is an extension of slurry injector A. Therefore, the SKUs follow the same sort of demand pattern as the SKUs of slurry injector A. Table 7 shows the profit that could be gained if the current suggestions of the MRP would be changed to the suggestions made by the model. Because of the values containing the order prices as well, the values have been set to indices (due to confidentiality). The value of SKU130/MRPsuggestions has been set to 1000 and the indices of other values are set according to this value.

Table 6 Total profit lot size-based discount model (Model 3)

SKU NR.	MRP suggestions	Model suggestions	Profit	Profit %
SKU 130	1000	766.59	233.41	23.3%

SKU 131	997.38	834.92	162.46	16.3%
SKU 132	2182.08	1793.41	388.67	17.8%
SKU 133	1707.50	1403.71	303.79	17.8%
SKU 134	1350.78	1310.34	40.44	3.0%
SKU 135	1083.72	740.66	343.07	31.7%
SKU 136	862.36	689.14	173.22	20.1%
SKU 137	413.13	350.17	62.96	15.2%
SKU 138	550.75	457.87	92.89	16.9%
SKU 139	3369.60	3280.59	89.01	2.6%
Total	**13517.31**	**11627.40**	**1889.91**	**14.0%**

If the reader wants to see the real values of the MRP and the model, the researcher suggests to read Appendix 3. The orange/yellow cells in Table 7 illustrate the values of SKUs that are in the MRP suggestions as we speak (23rd of June). The blue cells represent some SKUs that were in the previous MRP run (the run has been performed at the beginning of June). For these SKUs, the suggestions of the MRP could be compared to both the suggestions of the model and the actual approved suggestions by the master planner (the planned purchasing orders). For all five blue SKUs, the planner approved the exact suggestions made by the MRP. Therefore, for the blue SKUs the column "MRP suggestions" can be seen as the actual planned purchasing orders.

5.2 Expert opinion

After the suggestions by the model are compared with the values suggested by the current MRP, an expert opinion has been given by multiple stakeholders. These stakeholders are the planner and the head of supply chain. A couple of elements regarding the validity of the model should be elaborated on:

1) Some suggestions made by the model were unfeasible for the vision of the company. The models sometimes suggested that one order should have been placed for the entire year. Both the planner and the head of supply chain said that they will never buy one batch that covers the demand of the entire year if the total demand is more than the MOQ. Therefore, if the demand is more than 3 times the MOQ, a minimum of 3 orders will be placed per year (one order covers a maximum of 4 months of demand on average).
2) If a SKU has a high unit price and is used frequently throughout the year, the model suggests ordering frequently. This was in line with the opinions of the stakeholders, as they do not want to store these products for a long time.
3) To evaluate one SKU, the user of the model is busy for roughly 30 to 45 seconds (with both putting in the parameters, as well as running the model). The stakeholders consider this too long to use the model for the purchasing process of all parameters. Therefore, an elaboration should be done on the comparison of the models with the MRP with different input parameters. This comparison is stated in Section 5.3. The purpose of this comparison is to tell something about how to closely represent the models in terms of the parameters of the MRP.
4) Ideally, the stakeholders want to use the same planning procedure, with the implementation of the best values for the current planning parameters (LAP and MOQ). Therefore, they asked to relate the outcomes of the model to the current planning parameters in some way.

To be able to implement all suggestions made by expert opinions, the total costs per SKU in 2022 should be calculated when a different LAP has been implemented.

5.3 Comparison models with different LAPs

Currently, the company states a LAP, a MOQ, and an IOQ for every SKU in the planning tab. The total costs in 2022 have been tested with the implementation of different LAPs. Table 8 states the total costs in 2022 for a couple of SKUs with the implementation of different LAPs. The optimal LAPs per SKU are marked in green.

Table 7 Total costs for 2022 per SKU if different LAPs were implemented

SKU NR.	1-week LAP	2 weeks LAP		5 weeks LAP	6 weeks LAP		16 weeks LAP	17 weeks LAP
SKU 1	€0	€0		€0	€0		€0	€0
SKU 2	€38.37	€38.37		€38.37	€38.37		€27.65	€27.65
…								
SKU 76	€285.75	€209.86		€148.10	€163.21		€199.87	€199.87
SKU 77	€104.24	€95.67		€85.81	€85.81		€113.90	€103.84
SKU 78	€121.22	€121.22		€107.46	€107.46		€118.88	€118.88
…								
SKU 128	€25.10	€25.10		€25.10	€25.10		€25.10	€25.10
SKU 129	€50.16	€50.16		€38.73	€38.73		€28.13	€28.13

After analyzing all SKUs, the minimum amount of euros per SKU comes close to the optimal value that the model gives. The best LAPs that could have been chosen for 2022 give suggestions that are 1.90% worse than the total expected costs that the models suggest. Therefore, if the most optimal LAP is chosen per SKU, the total amount of euros spent in the ordering process comes close to the minimum amount of euros that the models suggest. The minimum period between two consecutive order placements that the model suggests is often equivalent (or comes close) to the LAP that gives the minimum amount. For example, when looking at SKU 76, the minimum number of periods between two consecutive orders that the model suggests is equal to 5. In Table 8, one can see the minimum amount of total costs related to a LAP of 5 weeks. Therefore, if a LAP of 5 weeks is chosen for this SKU, the MRP would give suggestions that almost represent the suggestions made by the model. If the LAPs that are equivalent to the minimum period between two consecutive order placements that the model suggests are chosen, the conclusion can be made that the best LAP has been chosen most of the time, but not all the time. In total, as stated above, the best LAP gives suggestions that are 1.90% worse than the models. If the minimum period between two consecutive order placements that the model suggests is chosen as the LAP, the suggestions are 2.67% worse than the model suggests. In comparison, the MRP suggestions are 15.06% worse than the model suggests. Therefore, the minimum number of periods between two consecutive order placements will drastically reduce the total expected costs.

For this analysis, we used the minimum number of periods between two consecutive orders of the suggestions of the model based on 2022 and used this number as the LAP for 2022. However, to get a good indication of whether a selected LAP drastically reduces the expected total costs in comparison with the MRP, a LAP should be chosen from the previous year(s) and be reviewed on the data of 2022.

5.4 Selecting the optimal LAP

As one can see in Sections 4.1 and 4.2, both models represent a multi-item lot sizing method. Up till now, the method has been divided into multiple single-item methods (as the models have been used on the data of each SKU per runtime). However, a small change in the VBA code makes sure that the code runs for all 129 SKUs at once. This run has been performed in roughly 15 to 20 seconds. The VBA code returns the optimal ordering process in 2022, with the assumption that the horizon was fixed. A new code has been written that elaborates on the suggested ordering process for 2022. This code returns the minimum period between two consecutive orders. Some small justifications for this minimum period have been made. Sometimes, the model states to place a really small order in week n and a big order in week $n + 1$. This would indicate a LAP of 1 period because that would be the minimum number of periods between two consecutive orders. Nevertheless, this minimum happened once a year for some SKUs, as the other orders were placed once every two weeks. Therefore, a LAP of 2 weeks would return a total cost that was less than the total cost with a LAP of 1 week. Therefore, if the minimum LAP would have been 1 week, but only happened once, the LAP has been stated to be 2 weeks.

This new code has been tested for 2021. Therefore, a LAP has been selected per SKU based on the data for 2021. This new LAP has been tested on the data of 2022 and the total costs can be compared to the total costs that the model suggests for 2022 and the total costs that the MRP currently generates with the current selection of the LAP. Table 9 shows the results of this newly selected LAP.

Table 8 Comparison newly selected LAP, model, and MRP suggestions

SKU NR.	Total cost model	Total cost new LAP	Total cost MRP	Difference model/MRP	Difference new LAP/MRP
SKU 1	€0	€0	€0	0%	0%
SKU 2	€21.80	€23.81	€47.83	54.42%	50.22%
…	…	…	…	…	…
SKU 72	€52.47	€57.80	€63.29	17.10%	8.67%
SKU 73	€19.12	€36.84	€74.13	74.21%	50.30%
SKU 74	€29.35	€40.87	€76.33	61.55%	46.46%
…	…	…	…	…	…
SKU 128	€20.14	€20.14	€30.64	34.27%	34.27%
SKU 129	€25.91	€40.29	€61.25	57.70%	34.22%
Total	€21835.89	€22995.56	€25708.05	15.06%	10.55%

As one can conclude from Table 9, the newly selected LAP returns a total cost over 2022 that is way less than the total cost that the MRP has returned. In fact, the model returns a decrease in the total cost of 15.06% compared to the MRP, as the newly selected LAP returns a decrease of 10.55%. Therefore, the newly suggested LAP (based on data from 2021) decreases the total costs for the 129 SKUs considerably in comparison with the MRP.

5.5 Conclusion

After the validation of the models, one can conclude that all the models provide suggestions that are equal to or less in value than the suggestions given by the MRP. This indicates that the model works exactly as it is supposed to work. In total, €3872.15 could have been saved for SKU 1 up until SKU 129 in comparison with 2022. For the lot size-based discount, one can conclude that a larger fraction per

SKU than the first models could be/have been saved for SKUs 130 up to 139. These savings could have been made for the upcoming 7 months (from July 2023 up until January 2024). Nevertheless, because the model has to run way too long to be able to implement it for the upcoming material requirements of all SKUs, an alternative method is needed. When choosing a LAP that is equal to the minimum number of periods between two consecutive orders that the model suggests, the total expected costs come close to the total costs stated by the models. A small change in the VBA code has been made for the company to be able to select the best LAPs per SKU in a short amount of time. The total difference between the suggestions given by the model in comparison with the suggestions given by the MRP is equal to 15.06%. The difference between the newly selected LAP obtained through the small change in the VBA code gives a 10.55% decrease in total costs in comparison with the MRP. The conclusions subtracted from Chapter 5 can be used as input for Chapter 6.

6. Implementation

Currently, the company uses a LAP, a MOQ, and an IOQ as planning parameters for each SKU. Because of Navision having only four ordering policies implemented in the ERP system (order, lot-for-lot, fixed order quantity & max order quantity), the company wants to stick to its current manner of ordering (“order” ordering policy for finished products and “lot-for-lot” ordering policy for all purchasing materials). This indicates that the company preferably wants the LAP and the MOQ to be changed to the most optimal values. In Section 5.3, a procedure for the most optimal LAP over 2022 has been stated for the 129 SKUs in the scope of this research. Section 6.1 states what should be done by the company in the upcoming timespan to make sure that all LAPs get the most optimal values and maintain the most optimal values.

6.1 Suggested actions

The LAPs selected through the data of 2021 are not always the same as the minimum number of periods between two consecutive orders that the model suggests in 2022. The LAP that the data of 2022 would have given is sometimes higher than 2021 and sometimes lower. The latter can create a problem regarding the total costs of the ordering process. If a SKU is used way more in 2022 in comparison with 2021, the LAP selected by 2021 will be way higher than optimal. It can happen that an order will be placed that covers the upcoming three weeks (LAP of 3 weeks), as the optimal placement would be to order every week (LAP of 1 week). This stated problem can cause a total amount of cost that is way higher than when having selected the optimal LAP. Therefore, to get a better indication of what is the best LAP, the company should use data from at least the previous two years to create a longer horizon over which the model gives suggestions.

To make sure that the models give a good indication for the LAP, the company should set the values at least once every four months, but preferably once every two months. The four months have been stated to be required because for all SKUs, the minimum order amount if the IOQ does not overrule the LAP is stated as one every 4 months. However, to make sure that the LAP is not too high, the LAP should be reviewed a bit more frequently than 4 months. If a SKU is ordered way more frequently after some time, the LAP will be lowered through the analysis made by the model.

The models use the material requirements of all SKUs that are reviewed. This indicates that the models could be used for all purchasing materials available in Navision. Therefore, not only the purchasing SKUs of slurry injector A could be reviewed through the models, but purchasing SKUs of other finished products as well. To be able to review other SKUs, the order cost should be determined per SKU, as the transport costs differ per SKU. Besides, the inventory holding percentage differs for all SKUs as well.

The researcher suggests the company to use the model for only one supplier at first. For a couple of months, the planner will get other suggestions than what the MRP currently gives, especially for SKUs that do not have a MOQ or IOQ. The planner can easily check whether these suggestions are in line with his view about the ideal batches to order. If after a couple of months, the planner often thinks that the suggestions are in line with his opinions, he can use the model for other suppliers as well. The choice to first use the model for one supplier is because of the ordering cost that could be determined easily for a lot of SKUs at once. If the reviewed supplier delivers their products without any charge, the total order cost only consists of the fixed order cost for all SKUs. If the supplier charges a fixed price for delivering their products, then the order cost should consist of the fixed cost plus a fraction of the price charged by the supplier (Section 2.3.2 elaborates on such calculations).

6.2 Conclusion

The minimum number of periods between two consecutive periods that the model suggests based on the data of 2021 has been stated as the newly selected LAP. This LAP has been tested on the data of 2022. After all, the selected LAP gives better suggestions for the requirements of the SKUs in 2022 than the MRP currently suggests. To make sure that the model is used in a way that maintains a good indication of what the most optimal LAP would be, the company preferably should run the model once every two months. To make sure that the occurrence of possible problems regarding the selection of LAPs that are too high is decreased, data from the previous two years should be used instead of one.

7. Conclusion

The company has been provided with an optimization model which can help SVgroup with determining the optimal lot sizes over a given period. This Chapter elaborates on the main research question stated in Chapter 1: *How to optimize the lot sizes of the raw materials at SVgroup in such a way that it minimizes the total inventory costs while storing sufficient raw materials to deliver the product on the due date?* Multiple sub-questions have been answered throughout this thesis. Section 7.1 summarizes all conclusions given in the last Sections of every Chapter. Section 7.2 illustrates all recommendations that can be given to the company after the performed research. Finally, future work that is suggested for the company to perform is stated in Section 7.3.

Because of the usage of required data of the previous two years, the model can only be used in the way stated above for SKUs that have been in Navision for some time. Because of the company currently having a newly implemented finished product, they want to set the most optimal values for the LAP of the SKUs of this finished product as well. However, it will not be possible to select the optimal LAP (because of the lack of historical data). The researcher recommends the company to do the following for products that do not have the required data in Navision yet: if the company wants to use the model for these products, the upcoming material requirements can be used instead of the usage of the past years. It is not possible to select a feasible LAP, because of the lack of historical data. However, the newly written VBA code can be used for multiple products at once. Therefore, for these items, the material requirements can be used as input to create better suggestions than the ones that the MRP gives.

7.1 Conclusion

The occurrence of different problems related to the ordering process initiated this thesis. The employees at the warehouse in Rijssen often have to handle really small orders, the planner has to perform long time intensive MRP runs, and the parameters that are being set on intuition and instinct. All those problems relate to each other. Therefore, an optimization tool has been developed to improve the order frequencies and amounts. The main goal of this tool is to find an optimal tradeoff between order and inventory costs. Throughout this thesis, multiple sub-questions were stated and answered. To conclude this thesis, the sub-questions, and key takeaways are stated below:

"What is the current situation at SVgroup with respect to determining the lot sizes and what causes the inventory problem?"
The purchasing materials that lie in the scope of this thesis are researched. Furthermore, MRP usage is researched. Currently, the LAP has been set once and the company does not know why this LAP has been set the way it has been set and does not know how to set the right values for the LAP either. The main problem that occurred throughout researching these two things was that the company does not know whether or not the current ordering process is optimal. Besides, they do not have any model that calculates the total amount of costs related to the ordering process. They do not quantify the different costs associated with this ordering process. Therefore, an analysis has been conducted for the two different costs (ordering + holding costs).

"Which methods known in the literature about the optimization of lot sizes could be used for the SKUs in the scope of the research?"
Firstly, the requirements of the new model have been stated based on what the purchasing materials suit best. Because of the company using a MRP that implements an accumulation strategy, the main objective is to only cover these material requirements. A multi-item could have been selected, but

the MRP makes suggestions for every SKU individually. To make sure that the lot sizing method can be used for all items in the scope of this research, some restrictions should be implemented in the model, because most SKUs have either a MOQ or IOQ or both. The assumption that the price of a SKU is fixed should be falsified by implementing the option to select incremental order discounts.

"How can the lot sizes of the raw materials of slurry injector A be optimized?"
Three main models have been programmed. Each one of these models relates to a method stated in the literature Chapter. The differences between the first two models lie in the fact that the first model is the standard model, with the second model implementing multiple restrictions to make sure that the ordering process of all SKUs can be reviewed. The third model falsifies the assumption that a SKU consists of one fixed price through the implementation of multiple incremental discounts.

"How does the proposed model perform?"
Multiple steps have been taken to validate the different models. Data from 2022 has been used to calculate the total costs of the solutions given by the models and the current values of the LAP, MOQ, and IOQ (the MRP). A clear decrease in total costs can be concluded after this analysis. Nevertheless, an expert opinion about the model is needed to make sure that the suggestions are in line with the view of the planner. Because of putting in a lot of data per SKU (as the models are run for each SKU), the required time to perform this run is considered too high. Therefore, the most optimal LAPs per SKU should be calculated to get an indication of how to select the most appropriate LAP per SKU. After these calculations, the conclusion could be made that the most optimal LAP for every SKU is often equal to the minimum number of periods between two consecutive orders suggested by models one and two.

"How can the proposed model be implemented in the ordering process of the raw materials at SVgroup?"
The company wants to get a model that can easily implement better values for the LAP. Because of the conclusion made after the previous question, the minimum number of periods between two consecutive orders should be chosen as the LAP. Both models 1 and 2 have been changed a bit to make sure that the code can run over multiple items at once. This reduces the runtime drastically. An analysis of the most optimal LAP in 2021 has been performed. Consequently, this LAP has been used for the data of 2022. The newly suggested LAP shows a big decrease in total costs over 2022 in comparison with the MRP.

7.2 Recommendations

Because of the conclusions that could be made after this research, multiple recommendations could be given to the company to make sure that the models are properly used and do not go to waste.

1) First of all, a consideration should be made by the company regarding how to proceed with the ordering process. If the company wants to just implement better values for the LAPs of some SKUs, the researcher recommends using the newly designed model that runs over multiple items at once. Besides, the company should begin by implementing the model for only one supplier. The order costs can easily be determined because these costs are related to the preferences of the supplier. Therefore, the order cost is often equal for all SKUs that have the same supplier.
2) For SKUs that do not have historical data, the model can be used, but the input should be changed. When determining the LAP, historical data is needed. Therefore, the LAP cannot be determined through this model for SKUs without historical data. However, we do have the upcoming material requirements for all SKUs. If the company wants to get a good indication of

what to order for these SKUs for the upcoming periods, the material requirements can be used instead of the historical data.

3) It is suggested to use the usage values of SKUs over a long period. The researcher suggests using two years of data instead of one. This leads to a LAP that is more reliable. This would also decrease the possibility of getting LAPs that are too long.
4) The researcher found that a lot of money could be saved through the usage of multiple prizes for different purchasing quantities. Currently, most SKUs have one fixed prize stated in the ERP system. However, in reality, different prizes for one SKU occur way more often than what is currently stated in the ERP system. The recommendation is given to ask more suppliers about the prizes that they charge for different order quantities for one SKU, to be able to reduce the total expected costs.

7.3 Future research

During this thesis, the focus has been on the suggestions that the MRP gives. At SVgroup, there is no cycle stock implemented in the planning tab of the SKUs. At the beginning of this thesis, the researcher chose to focus on only the cycle stock, because the company can easily implement the suggested changes. Because of the safety stock not being present at the moment, the company would hesitate to implement it, just because they haven't used it before. Therefore, future research could focus on the implementation of safety stocks.

Besides, in the scope of this research, it is defined that only the purchasing materials will be reviewed throughout this research. Future research could focus on the lot sizing for semi-finished products and finished products as well. This could help the company to get a better indication of what the material requirements of the SKUs should be over a certain time period.

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