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Optimizing component availability at Hittech Multin

A master thesis in which component supply at Hittech Multin is analyzed. A decision-making model is proposed to make sure that in a required percentage of the production orders all components are present, while total costs are minimized.

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Management summary

Introduction

This thesis assignment has been carried out for the Supply Chain Management department of Hittech Multin. Hittech Multin develops and assembles high-tech mechatronic systems. Their customers are mostly market leaders that operate on the edge of what is technologically feasible. The goal of this assignment is to become more effective and in control of the supply side of the company.

Problem description

Currently in 88% of all production orders all components are present on or before the planned production date, while the required percentage is 98%. Delayed production orders are caused by missing components. The main root cause for these missing components is that suppliers deliver components later than expected and thus later than the planned production date. Therefore, we formulated the following research objective: "Develop a decision-making model to ensure that in 98% of all production orders all components are delivered on or before the planned production date, while minimizing the total costs and keeping in mind inventory requirements". First, we analysed the current situation, then chose the main root cause and finally created a decision-making model, based on the literature review, to meet all requirements in the objective.

Analysis of the current situation

About 40% of all components were delivered later than expected and contributed to the main root cause. These are the so-called "unreliable components". About 85% of the unreliable components form together 20% of the total value of the unreliable components. This means that many cheap components also cause delayed production orders. For us, cheap components may never be the reason for delayed production orders. During this thesis assignment we researched different order policies for the components of the end products. For the cheap components we used an inventory model that considers quantity discounts. Currently Hittech Multin uses a fixed one-week safety lead time when ordering components. However, this does not result in the desired percentage of production orders for which all components are present on time. Therefore, we used a safety lead time order policy for expensive components. Only 20% of the suppliers, supplied about 80% of the unreliable components. This means that the improvement of supply performance of a small group can greatly improve the overall supply performance. Therefore, we researched literature on how supply performance can be improved by improving the supplier-buyer relationship. Finally, Hittech Multin has the inventory requirements on the height of the inventory. The maximum is two months' worth of inventory. Because this is chosen arbitrarily, we have taken this into account as a soft constraint during the thesis assignment.

Literature research and problem approach

We researched literature to find an inventory model, a safety lead time model, and ways to improve supply performance. The inventory model had to be focussed on an assembly system including stochasticity in the supply lead times and stochasticity in customer demand for all components combined in an end product. In addition, the model had to include quantity discounts and minimum order quantities for components. We could not find an inventory model that met all these requirements. Therefore, we decided to use a different approach where we also could combine the safety lead time components with the inventory components. We built a simulation in which we combined all components of an end product. Each component, in this simulation, is either ordered with a safety inventory or a safety lead time. The simulation calculates the percentage of orders for which all components are present on or before the planned production date, given the order policy per component. In addition, we implemented an optimization algorithm (the particle swarm optimization algorithm) in the simulation to improve the solution. The goal of the simulation is to meet the required percentage production orders for which all components are available, while the total costs are minimized.

We needed start solutions for all components to reduce the solution space for the optimization algorithm. Therefore, we found an inventory model and safety lead time model that calculated the best start solution for each component individually. From there on, the simulation optimized the values for the situation in which all components were combined. Finally, we researched how a customer can become a preferred customer which will lead to improved supplier performance.
During the research we ran experiments for two article groups (Article group 1 and Article group 2). All components in an article group belong to the group of products for one customer. We ran four scenarios per article group in the simulation: (1) the current order policy of Hittech Multin, (2) all components are ordered with an inventory order policy, (3) all components are ordered with a safety lead time and (4) a scenario in which one part of the components is ordered with an inventory order policy and the rest is ordered with a safety lead time. Finally, we concluded that the historical data of the lead time is the most uncertain input parameter of the models. Therefore, we performed sensitivity analyses on the lead time uncertainty.

Results

For Article group 1, all components can best be ordered with a safety lead time, called the "safety lead time order policy". Compared to the current order policy, the percentage of late production orders late is reduced from 19.1% to 1.1%, while total costs only increase from €167,000 to €168,700. The inventory throughput time meets is 1.99 months, which is within the required 2 months.
For Article group 2 one part can best be ordered with a safety lead time and the rest can best be ordered with a safety inventory, called the "combined order policy". Compared to the current order policy, the percentage of late production orders is reduced from 89.1% to 1.8%, while the total costs are reduced from €3,352,000 to €3,272,000. The inventory throughput time remains below the required two months.
Regardless of the supply uncertainty, the safety lead time order policy performs similar or better than the current order policy for both Article group 1 and Article group 2. The percentage of production orders that start on time always meet the required 2% for the safety lead time policy, while this is not always the case for the current order policy. Further, the total costs of the safety lead time order policy are similar to or lower than the total costs of the current order policy.

Conclusions and recommendations

First, the current policy of Hittech Multin does not result in the desired percentage of orders for which all components are present on or before the planned production date. A change of order policy can help achieve the required percentage. For Article group 1 this means ordering the components with a safety lead time. For Article group 2 this means ordering the components with a combined order policy.
Second, when creating a good supplier-buyer relationship, suppliers greatly value social factors like communication and early involvement. Not only economic factors are important, but social factors are equally important to improve the relationship and therefore the supply performance. When improving the relationship with the suppliers, the most important recommendation is a change of perspective from 'What can and should the supplier do for me?' to 'How can we together make sure that the supplier delivers according to expectation?'.
Finally, at the moment the quality of the historical lead time data is poor. Therefore, the measurements of the historical lead time data should be changed to improve the quality. A better quality of the data results in more accurate expectations of the delivery time per component. More accurate expectations mean less supply uncertainty, and this makes it easier to produce according to the production plan.

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Abbreviations and terms

List of abbreviations

Abbreviation:	Explanation
DPP:	Development Project Process
BOM:	Bill Of Materials
ERP system:	Enterprise Resource Planning system
Planning:	Planning department
MPS:	Master Production Schedule
MRP:	Materials Requirement Planning
Purchasing:	Purchasing department
TPM:	Technical Production Manager
Warehousing:	Warehouse department
Inspection:	Inspection department
Production:	Production department
JIT:	Just In Time
MIS:	Mechanic Improvement Specialist
KPI:	Key Performance Indicator
MOQ:	Minimum Order Quantity
EOQ:	Economic Order Quantity
SS:	Safety Stock
PSO algorithm:	Particle Swarm Optimization algorithm
Excel VBA:	Excel Visual Basic Applications
TC:	Total Costs
WACC:	Weighted Average Cost of Capital
FTE:	Full Time Equivalent
WBS:	Work Breakdown Structure
PID:	Project Initiation Document

List of terms

Master Production Schedule:	The anticipated build schedule for those items assigned to the master scheduler. It represents what the company plans to produce expressed in specific configurations, quantities, and dates.
Material Requirement planning:	A tool that allows the firm to plan the material requirements to meet the demand for products expected to be manufactured in a given time.
Article group:	Group of components belonging to the products for a certain customer.
VivD:	The system in which all disruptions and supplies are logged.
Critical component:	When this component lacks, the production of a production order cannot start.
QLTC method:	Method to choose a supplier based on Quality, Logistics, Technology, and Costs.
Reorder level:	The inventory position at which an order is placed for new components.
Order-up-to-level;	The target level for the inventory. The moment an order is placed for new components the amount is ordered that returns the inventory position to the order-up-to-level
Order size	The number of components ordered each time an order is placed.
(R,s,S) model	The inventory model that is based on the Review period (R), reorder level (s) and order-up-to-level (S).
Complete production orders:	A production order for which all components are present on or before the planned production date.

Economic Order Quantity:	The order quantity that minimizes the total holding, order, and purchase costs.
Fill Rate:	The fraction of demand satisfied directly from shelf.
Excel VBA:	An implementation of Microsoft's event-driven programming language.
EOQ-(R,s,S) model:	The Excel model in which the EOQ and (R,s,S) models are combined.
Simulation model:	The Excel model in which the simulation and the PSO algorithm are combined.
Navision:	The former ERP system

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1. Introduction

In this chapter, we introduce the company, the company processes, the problem description, the research objective, the research questions, the problem approach, the scope of the project, and the outline of the thesis.

1.1. Company introduction

Hittech Multin is part of the Hittech Group, which consists of 9 different companies. Each company is self-directing, but not completely independent and has a maximum of around 120 employees to make sure they are flexible, customer-oriented, and entrepreneurial.

This master thesis is performed for Hittech Multin. They develop and assemble high-tech mechatronic systems. The development of these systems can be done in one of the following two ways. The first option is that the systems are developed by Hittech Multin and then produced in series. The second option is that the idea is already worked out by the customer and Hittech Multin offers a so-called "build to print" service. This means they produce the product idea in series, according to the specifications provided by the customer. The market Hittech Multin produces for is high-mix / low-volume, such as the semiconductor industry, the medical sector, and the laboratory market. Their customers are mostly market leaders that operate on the edge of what is technologically feasible (e.g. ASML). This research is performed for the Supply Chain Management department of Hittech Multin. The goal is to become more effective and in control of the supply side of the company.

1.2. Processes of Hittech Multin

The company process of Hittech Multin can be divided into two categories. First, the development of a new product, which is called the Development Project Process (DPP). Second, the series production which is managed by Supply Chain Management and Operations Management. During this master thesis we focus on Supply Chain Management and series production. However, during the DPP certain decisions are made that create the start situation for series production. Therefore, the DPP will briefly be introduced and thereafter we fully focus on series production.

1.2.1. Development Project Process

The DPP starts when a (potential) customer proposes either a product idea or the blueprint for a new product to Hittech Multin. During the DPP the idea is worked out, a prototype is created and the logistics needed to produce the product is thought of. When the DPP is finalized, the Bill Of Materials (BOM) is compiled, the final suppliers are selected, the lead time per supplier and production costs per product are determined and registered in the Enterprise Resource Planning (ERP) system, and the contract with the customer is drafted and finalized.

1.2.2. Supply Chain Management

Before production starts, the three departments that form Supply Chain Management, cooperate to provide an optimal production environment. The total structure of the organization can be found in Appendix A. These three departments are the planning, purchasing, and warehousing departments. Each department will be discussed separately.

Planning department

Hittech Multin has two kinds of planning: aggregate planning and materials planning. Both will be discussed below.

Aggregate planning

The planning department (from here on called *Planning*) makes an aggregate planning for a time horizon of two months ahead, based on the forecasted and confirmed demands of the customers. Aggregate planning is "a process by which a company determines planned levels of capacity, production, subcontracting, inventory, stock outs, and even pricing over a specified time horizon. The goal of aggregate planning is to build a plan that satisfies demand while maximizing profit" (Chopra & Meindl, Supply Chain Management: Strategy, Planning, and Operation, 2013). When Planning finishes the aggregate planning, the operations managers are responsible for creating sufficient capacity at the moment of production. The aggregate planning is updated every week to make sure there are always enough resources to meet demand.

Materials planning

A global production planning is made for one year in advance, based on the demand forecasts the customers provide. This yearly estimate serves multiple purposes. First, it is used for the budget in the annual plan. Second, this rolling forecast of customer demand is used to create a Master Production Schedule (MPS) every week. (Norman & Fogarty, 1990) describe the MPS as: "The anticipated build schedule for those items assigned to the master scheduler. It represents what the company plans to produce expressed in specific configurations, quantities, and dates". All outstanding production orders are reviewed and in the MPS is stated which actions should be taken to make sure that demand is met. Finally, the yearly forecast is used for informing the supply chain on the expected demand, for ordering long lead time items and for planning internal capacity. The planning is reviewed and adjusted every week.

Based on the MPS the Material Requirement Planning (MRP) is created. MRP is "a tool that allows the firm to plan the material requirements to meet the demand for products expected to be manufactured in a given time" (Esposito & Passaro, 1997). The materials are planned per article group, which is a group of materials belonging to one or multiple products for a certain customer. The initial order planning for the materials is reviewed every week and in the MRP is stated which actions should be taken to make sure that demand is met.

Purchasing department

The purchasing department (from here on called *Purchasing*) is responsible for finding, selecting, and contracting new suppliers. Further, they are responsible for the evaluation of the suppliers. Finding, selecting, and contracting suppliers happens when new products, developed by Hittech Multin or by the customer itself, are introduced or when existing products are modified. When selecting new suppliers, Purchasing works together with the Technical Production Managers (TPMs), who are part of the Operations department.

Warehousing department

The warehouse department (from here on called *Warehousing*) has two main responsibilities. First, they are responsible for booking in the delivered components. When the components arrive, Warehousing checks if the components are indeed the requested components, if the right amount is delivered, and if the components are in good condition. When components are damaged, they are brought to the inspection department (from here on called *Inspection*). At Inspection, what to do with the damaged components is determined. After the components are booked in at Warehousing, they are either brought to the warehouse itself, to Inspection, or straight to the production department (from here on called Production).

Besides booking in, Warehousing is responsible for order picking. Right before Production starts producing, they notify Warehousing to start picking. Per product the right components in the right amount are picked and deposited in a central place where Production can pick them up for production.

1.3. Problem description

One of the goals of Hittech Multin is that at least in 98% of all production orders all components are present on or before the planned production date. Company data shows that currently 88% of the production orders started on time. All late production orders were caused by missing components on the planned production date. The calculations for this percentage can be found in Appendix B. A part of this percentage consists of orders that started on time but had a shortage of some of the components. The historical data does not show which percentage of the orders this is. This means that the actual amount of orders starting on time with all components present is even lower than the 88% we calculated. In Chapter 2, we will discuss what the causes are of missing components.

Component shortages on production orders often have large consequences. When shortages occur, rushed ordering of other production orders is often not an option, because the other orders often lack components too. Hittech Multin orders components on a Just In Time (JIT) base, which results in no or low inventory of components. Expediting a future production order is therefore often not possible. Missing components almost always result in a delay for the customer. Besides the delay of the production order, the production planning of other orders is also affected. When a production order is delayed, it must be rescheduled to a moment when a different production order is executed. This means that more work must be done in the same period or that other production orders are also delayed. Therefore, missing components have a big impact on the entire production planning.

Besides the goal of orders started on time, Hittech Multin has a requirement on the height of the inventory. We will discuss this requirement in Chapter 2, but the result is that having safety stocks for all components is an acceptable solution for Hittech Multin. Therefore, the company wants to reduce delayed production orders due to missing components, while meeting the requirement on the height of the inventory.

1.4. Research objective

The desired output for the assignment is a method to make sure that in 98% of all production orders all components are present at the production site on time. Hittech Multin wants this to be achieved while meeting the inventory requirements. Further, the total costs should be minimized. A feasible solution with high costs is also not desirable. Therefore, we formulate the following research goal:

"Develop a decision-making model to ensure that in 98% of all production orders all components are present on or before the planned production date, while minimizing the total costs and keeping in mind the inventory requirements".

1.5. Research questions

We outlined the research framework in Figure 1. Based on the research framework the following research questions are formulated:

I. Analysis of the current situation at Hittech Multin and its performances.
   1. Which components are delivered most reliably/unreliably? And how reliable are these component deliveries?
   2. Which components are most/least valuable? And what are the values of the components?
   3. Which suppliers are most reliable/unreliable? And how reliable are these suppliers?
   4. What agreements does Hittech Multin have with its suppliers?
   5. What order policy does Hittech Multin use?
   6. What are the inventory requirements of Hittech Multin?

II. Literature review.
   8. What inventory model can be used to make sure there is sufficient stock while total costs are minimized?
   9. What safety lead time model can be used to make sure the components are on time at Hittech Multin while minimizing the number of days in stock?
      a. What are the root causes for missing components? And what is the impact of each cause?
   10. How can a good supplier-buyer relationship be established to improve supply performance?

III. Model formulation and development.
   11. What are the requirements and constraints for the decision-making model?
   12. What input data is used? How are those input data collected? And what output should be obtained from the model?

IV. Result evaluation and model validation.
   13. How can the model be validated and verified?
   14. What are the new holding, order, and purchase costs?
   15. What is the new percentage of production orders that have all components present before or on the planned production date?
   16. What actions should be taken by Hittech Multin to implement the model successfully?

V. Conclusions and discussion.
   In the final phase of the thesis, we conclude the findings and provide a discussion.

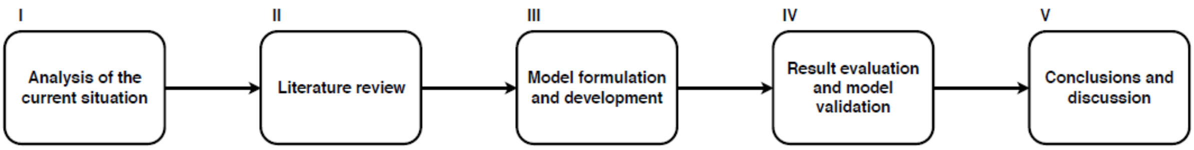

Figure 1: Research framework

1.6. Problem approach

In this section, we describe the problem approach to answer each research question. The complete project planning can be found in Appendix C.

I. Current situation

1. **What are the root causes for missing components? And what is the impact of each cause?**
   We will interview employees from the different departments, part of Supply Chain Management, to determine the root causes of missing components at the start of production. We will analyze company data to validate whether the provided reasons indeed attribute to the low component availability and to which degree. We will collect the data from the hard drives of Hittech Multin, the ERP system, and VivD (the system in which all disruptions and supplies are logged). When we lack data for a cause, we will interview employees of the company to provide an estimation of the impact of the cause. We will answer this research question in Section 2.1.
2. **Which components are delivered most reliably/unreliably? And how reliable are these component deliveries?**
   We will analyze the company data (hard drives, ERP system, and VivD) to find out which components are delivered late most often. Further, we will determine how unreliable these components are in terms of days delivered too late. We will answer this research question in Section 2.2.
3. **Which components are most/least valuable? And what are the values of the components?**
   We will analyze the company data (hard drives, ERP system, and VivD) to determine the component values. We want to get an idea if components in a certain price class cause the most problems or if the component value does not play a role. We will answer this research question in Section 2.3.
4. **Which suppliers are most reliable/unreliable? And how reliable are these suppliers?**
   We will analyze the company data (hard drives, ERP system, and VivD) to find out which suppliers are reliable/unreliable and how reliable they are. We will answer this research question in Section 2.4.
5. **What agreements does Hittech Multin have with its suppliers?**
   We will analyze the agreements Hittech Multin has with the different suppliers. We want to get an idea if the performance of a supplier depends on the agreement it has with Hittech Multin. We will answer this research question in Section 2.5.
6. **What order policy does Hittech Multin use?**
   We will interview Planning to find out how they order components and why they order in that way. We will answer this research question in Section 2.6.
7. **What are the inventory requirements of Hittech Multin?**
   Hittech Multin has requirements on the height of the inventory. We will determine what these requirements are, so we can take them into account in the decision-making model. We will answer this research question in Section 2.7.

II. Literature review

8. **What inventory model can be used to make sure there is sufficient stock while total costs are minimized?**
   Some of the components are cheap components. We believe it is not worth focussing too much attention on these components, but stock them instead. In Sections 3.1 and 3.2 we will review the literature to determine what inventory models can be found in the literature to make sure enough stock is available, while minimizing the holding, order, and purchase costs.
9. **What safety lead time model can be used to make sure the components are on time at Hittech Multin while minimizing the number of days in stock?**
   Some components are probably too expensive to be stocked and therefore should be ordered differently. We will research the possibility of ordering these components with a safety lead time, to make sure they arrive on time. In Section 3.3 we will review the literature to find out what models are available to calculate the desired length of the safety lead time.
10. **How can a good supplier-buyer relationship be established to improve supply performance?**
    Suppliers play an important role in making sure the components are on time at Hittech Multin. We expect that improving the supplier-buyer relationship can also improve supply performance. In Section 3.4 we will review the literature to find out how a good relationship between the supplier and buyer can be beneficial for the supplier performances and how such a relationship can be established.

III. Model formulation and development

11. **What are the requirements and constraints for the decision-making model?**
    The people who must work with the decision-making model will have certain requirements and constraints for the model, both on the interface and the content of the model. With the help of interviews, we will determine what these requirements and constraints are. We will answer this research question in Section 4.1.
12. **What input data is used? How are those input data collected? And what output should be obtained from the model?**
    For the model, certain input data is used. This input data needs to be collected (from the hard drives of Hittech Multin, the ERP system, and VivD). Also, certain output data will be generated by the model. We will keep in mind the research objective and model requirements to determine what input data must be used and what output must be generated by the model. This research question will be answered in Sections 4.2, 4.3, and 4.4.

IV. Result evaluation and model validation

13. **How can the model be validated and verified?**
    We need to verify whether the results generated by the model are correct and accurate. After verification, we validate to see if the results satisfy the requirements. This research question will be answered in Sections 4.3 and 5.1.
14. **What are the new holding, order, and purchase costs?**
    The model will result in new holding, order, and purchase costs. We will compare these to the costs in the current situation. This research question will be answered in Chapter 6.
15. **What is the new percentage of production orders that have all components present before or on the planned production date?**
    The model will result in a new percentage of orders that have all components present on time and can therefore start on time. We will compare this percentage to the current situation. This research question will be answered in Chapter 5.
16. **What actions should be taken by Hittech Multin to implement the model successfully?**
    We aim to design a new decision-making model that will be used after we finish the thesis assignment. Implementing a new model will always include certain challenges. We will describe what those challenges are and how to deal with them to successfully implement the model. This will be done in Chapter 6.

1.7. Scope

We define the scope of the thesis to incorporate the company preferences while maintaining a manageable problem size. Therefore, we defined the following limitations:

- We only consider products in series production. Products that are still in the DPP are not considered. These products do not have a standardized production process with fixed suppliers yet.
- We only consider the problems in the process until the moment the production starts. The challenges that occur during the production of a product are out of scope for this assignment.
- Some production orders start on time, but with a shortage of some components, as highlighted in the problem description. Production orders starting with a shortage is against the policy of Hittech Multin because this can cause a loss of quality and the production order takes longer to complete. However, production orders starting with shortages does frequently occur, but we have no data about how often this happens. Therefore, for this thesis, we will leave these production orders out of the scope and assume that a production order can only start when all components are available.

1.8. Outline of the thesis

The outline of the thesis will follow the research questions. In Chapter 2, the current situation at Hittech Multin is analyzed. This analysis is based on qualitative research, like interviews, and quantitative research, like data analysis, to substantiate the found problems. At the end of this chapter, we select the problems we will try to solve during this thesis assignment. In Chapter 3, a literature review is performed, which helps us solve the chosen problems. In Chapter 4, the model is developed, verified, and presented. In Chapter 5, different scenarios are created to test and validate the model. In Chapter 5 the results are presented and analyzed. In chapter 6 we provide an implantation plan for the model. Further, we discuss how supply performance can be improved. Finally, chapter 7 will contain conclusions and a discussion. The overall planning of this thesis assignment can be found in Appendix C.

2. Analysis of the current situation

In this chapter, we will answer research questions one to seven. As discussed in the previous chapter, the postponed production orders are caused by missing components on the planned production date. Here, we will determine the root causes of missing components and the impact of each cause, the reliability of component deliveries, the value of components, and the supply reliability of the suppliers. In addition, we discuss the agreements with the suppliers, the order policy Hittech Multin uses and the inventory requirements.

2.1. Root causes components missing at production site

In this section we answer the first research question: *"What are the root causes for missing components? And what is the impact of each cause?"*

Based on company data and interviews, several root causes are identified for components missing at production site. The root causes and corresponding impacts are depicted in the problem cluster in Figure 2. More causes of missing components can be considered. For example, too few items being picked by Warehousing. However, these causes result in production orders starting with shortages and not in postponed production orders. As explained in Chapter 1, we leave production orders starting with shortages out of the scope. The impact of each root cause can also be found in Figure 2. Some root causes have a percentage of less than 1, as can be seen in the figure. We created our own dataset due to missing historic data about postponed production orders. This resulted in a limited dataset in which some root causes did not occur. Based on interviews, however, we know that these root causes do occasionally occur. These root causes have such a small impact that we will not investigate them during the remainder of this thesis. Still, we want to provide a complete overview of the situation. Therefore, we briefly discuss these root causes. The root causes that occur frequently are discussed in more detail. A description of the data used, and calculations done can be found in Appendix B.

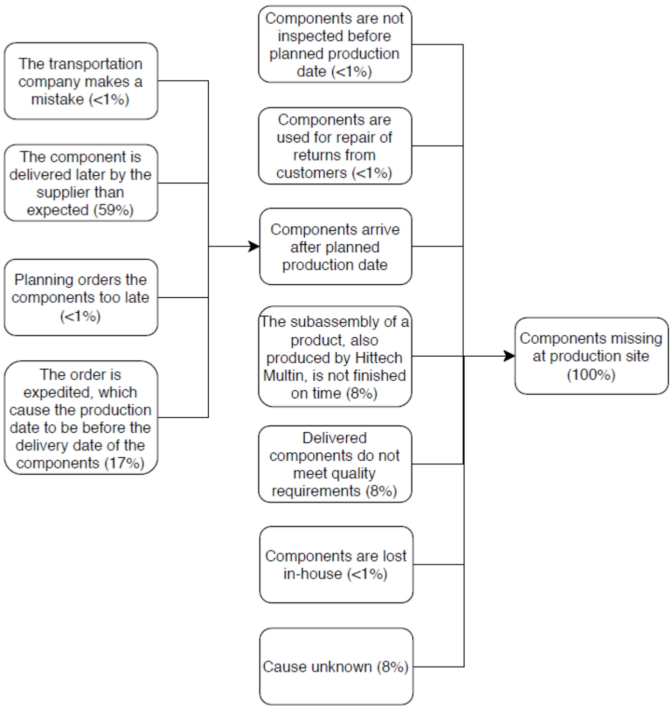

Figure 2: Problem cluster components missing at production site

2.1.1. Components are still in inspection

A part of the components needs to be inspected to make sure the quality requirements are met before they can be used in production. Inspecting such a component does not take longer than 15 minutes. When a component is at inspection the system classifies such a component as booked-in and ready for production. Planning is not able to see that the component is unavailable and allows the start of a production order. When the component is critical (meaning that the production cannot start without this component), the order is not complete and will be postponed until the missing component is inspected. This cause did not occur in our dataset. Therefore, we asked the mechanic improvement specialists (MIS), who are responsible for inspection, to estimate how often this root cause occurs. Only a few times a year it happens that such a component is critical and not inspected on time, which causes a production order to be postponed. Based on a total of about 3700 production orders per year, we can conclude that the impact of this cause is small.

2.1.2. Components are used for repair of return orders from customers

Components that are intended for a certain production order can be used for repairs of products returned by the customer to Hittech Multin. When such a component is not replenished before the start of a production order and the component is critical, the production order will be postponed. In our dataset, no production order was postponed due to missing components because of repairs. We can conclude that the impact of this root cause is small.

2.1.3. Components arrive after planned production date

A reason for missing components is that the components arrive later than the planned production date. This root cause can be divided into four sub-causes:

- The transportation company makes a mistake.
- Components are delivered later by the supplier than expected.
- Planning orders the component too late.
- Orders are expedited, which cause the production date to be before the delivery date of the components.

All four causes are discussed below.

Transportation company makes a mistake

The first sub-cause is the transportation company making a mistake during delivery. In our dataset, this sub-cause did not occur. We asked Purchasing to estimate how often this occurs. In their estimate, mistakes from the transportation company are hardly ever the reason that components are late for production. Hittech Multin considers three working days as a safety margin to cover supply uncertainty of components. Small mistakes from the transportation (i.e. one- or two-day late delivery) therefore remain unnoticed. Consequently, only large mistakes can cause components to be too late for production. Based on a total of about 3700 production orders per year, we conclude that the impact of this root cause is small.

Components are delivered later by the supplier than expected

The second sub-cause is a supplier taking longer to deliver a component than expected. This can be caused by the supplier, which has a longer lead time than agreed upon, or the expectation of the lead time at Hittech Multin is wrong. In Section 2.5 we discuss what kind of agreements Hittech Multin has with its suppliers and how the expected lead times are determined. With historical data we calculate that out of 19,500 deliveries, 31% was delivered later than expected. A clarification of the data and calculations can be found in Appendix B.

In Table 1, we present the distribution of late supplies. Between receiving the components and the start of production, the components are stored in the warehouse, where they are possibly inspected and picked. Hittech Multin considers a total safety margin of five working days to cover supply uncertainty (three working days) and all other tasks that must be performed by Warehousing (two working days). Supplies that are delivered between one and three working days late are covered by the safety margin for supply uncertainty. Therefore, such supplies are considered on time by Hittech Multin. As can be seen in Table 1, 36% of late supplies fall in this category. Supplies that are delivered four or five working days late are undesirable but are within the safety margin of five working days. If, in such a situation, the remaining components of a production order are present, the production order can start on time or with a small delay. This category contains 11% of the late supplies in our dataset. Supplies that are delivered six to ten working days late cause for certain a delay of the production order if no inventory is available. This category contains 17% of the late supplies in our dataset. Supplies that are delivered more than ten working days late mean a delay of at least one week if no inventory is available. This category contains 36% of the late supplies of our dataset.

We calculate that in a total of 59% of all components missing at production site, components are delivered later than expected.

We conclude that components being delivered later than expected is the main cause of missing components at production site. Further, of all late delivered components, 64% are at least an undesirable amount of days late delivered. 53% of the deliveries were even delivered later than the complete safety margin of 5 working days.

Table 1: Distribution of late supplies

Working days too late	Number of supplies	Percentage
1-3	2410	36%
4-5	696	11%
6-10	1134	17%
>10	2559	36%

Planning orders the components too late

The third sub-cause is a planner who orders the components too late. All planners have been assigned a group of products for which they are responsible. This responsibility includes ordering all components on time according to the expected lead time in the ERP system. When the planner forgets to order a component, the component arrives late. When such a component is critical and no stock is left, the production order is postponed until the component is delivered. In our dataset, no production order was postponed due to components ordered too late by the planners. We expect the number of postponed production orders due to late ordering to be low, as the probability that the combination occurs of a) the planner forgetting to order, b) the component is critical, and c) a lack of inventory, is small. Often, if a planner forgets to order, the production order starts with a shortage. This is out of the scope as previously discussed in Chapter 1. Therefore, we can conclude that the impact of this root cause is small.

A customer order is expedited

The fourth sub-cause is a customer who requests to expedite the delivery date of a product, a so-called "re-in". Hittech Multin does not guarantee that the new delivery date will be met. However, in the branch in which Hittech Multin operates, certain customers require that Hittech Multin offers the option to expedite a production order. Therefore, Hittech Multin tries everything possible to expedite the production order. In the ERP system the planned production date and the planned order date of components are expedited. This can result in components that have to be delivered on a shorter term than the expected supply lead time. The supplier will be requested to deliver such components as soon as possible. If the components cannot be delivered on time and there is no inventory available, the components are not available on the adjusted planned production date. In the ERP system the production date of the order is already expedited, and the production order must be postponed. We calculate that 17% of the delayed production orders are caused by expedited production orders.

2.1.4. Sub-assemblies of the product are not produced on time

Some products contain sub-assemblies that are also produced by Hittech Multin. Such sub-assemblies are considered components of the final product production order. When a sub-assembly is not produced on time, a production order, that contains the sub-assembly, is postponed too. We calculated that 8% of the postponed production orders were caused by a sub-assembly that was not produced on time.

2.1.5. Delivered components do not meet the quality requirements

Not all components delivered to Hittech Multin meet quality requirements. When a component does not meet the quality requirements and there is no stock left or it is not possible to get a replacement component delivered on time, the production order needs to be postponed. We calculated that 8% of postponed production orders were caused by components not meeting quality requirements.

2.1.6. Components are lost in-house

Sometimes, components are lost in the warehouse or elsewhere at Hittech Multin, without a specific reason. When such a component is critical and there is no stock left, the production order is postponed. In our dataset, no production order was postponed due to missing components that were lost in-house. Therefore, we conclude that the impact of this root cause is small.

2.1.7. Conclusion

We determined how much each root cause contributes to the missing components at production site. As can be seen in Figure 2, not all causes described above appeared in our dataset. The impact of these causes was so small that we will not investigate these root causes.

Of the four remaining root causes, components delivered later than expected by the supplier has with 59% by far the largest impact on missing components at production site and thus on postponed production orders. The impact is almost twice as high as the three remaining root causes combined. During the remainder of the thesis, we will therefore focus on components that are delivered later than expected by the suppliers. Now that we choose to solve this core problem, our research objective as stated in Section 1.4 is no longer possible. Therefore, we formulate the following adjusted research objective:

"Develop a decision-making model to ensure that in 98% of all production orders all components are delivered on or before the planned production date by the suppliers, while minimizing the total costs and keeping in mind inventory requirements."

2.2. Reliability of component deliveries

In this section we answer the second research question: *"Which components are delivered most reliably/unreliably? And how reliable are these components deliveries?"*

To determine the reliability of the component deliveries we calculated the average days delivered late per component. We elaborate on the calculations in Appendix B. As explained in the previous section, components delivered between one and three working days late are still considered on time. Therefore, we divided the components in four classes:

1. Components always delivered zero days late
2. Components on average delivered between 0.01 and 3 working days late with a maximum of 3 working days delivered late
3. Components on average delivered between 0.01 and 3 working days late with at least 1 delivery delivered more than 3 working days late
4. Components on average 3.01 or more working days delivered late.

The first two component classes are never delivered more than three working days late. Therefore, these components do not cause delayed production orders. Class 3 and 4 components are delivered more than three working days at least once and potentially contribute to delayed production orders. In Table 2, the distribution of the 3431 components to the right class can be found.

As can be seen, 59% of the components are either always delivered on time or within the safety margin of three working days (classes 1 and 2). All production orders postponed due to components being delivered too late are caused by components from classes 3 and 4, representing 41% of the components. On average, 15% of those components are delivered between 0.01 and 3 working days late. These class 3 components are more reliable than the class 4 components, representing 26% of total components. This class is on average 3.01 or more working days late.

We can conclude that 59% of all components have always been delivered on time and are therefore not the cause of postponed production orders. The remaining 41% of the components have been delivered more than three working days late at least once and are potentially responsible for postponed production orders. For the remaining of this chapter, we will investigate these 41% (1387) of all components, which from here on are classified as "unreliable components".

Table 2: Distribution of components per class

Class	Class description	Percentage of components
1	All deliveries were 0 working days late	44%
2	On average between 0.01 and 3 working days late with a maximum of 3 working days late	15%
3	On average between 0.01 and 3 working days with at least 1 delivery more than 3 working days late	15%
4	On average 3.01 or more working days late	26%
	Total	**100%**

2.3. Value of components

In this section we answer the third research question: *"Which components are most/least valuable? And what are the values of the components?"*

In Figure 3, the distribution of the prices of the unreliable components is depicted. As can be seen, only a few components are expensive and most of the components are (relatively) cheap. To determine the impact of the most expensive components, we apply the Pareto principle, which suggests that "roughly 80% of the impact comes from only 20% of potential causes" (Harvey & Sotardi, 2018). In our situation, only 15% (208) of the 1837 components are responsible for 80% of the total value (calculated by summing the prices of the components). The 15% most expensive components start at €165.86, which means that 85% of all unreliable components cost less than €165.86. Cheap components may, in our opinion, never be the reason a production order is delayed. A good option could be to stock these components to make sure they are available for a predefined percentage of the production orders. In the next chapter we will research literature to determine what inventory models are available and which is best suited for Hittech Multin. In Chapter 4, we will determine which components should be ordered based on an inventory order policy and which components should be ordered with a different order policy.

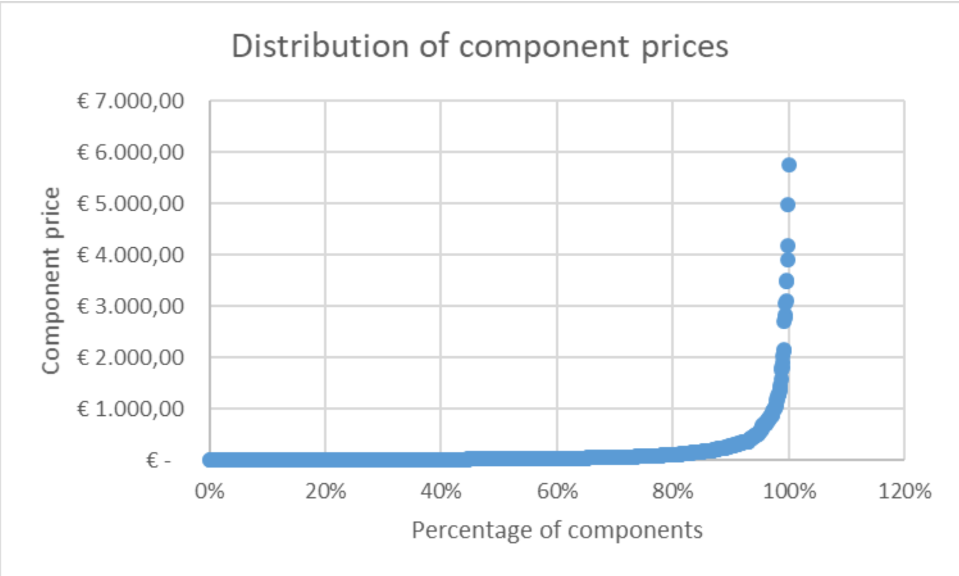

Figure 3: Distribution of component values

2.4. Reliability suppliers

In this section we answer research question four: *"Which suppliers are most reliable/unreliable? And how reliable are these suppliers?"*

We investigate the 1387 late delivered components to give an insight into which suppliers are responsible for these deliveries. Out of 326 suppliers, 193 are responsible for the supply of these components. We calculate that only 20% (49) of unreliable suppliers are responsible for 78% of the components (1109). An overview of these suppliers can be found in Appendix D. This means that if the supply performances of a relatively small group of suppliers can be improved, the overall performances can greatly be improved. In Chapters 3 and 6, we will research how the supplier performances can be improved.

2.5. Agreements with suppliers

In this section, we answer research question five: "What agreements does Hittech Multin have with its suppliers?"

During the last phase of the Development Project Process (introduced in Chapter 1), the final suppliers are selected. The selection is done with the help of the QLTC method. This means that the choice of supplier is based on Quality, Logistics, Technology, and Costs. The corresponding delivery time, cost per component, and quantity discounts are registered in the ERP system. Some of the suppliers that represent a large value for Hittech Multin sign a purchasing contract. The contract contains agreements about the price and percentage of deliveries that must be delivered on time. For some of the suppliers Hittech Multin provides a six-month rolling non-binding forecast per component.

All suppliers are evaluated every month. The Key Performance Indicators (KPIs) on which suppliers are evaluated can be found in Appendix E. When a supplier performs badly, Purchasing should demand an improvement plan from the supplier with goals and deadlines to improve the supply performance. In reality, such an improvement plan is hardly demanded due to a lack of time. Suppliers that keep underperforming run the risk of losing future quotations or to be replaced by a different supplier. However, finding and selecting a different supplier is a very time-consuming activity, because most of the components are designed and produced specifically for Hittech Multin. Switching suppliers every other day is therefore not possible and the replacement of a supplier does not occur frequently. Currently no other measures are taken by Hittech Multin for bad performing suppliers.

2.6. Order policy

In this section, we answer research question six: *"What order policy does Hittech Multin use?"*

Hittech Multin orders two kinds of products: the production components and so-called "off-the-shelf" components. Production components are components solely designed and produced for Hittech Multin. Off-the-shelf components are produced for multiple customers of the supplier. A part of the off-the-shelf components is classified as floorstock components. These are small, cheap components used in multiple products, for example nuts and bolts. Hittech Multin has a policy that these components may never be the reason that production stops, so these components are bought in bulk.

The rest of the components are ordered based on the forecasted and actual demand. All confirmed and forecasted customer orders are evaluated every week. Planning checks if the required components for the production orders are available. When a required component is not available, Planning places an order on the planned start date of production minus the expected supply lead time and a safety margin of five working days (described in Section 2.1.3). Planning orders all the components that need to be ordered once a week. The review period is thus one week.

The order size equals the amount needed for the production order. Most suppliers have quantity discounts (lower price per piece when the amount ordered increases) for components. Therefore, some planners order larger amounts of some components, but this is not customary. Another reason to order in larger amounts than needed is the Minimum Order Quantity (MOQ) set by the supplier. A MOQ means that Hittech Multin is obligated to order a minimum quantity, otherwise the component cannot be ordered at all or against high costs.

Important to note is that the expected lead times often not match the actual lead times. There are several reasons for this: (1) Hittech Multin does not actively check if the expected lead times, registered in the ERP system, are still accurate. The lead times are only updated when the supplier reports that lead time has changed. Suppliers also do not actively check if the lead time expected by Hittech Multin matches their expectations of the lead time. This results in a mismatch between the lead times expected by Hittech Multin and the actual lead times of the suppliers. (2) The supplier and Hittech Multin have a different definition of lead time. This mismatch occurs when Hittech Multin and the supplier start and stop measuring the lead time at different moments. These differences in definition can cause up to a five working days difference between expected and actual lead time. (3) Some suppliers are not able to send all the components on time, but can send a part of the components. Only a few of the components arrive later than expected, but in the ERP system the complete delivery is registered as too late. (4) Warehousing books the delivery later in than the actual arrival date, because they are too occupied with other work. All four causes have led to a delivery database, which is not as precise as we would like. In Chapters 4 and 5, we will discuss how this impacts our model and what Hittech Multin can do to improve the accuracy of the data.

From the impact of the main root cause, we can see that the current order policy does not work as Hittech Multin hoped. In Section 2.3, we announced we will look into an inventory model for the cheap components. For the components that are too expensive for the inventory model, we will research a safety lead time order policy. In Chapter 3, we will research literature to determine what safety lead time models are available and which one we will use.

2.7. Inventory requirements

In this section, we will answer research question seven: “What are the inventory requirements of Hittech Multin?”

The height of the inventory is dependent on the total turnover. When the sales of products increase, the turnover usually increases too, as well as the inventory. Therefore, the total inventory is measured as months’ worth of inventory. This is measured by dividing the total value of inventory at a certain moment in time by the expected turnover for the next month. Hittech Multin requires a maximum throughput time of two months, meaning a maximum of two months’ worth of inventory. These two months are arbitrarily chosen by Hittech Multin and could be altered. Therefore, we will take the two months into account as a soft constraint. We attempt to limit the inventory, but it is not a must if we can achieve a lower total cost with more inventory.

2.8. Conclusion

In this chapter we analyzed the current situation and answered the first seven research questions. In Section 2.1, we showed that components delivered by the supplier later than expected are the main root cause. Therefore, we will investigate this root cause during the rest of the thesis and formulate a solution.

In Section 2.2, we researched the reliability of the component deliveries. We showed that 59% of all components are either completely on time or within the three-day safety margin. The other 41% are components that contribute to the root cause. We investigated these 1387 components, classified as "unreliable components", more carefully.

In Section 2.3 we showed that, of the unreliable components, the 15% most expensive components add up to 80% of the total value. We concluded that cheap components may never be the cause of delayed production orders and we initiated the idea of stocking these components. In Chapter 3, we will research literature for the inventory order model and determine which model to use. In Chapters 4 and 5, we will determine which components should be ordered with an inventory order policy and which components should be ordered differently.

In Section 2.4, we showed that 193 of the 326 suppliers are responsible for the delivery of unreliable components. Subsequently, we showed that only 20% of the unreliable suppliers are responsible for 78% of the unreliable deliveries. We concluded that by improving the supplier performances of this small group we can greatly improve the overall supply performance. In Chapter 3, we will research how the supplier-buyer relationship can be improved to help improve the supply performances.

In Section 2.5 we discussed that only a small part of the suppliers has a contract and receives a six-month rolling non-binding forecast. All suppliers are evaluated every month, but there are few consequences for suppliers that perform badly.

In Section 2.6, we discussed the order policy Hittech Multin use. We discussed that the order moment is the planned production date minus the expected lead time and a five days safety margin. The order size is equal to the amount needed for production unless there is a minimum order quantity. Moreover, we discussed that the expected lead times often do not match the actual lead times. We concluded that the current order policy does not result in the desired percentage of components delivered before the planned production date. Therefore, besides the inventory order policy, we will research the option of a safety lead time order policy. In Chapter 3 we will research literature for safety lead time models and determine which model to use.

In Section 2.7 we showed that Hittech Multin has as the requirement that the total value of inventory is not allowed to exceed two months' worth of inventory. These two months are chosen arbitrarily, so during this thesis we will keep this in mind as a soft constraint.

3. Literature review

As described in the previous chapter, we plan to use an inventory order policy for the cheap components and safety lead time order policy for expensive components. In this chapter, we describe the results of our literature review. We start with the literature review for the inventory model, then describe an optimization algorithm used in the inventory model, followed by the safety lead time model, and finally we discuss how we can improve the supplier performances by improving the supplier-buyer relationship.

3.1. Inventory model

In Sections 3.1. and 3.2, we answer research question eight: *"What inventory control policy can be used to make sure there is sufficient stock while total costs are minimized?"*

We search for a model with which we can calculate the right reorder levels, order-up-to-levels, and order sizes for several components to make sure that in 98% of the time all components are present before the planned production, while the total costs are minimized. The reorder level is the inventory position at which Hittech Multin would place the order for new components. The order-up-to-level is the target level for the stock. The moment an order is placed for new components, the amount that returns the inventory position to the order-up-to-level is ordered. The order size is the number of components ordered each time an order is placed. Generally, the order size is the difference between the reorder level and order-up-to-level.

The desired model must focus on an assembly system (as used at Hittech Multin) and the model must take the different components in an end-product into account. This means that we look for a so-called "multi-item inventory assembly system" model. Important is that the model should incorporate stochasticity in supply lead time and stochasticity in the height of demand. Moreover, we want to include quantity discounts and MOQs. From the models we found, the model of (Hausman, Lee, & Zhang, 1998) approximates our situation best. They describe a model that helps to determine the right reorder levels for a multi-item inventory assembly system. The model considers a review period and looks into a correlation on the demand side. A large advantage of this model is that we only need one inventory model to determine the correct values for all components of an end product. The model also has some disadvantages. First, the model only considers deterministic lead times. Second, the model does not include quantity discounts. Finally, the model does not include MOQs. These three factors are an important part of our research and adjusting the model to include all of these is not trivial. The other models we found in literature also did not incorporate all characteristics described above.

Therefore, we decide to use a different approach, on which we elaborate in Chapter 4. In short, the approach works as follows: As discussed in Chapter 1, we research the effects of two different order policies. The first policy keeps components in inventory and orders components when the inventory position falls below a certain reorder level. The second policy orders components with a safety lead time in the amount needed for production. To this end, we build a simulation in which we combine all components of an end-product. Each component in this simulation is either ordered with a safety inventory or a safety lead time. The simulation calculates the percentage of orders for which all components are present on or before the planned production date given the order policy per component. Furthermore, we implement an optimization algorithm in the simulation to improve the solution. The goal of the simulation is to meet the required percentage of production orders for which all components are available, while the total costs are minimized.

In the rest of this section, we research literature for an inventory model that helps us find a good starting solution for the components ordered with a safety inventory. In Section 3.2 we research literature for an optimization algorithm. In Section 3.3 we research literature for a safety lead time model that finds good starting solutions for the components ordered with a safety lead time.

Instead of a multi-item inventory model, we search for a single-item inventory model that includes all requirements described above. With this model we calculate the reorder levels, order-up-to-levels, and order sizes for each component individually. These values are used as a starting solution in the simulation. Orders for which all components are present on the planned production date are from here on called "complete production orders". In our literature research we found the (*R,s,S*) model described by (Silver, Pyke, & Thomas, 2016). In this model, *R* is the review period. When the inventory position drops below the reorder level s an amount is ordered to raise the inventory position to the order-up-to-level *S*. The order-up-to-level is calculated based on the reorder level, the undershoot and the order size. Undershoot occurs if a customer orders an amount that causes the inventory position to drop below the reorder level. The number of components below the reorder level is called the undershoot. The undershoot problem is serious in an (*R,s,S*) model because we have to wait until the review moment before ordering new products. The order size is calculated with the help of the Economic Order Quantity (EOQ) model. When calculating the EOQ we take quantity discounts into account. An elaborate overview of the EOQ including quantity discounts can be found in Appendix F. The found order quantities of all components then serve as input for the (*R,s,S*) model.

We know that Hittech Multin orders once a week, so the review period R is one week. The reorder level is based on the expected demand during lead time and review period plus a safety stock. The formula for calculating the reorder level is the following:

$$s = X_{L+R} + k * \sigma_{L+R} \tag{3.1}$$

X_{L+R}: Expected demand during lead time and review period
k: Safety factor
σ_{L+R}: Standard deviation of demand during lead time and review period
L: Lead time
R: Review period

We use the historical demand data from the ERP system to calculate the expected demand and the standard deviation of demand. The second term on the right-hand side of formula (3.1) represents the Safety Stock (SS). The SS is the amount of inventory kept on hand, on average, to allow for the uncertainty of demand and the uncertainty of supply in the short run (Silver, Pyke, & Thomas, 2016). The SS consists of the standard deviation of demand during lead time and review period times the safety factor. The safety factor determines the probability of running out of stock. We first describe how the standard deviation is calculated and then determine s and k.

We assume that demand and lead time are independent. This assumption might not always hold in reality, but we use the output of the (*R,s,S*) model as input for the simulation model. During the simulation, we change the values to make sure the percentage of complete orders meets the requirement. Therefore, for now it is sufficient to use an approximation. We calculate the standard deviation of lead time and review period as follows:

$$\sigma_{L+R} = \sqrt{E[L+R]Var[D_p] + E^2[D_p]Var[L]} \tag{3.2}$$

$E[L+R]$: Expected lead time plus review period
D_p: Demand per period
$Var[D_p]$: Variance of demand per period
$E[D_p]$: Expected demand per period
$Var[L]$: Variance of lead time

With the EOQ, we try to minimize the total costs and with the safety factor we make sure that for a certain percentage of the orders can be filled from stock. To determine the safety factor, we can use P_1, P_2, and P_3. P_1 is the Cycle Service Level, which is the probability of no stock out per replenishment cycle. P_2 is the Fill Rate, which is the fraction of demand satisfied directly from shelf. P_3 is the Ready Rate, which is the fraction of time during which net stock is positive. In our situation we want to make sure that at least a required fraction of demand is satisfied from stock all the time, so we use the Fill Rate.

Subsequently, we determine *s* and *k* simultaneously and use these to calculate *S*. Therefore, we need the following formula for the order quantity:

$$Q = S - s + E[Z] \qquad (3.3)$$

Where $E[Z]$ is the approximated value of the expected undershoot and is calculated as follows:

$$E[Z] \approx \frac{\sigma_R^2 + \hat{x}_R^2}{2\hat{x}_R} \qquad (3.4)$$

σ_R^2: Variance of demand during the review period
$\hat{x}_R$: Average demand during the review period

With historical demand data, we calculate the expected undershoot. Furthermore, in our situation, *Q* is predetermined by the EOQ. This means that we already know the total value of the right-hand side of equation (3.3). Now only *s* and *S* are left unknown.

We can determine the value of s with the following equality:

$$\sigma_{L+R}^2 J_u\left(\frac{s-\hat{x}_{L+R}}{\sigma_{L+R}}\right) - \sigma_L^2 J_u\left(\frac{s-\hat{x}_L}{\sigma_L}\right) = 2(1-P_2)\hat{x}_R\left[S - s + \frac{\sigma_R^2+\hat{x}_R^2}{2\hat{x}_R}\right] \qquad (3.5)$$

$\hat{x}_L$: Average demand during lead time
σ_L: Standard deviation of demand during lead time
$\hat{x}_{L+R}$: Average demand during lead time plus review period
σ_{L+R}: Standard deviation of demand during lead time plus review period

$J_u(k)$ is a special function of the normal distribution which can also be written as :
$J(k) = (1 + k^2)[1 - \Phi(k)] - k\varphi(k)$
Φ: The cumulative distribution of the normal distribution
φ: The probability density function of the normal distribution

We know that the left- and right-hand side of formula (3.5) should be equal. We can substitute equation (3.3) in equation (3.5), resulting in the following equality:

$$\sigma_{L+R}^2 J_u\left(\frac{s-\hat{x}_{L+R}}{\sigma_{L+R}}\right) - \sigma_L^2 J_u\left(\frac{s-\hat{x}_L}{\sigma_L}\right) = 2(1-P_2)\hat{x}_R Q \qquad (3.6)$$

Now we have an equation where *s* is the only unknown variable. We determine the *s* (and therefore *k*) with the help of the goal seek function of excel. After finding *s,* we can calculate *S* with the help of formula (3.3) and then we have found all the values we were looking for.

Important to note is that the lead time variability causes a serious increase in demand variance over lead time as can be seen in formula (3.2). This results in a serious increase in safety stock. For Hittech Multin, it is therefore not only important to reduce the supply lead times, but also the supply uncertainty. In Section 3.4, we research literature on how to improve the supplier-buyer relationship, which will lead to improved supply performances and thus less supply uncertainty. Finally, in Chapter 6, we discuss what Hittech Multin can do to improve the supplier relationship and therefore supplier performances.

3.2. Particle Swarm Optimization algorithm

With the (*R,s,S*) inventory model and the EOQ formula, we can calculate the order size, reorder levels, and order-up-to-level for each component individually. When inputting these values for all components combined in the simulation model, we obtain a percentage of orders for which all components are present on time. The next objective is to improve the values of all components to make sure this percentage meets the required 98%. The search parameter space for possible solutions for the simulation is large. Therefore, we searched the literature for an optimization algorithm that can help to find good solutions. During the literature review found the meta-heuristic Particle Swarm Optimization (PSO) designed by (Barzegar & Seifbarghy, 2014) that can help us find a good solution for the optimization problems.

The PSO algorithm is a meta-heuristic method inspired by the collective behaviour of natural organisms like birds and schools of fish. In these communities, there is no coordinative behaviour without central control. In this algorithm each solution is like a bird in a group of birds and is called a particle. All particles have their specified fitness value, which is obtained from the fitness function. The fitness value is the result of a candidate solution. In our situation the fitness value represents the total costs. One candidate solution represents the set of components of an end-product with certain reorder levels and order sizes. The goal of the algorithm is to optimize the fitness value of the particles, to minimize the total costs. The solution is only acceptable if a predefined percentage of complete orders is achieved. The model has the following inputs:

Sets:

$I = Number\ of\ particles.$

$T = Number\ of\ iterations.$

$A = Number\ of\ components\ belonging\ to\ an\ end\ product.$

Parameters:

$w = Inertial\ weight\ factor. Dependent\ on\ this\ factor\ the\ \ particle\ explores\ or\ exploits\ more.$

$c_1 = Cognitive\ learning\ factor. This\ factor\ indicates\ the\ attractiveness\ of\ each\ particle$
$\quad relative\ to\ its\ own\ best\ found\ solution.$

$c_2 = Social\ learning\ factor. This\ factor\ indicates\ the\ attractiveness\ of\ each\ particle$
$\quad relative\ to\ the\ global\ best\ found\ solution.$

Variables:

$v^i(t) = The\ current\ velocity\ of\ particle\ i$

$v^i(t+1) = The\ new\ velocity\ of\ particle\ i$

$r_1, r_2 = Random\ variables\ between\ 0\ and\ 1$

$x^i(t) = Current\ position\ of\ particle\ i$

$x^i(t+1) = New\ position\ of\ particle\ i$

$x^{PBest,i}(t) = Best\ position\ ever\ reached\ by\ particle\ i\ until\ iteration\ t$

$x^{GBest,i}(t) = Best\ position\ ever\ reached\ by\ all\ particle\ until\ iteration\ t$

Decision variables:

$Q^{a,i,t} = The\ order\ quantity\ of\ component\ a\ of\ particle\ i\ in\ iteration\ t$

$RL^{a,i,t} = The\ reorder\ level\ of\ component\ a\ of\ particle\ i\ in\ iteration\ t$

The PSO algorithm consist of the following steps:
Step 1: Initialisation
In this section we give an idea of how we determine the initial values. In Chapter 4 we will determine the values.

With the help of the (*R,s,S*) and EOQ models we found the start values of *Q* and *RL* for each component. At *t* = 0, we determine initial values for each component in each particle based on these values. We perform one simulation run to determine the total costs (fitness value) and the acquired fill rate. If the required fill rate is not met, we increase the values of *Q* and *RL*. The moment the required service level is met we draw a random value within a +10% and -10% bound of the *Q* and *RL* values as starting values.

The inertial weight factor is a number between 0 and 1 and determines how much a particle explores (high factor) versus exploits (low factor). We want to explore possible solutions in the beginning and exploit the best-found solutions in the end. Therefore, we start with a high inertial weight factor and gradually decrease the factor as the number of iterations increases.

The ratio c_1/c_2 determines whether a particle converges towards the global best solution or its personal best solution. In our case, we value the global best-found solution more than the local best found solution, so we make sure that the c_2 is larger than c_1.

Step 2: Determine the position and velocity of each particle
A particle represents a point in the designed space, called the current location, and is a candidate solution to the problem. In our situation the position of a particle represents the values of the decision variables. Each particle tries to improve its current position by moving to a different position, so by changing the decision variables. The speed with which the decision variables are changed is called the velocity. A high velocity indicates a large change of the decision variables, while a low velocity indicates a small change. During step 2 we determine the current position and velocity of a particle.

Step 3: Updating velocities
During each iteration we update the velocity of the particle, which will then be used to update the particle location. The new velocity is calculated with the following formula:

$$v^i(t+1) = wv^i(t) + c_1 r_1 \left(x^{PBest}(t) - x^i(t)\right) + c_2 r_2 \left(x^{GBest}(t) - x^i(t)\right) \qquad (3.7)$$

The new velocity is calculated based on three factors: the current velocity, the personal best position, and the global best position. The first term of the right-hand side represents the current velocity and is multiplied by the inertial weight factor (the particle tends to maintain its current velocity by this factor). The second term makes sure the particle tends to go in the direction of its personal best-found position by using the distance between its current position and its personal best. Each iteration a new random r_1 is drawn between 0 and 1, which determines how much the particle will go into the direction of its own personal best. The third term makes sure the particle tends to go in the direction of the global best-found position by using the distance between its current position and the global best. Each iteration a new random r_2 is drawn between 0 and 1, which determines how much the particle will go into the direction of the global best.

Step 4: Updating position
Based on the direction, each element updates its position according to the following formula:

$$x^i(t+1) = x^i(t) + v^i(t+1) \qquad (3.8$$

After updating, the element moves to its new position and its fitness function is calculated again.

After a predefined number of iterations, the PSO algorithm is finished. The number of iterations we use is determined in Chapter 4.

3.3. Safety lead time model

In this section we answer research question nine: *"What safety lead time model can be used to make sure the components are on time at Hittech Multin while minimizing the number of days in stock?"*

In this section we research the literature for a model that helps us finding the starting solutions for components ordered with a safety lead time in the simulation. As discussed earlier, both the demand and lead times are stochastic. The demand uncertainty consists of two elements: uncertainty in the moment of the demand and uncertainty in the height of the demand. However, in Chapter 1, we discussed that we leave re-ins out of the scope of the research, so once a customer places an order, the order moment is fixed. This also means that the production date of a production order is not uncertain anymore and can therefore be considered deterministic instead of stochastic. The second uncertainty in demand, the height of demand, does also not apply for components ordered based on a safety lead time policy. We do not hold inventory for these components and only order components when a customer places an order. When we order components, we only order the number of components needed to produce the customer orders. This means that the height of demand is known the moment a customer places an order and we can therefore consider the height of demand also deterministic for safety lead time components. This means that we can consider the demand for safety lead time components completely deterministic and there is only stochasticity left in the lead time.

We expect a supplier to deliver the same component in about the same lead time. Sometimes it might take a bit longer, sometimes a bit shorter, but most of the time around the expected lead time. We therefore assume a normal distribution of the lead time as is done by (Das & Abdel-Malek, 2003). (Tyword & O'Neill, 1997) discussed that the normal approximation of the lead time is robust. We therefore deem this assumption reliable and we will use it in our research. Now we can use standard statistics to calculate the safety lead time.

With historical data from the ERP system we calculate the average lead time and standard deviation of the lead time of each component. We depict the distribution of the lead time as a normal shaped graph as can be seen in Figure 4 from (Larsen & Marx, 2012). We calculate x, which represents the total order lead time (expected lead time and safety lead time), with the following formula:

$$Order\ lead\ time = \mu + z * \sigma \tag{3.9}$$

μ: Average lead time, so in our situation the expected lead time
σ: Standard deviation of the lead time

We calculate z with the following formula:

$$\Phi\left(\frac{z-\mu}{\sigma}\right) = P(Z < z) \tag{3.10}$$

We know that $P(Z < z)$ = 0.98. With the Norm.Inv function of Excel we calculate the value of z given the desired on-time percentage, the μ and σ.

The safety lead time is the difference between the order lead time and the expected lead time.

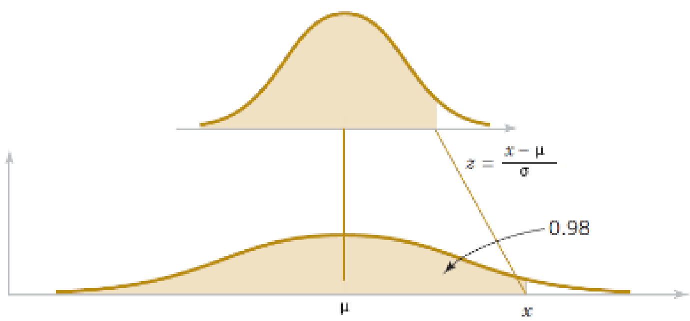

Figure 4: Normal distribution graph

3.4. Establishing a good supplier-buyer relationship

In this section we will answer research question ten: *"How can a good supplier-buyer relationship be established?"*

Becoming a preferred customer brings many benefits. For example, (Bew, 2007) found that suppliers grant their preferred customers preferential treatment in the allocation of materials, first access to new product ideas, and unique cost reduction opportunities. Maintaining a good relationship with your supplier and becoming a preferred customer can thus be rewarding. In contrast to the classical view of marketing, which assumes a competition for customers, research in supplier satisfaction and the preferred customer concept takes the viewpoint of customers competing for capable suppliers (Vos, Schiele, & Hüttinger, 2016). Companies reduce the number of suppliers to receive benefits, such as lower transaction costs and economies of scale. This causes supplier reduction, which can lead to oligopolistic supply market structures (Lavie, 2008) and (Vos, Schiele, & Hüttinger, 2016). Consequently, supply chain management must shift its focus from striving for the lowest possible purchasing price in every transaction to a more differentiated portfolio approach, with more attention paid to the role of strategic suppliers, as they are important for firms and are typically difficult to manage (Hüttinger , Schiele, & Veldman, 2012). Only recently has supply management literature begun asking how buyers can secure their key suppliers' benevolence (Hüttinger , Schiele, & Veldman, 2012). (Schiele, Veldmand, & Hüttinger, 2011) and (Schiele , Veldman , Hüttinger, & Pulles, 2012) argued that the three constructs, customer attractiveness, supplier satisfaction, and preferred customer status, determine whether buyers are awarded privileged treatment by the supplier.

Customer attractiveness is the expectation that a supplier has towards the buyer at the moment of initiating or intensifying a business relationship (Schiele, Calvi, & Gibbert, 2012). Customer's size and potential purchases appear to play a major role for suppliers regarding evaluating a customer's attractiveness (Hüttinger , Schiele, & Veldman, 2012) . However, smaller firms can compensate for lower economic attraction by using other elements, such as technological expertise or interesting modes of cooperation (Christiansen & Maltz, 2002).

(Hüttinger , Schiele, & Veldman, 2012) observe two major tendencies for supplier satisfaction: (1) Cooperation, rather than competition, appears to be the supply management strategy that promotes the highest levels of supplier satisfaction. Supplier satisfaction is driven primarily by a relationship-based supply chain strategy. Where buyers are more focused on performance and outcomes, suppliers appear to place more importance on the relationship atmosphere and development of norms. (2) The attendant modes of interaction (e.g. information sharing) and operational excellence (billing, delivery, forecasting, and planning) appears to be major perquisites for supplier satisfaction.

To become a preferred customer price and volume play a role but are certainly not the only drivers for suppliers to treat an organization as a preferred customer. (Hüttinger , Schiele, & Veldman, 2012) found in the literature that multiple drivers are identified like communication, early involvement, and responsiveness, so mainly social factors.

(Schiele , Veldman , Hüttinger, & Pulles, 2012) grouped the drivers for all three stages and created an overview. This overview is depicted in Figure 5. Some drivers are not stage-specific and the boundaries are therefore expressed as broken lines, that separate each stage. (Hüttinger , Schiele, & Veldman, 2012) conceptualize suppliers evaluating a customer relationship as a function of the attraction and satisfaction within a relationship versus the comparison level of alternatives. If this knowledge about the drivers of the different cycle stages is adopted adequately by buyers, customer attractiveness and supplier satisfaction can be increased until it surpasses the levels suppliers experience with alternative customers. If this is the case, one customer is awarded preferred customer status and receives a more preferential treatment than other customers.

We can conclude that to establish a good supplier-buyer relationship, the customer attractiveness and supplier satisfaction must be established. These are partly dependent on economic factors, but also largely on social factors like cooperation and information exchange. When both are high, the preferred customer status can even be achieved.

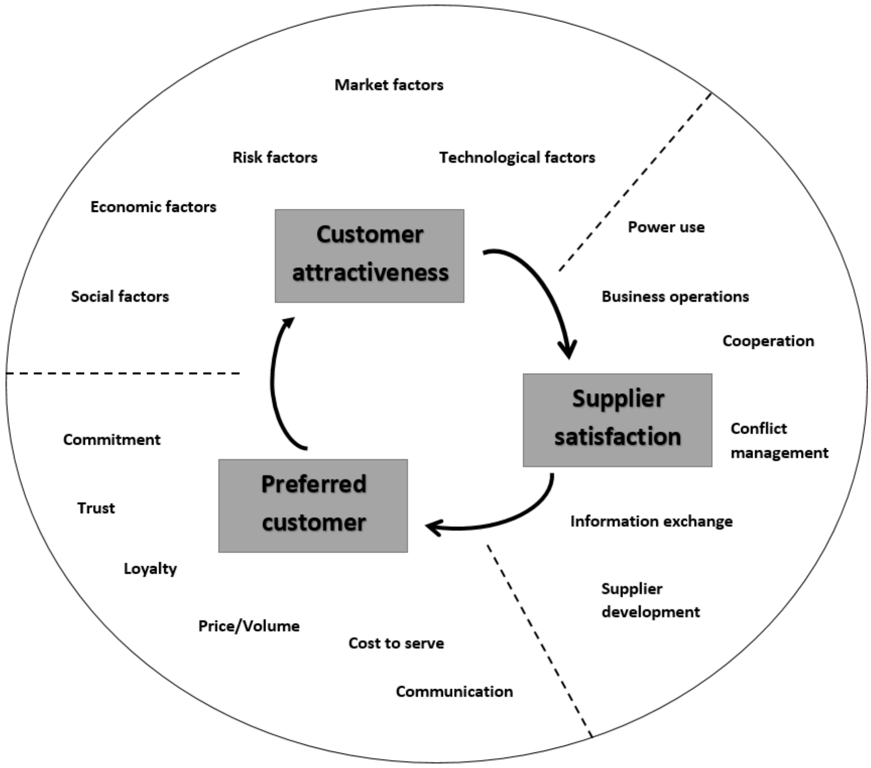

Figure 5: Drivers per stage by (Hüttinger , Schiele, & Veldman, 2012)

3.5. Conclusions

In this chapter, we researched literature for an inventory model, a safety lead time model, and for ways to improve the supplier-buyer relationship to improve supplier performance. We did not find an inventory model that met all requirements and therefore chose a different approach. We found the (*R,s,S*) model as an inventory model for each component individually. One of the inputs for this model is the predetermined order size. To determine the order size, we used the EOQ model that also takes quantity discounts into account. With both models we can calculate the reorder level, order-up-to-level, and order size for each component to make sure the fill rate is 98%.

These values are used as start values for a simulation we will build. In this simulation, we can calculate the percentage orders that start on time and total costs given the start values. In this simulation, we build an optimization algorithm that improves the reorder level and order size per component to make sure the predefined percentage orders on time is met while total costs are minimized. The optimization algorithm we found in the literature is called the Particle Swarm Optimization algorithm.

For the components that are ordered with a safety lead time a different model was found. Components are only ordered when a customer order occurs and in the amount needed to fulfill the customer order. Expedited orders are out of the scope of this research, so when a customer order is placed the date and height are fixed. Demand for safety lead time components is therefore assumed deterministic, which means that we are only left with stochasticity in lead time for these components. Further, we assumed that the lead times are normally distributed. We can calculate the average lead times and standard deviation of the lead times with historical data. With these values we can determine how much safety lead time we need to make sure that in 98% of the time the component arrives before the planned production date.

Finally, we determined how a customer can become a preferred customer which will lead to improved supplier performance. Economic factors are only partially responsible for customer attractiveness and supplier satisfaction. Suppliers greatly value social factors like communication and early involvement. We will use the presented model to determine what Hittech Multin can do to improve supplier relationships and therefore the supplier performances. This will be discussed in Chapter 6.

4. Models

We built two Excel models for Hittech Multin to solve the research objective. In this chapter we first explain the models, including the model requirements and constraints. Subsequently, we provide an overview of the input parameters, output parameters, decision variables, and model assumptions of all models and elaborate on the complex ones. Finally, we discuss the different scenarios we will test in the simulation. Each scenario represents a single order policy or a combination of order policies. Both Excel models will be run for two different article groups (Article group 1 (small article groups) and Article group 1 (large article group)). In this chapter, we only design the experiments for Article group 1 and thus only discuss the experimental input parameters for this article group. Based on the results of these experiments, we will adjust input parameters for Article group 2. In this way, we make sure that the experiments for the large article group can be run in an acceptable time, while still providing reliable results.

4.1. Model explanation, requirements, and constraints

In this section we answer research question eleven: *"What are the requirements and constraints for the decision-making model?".* First, we give a global explanation of the two Excel models we built for Hittech Multin. Then, we discuss the requirements and constraints of the models.

4.1.1. Model explanation

In Chapter 1 we described that the current order policy does not result in the desired percentage complete production orders. Furthermore, we discussed that we research the impact of ordering components with a safety inventory or ordering components with a safety lead time. In Chapter 3 we described the EOQ model and (*R,s,S*) models and decided to combine these models to determine the reorder level and order size for each component individually. Per component, the calculated reorder level and order size minimizes the total costs, while the fill rate of that component meets the requirement. These calculations are done in the first Excel model. The model built in the first Excel file is from here on called the "EOQ – (*R,s,S*) model". The output of this model (the reorder level, order-up-to-level, and order size) is used as the start solution in the simulation for all components ordered with an inventory order policy.

Besides the components ordered with a safety inventory, we have components that are ordered with a safety lead time. In Chapter 3, we discussed that we consider the demand for the safety lead time components deterministic. Furthermore, we assumed that supply lead times are normally distributed and that we use standard statistics to calculate the safety lead time per component. These calculated safety lead times are used as starting solutions for the components in the simulation that are ordered with a safety lead time order policy.

Now, we have the start solutions for both inventory and safety lead time components, and we can run the simulation to determine the percentage of complete production orders with the given starting solutions. Due to the uncertainty in both lead time and demand, the overall percentage of complete production orders will not meet the requirement on the first try. Therefore, we need to improve the reorder levels and order sizes for the inventory components and the length of the safety lead time for safety lead time components. The parameter space for the inventory components is large, because the degree in which the order level and order size per component must be adjusted differs per component. Therefore, we use the PSO algorithm, described in Chapter 3, to help us find good reorder levels and order sizes per component. The parameter space for the safety lead time components is smaller, because we calculate one standard safety factor for all safety lead time components. When searching for the right safety factor we manually increase or decrease the safety factor until the percentage of complete orders meets the requirement.

In the second Excel-file, we built the simulation. The PSO algorithm uses the simulation to test the percentage complete orders when the reorder levels and order sizes of the components are adjusted. Therefore, we integrated the PSO algorithm in this Excel file. The model built in this Excel file is from hereon called the "Simulation model".

This means that we use the EOQ – (*R,s,S*) model to calculate the initial solutions for the components ordered with an inventory order policy. The initial values consist of the reorder level, order size, and order-up-to-level per component. We use the normal approximation of the lead times to calculate the safety lead time per safety lead time component. In the Simulation model, we calculate the percentage of complete orders when all components of an end product are combined. Then, we improve the reorder levels and order sizes of the inventory components with the PSO algorithm in this Excel file. Finally, we manually adjust the safety factor for the safety lead time components until the percentage of complete production orders meets the requirement.

4.1.2. Model requirements and constraints

In order to create the EOQ – (*R,s,S*) model and simulation model that can be used accurately as well as effectively, they have to meet certain requirements and constraints. These requirements and constraints are determined together with the planners and purchasers. We start with the requirements and constraints for the interfaces of both models and then discuss the requirements and constraints for the models themselves. All requirements and constraints apply to both models unless specifically stated otherwise.

The interface requirements and constraints are the following: (1) The models must be created in Excel with Visual Basic for Applications (VBA). Employees at Hittech Multin have experience with Excel VBA. Therefore, they will be able to work with the model and, if necessary, to adjust the model after we finish this thesis assignment. (2) The models must contain a clear interface that shows the input and output parameters of the model. (3) The output must be produced with only a few clicks on the buttons. Running the models must be easy. (4) All buttons and input fields must be clearly explained either beside the button/field itself or in a separate section. The explanation must be in Dutch. (5) Loading in new, more up-to-date, input data must be easy. The old data must be erased manually before new data is loaded. (6) The model must be secured to make sure no one can alter the model, except authorized persons.

The model requirements and constraints are the following: (1) The models must consider MOQs. (2) The models must consider stochastic demand and supply lead times. (3) Commonality in components between products almost exclusively exists within article groups. The model must be used separately per article group to make sure the calculations do not become too complex but do have to consider component commonality. (4) The model must take into account quantity discounts.

4.2. EOQ – (*R,s,S*) model

In the rest of this chapter we will answer research question twelve: *"What input data is used? How are those input data collected? And what output should be obtained from the model?"*

The logic of the EOQ – (*R,s,S*) model is illustrated in Figure 6. The model starts with a certain order batch size for each component, which is calculated by the EOQ model. We provide an overview of all input parameters, output parameters, and decision variables for the complete model in Appendix G. In this section, we discuss the more complex ones as well as the assumptions made in the model.

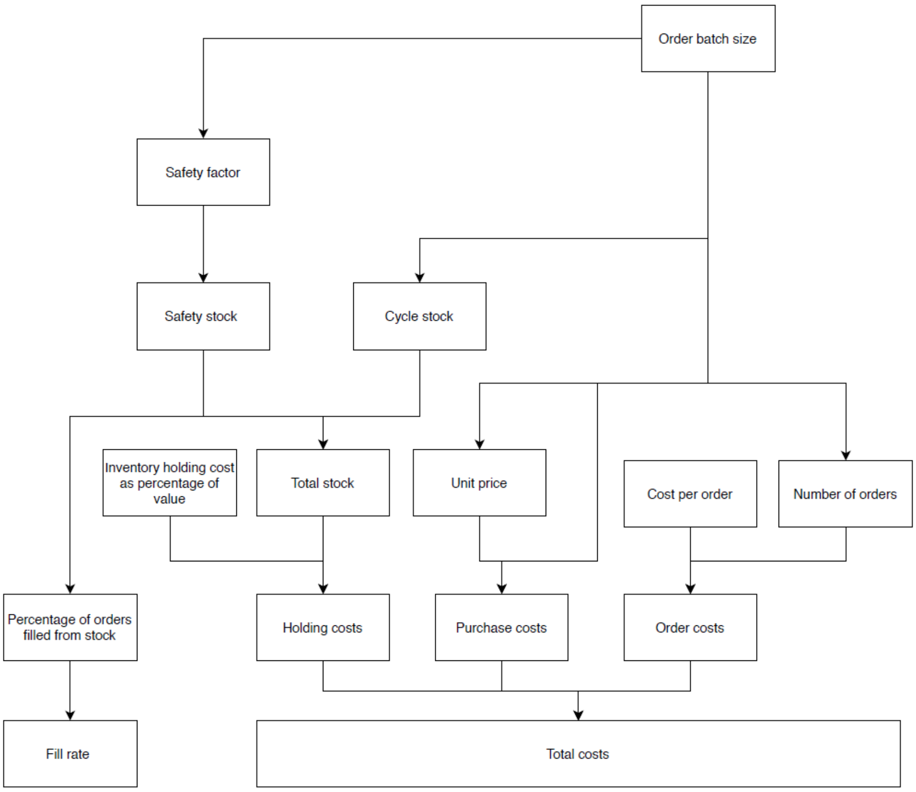

Figure 6: Logic EOQ – (R,s,S) model

4.2.1. Input parameters

Products to make

Each article group consists of components belonging to one or multiple products. All products in an article group can be considered as different versions of the same product or as subassemblies that are separately sold to the customer. Most components in the different products are similar, but there are small differences in component composition between products. Article group 1 consists of three different products that contain a total of 67 different components. The prices of these components range from €0.06 to €71.92 each. Of those 67 components, 27 are floorstock components. These components are ordered in bulk with the current order policy.

Article group 2 consists of one product that contains 365 different components. The price of these components ranges from €0.01 to €1882.71 each. Of those 365 components, 115 are floorstock components.

All components belonging to all products of an article group, along with the MOQ for each component and the prices can be found in the BOM. All prices and quantity discounts per component can be found in the ERP system.

Demand

The average demand and standard deviation of demand are calculated with historical demand data from the ERP system. Although we have historical data starting halfway in 2017, we only use historical data starting from the end of 2018 until the end of 2019. Both Hittech Multin and the suppliers informed us that 2018 was an extraordinary year, mostly because demand from one customer (cannot be named due to confidentiality) was extremely high. In 2019 the demand stabilized on the former level again and expected is that this will continue for the coming year. Demand in 2018 is a bad representation of the demand for the coming year and will therefore not be used. The Article group 1 component with the lowest demand has on average 1 unit demand per week. The Article group 1 component with the highest demand has on average 118 units demand per week. The Article group 2 component with the lowest demand has on average 1 unit demand per week. The Article group 2 component with the highest demand has on average 374 units demand per week.

Fixed costs to place an order

We calculate that the costs to place an order are €31. The calculations can be found in Appendix H. (Durlinger, 2013) states that the costs per order range between €10 and €150, with an average of €45. Our estimate is lower than the average, but within the ranges and therefore deemed reliable. Important to note is that these costs are incurred per order rule. This means that it does not matter if, for example, five different components are ordered at one supplier or five different suppliers. The total order costs are five times the fixed cost to place an order.

Holding costs as percentage of the component value per year

The holding costs per year as percentage of the component are 24%. The calculations can be found in Appendix H. (Durlinger, 2013) states that the holding costs percentage ranges between 9% and 63% with an average of 22%. Our estimate is near the average and therefore deemed reliable.

Required fill rate

The fill rate is the fraction of demand satisfied directly from shelf. In Chapter 1 we determined that in 98% of all production orders the materials should be present at the production site on or before the planned production date. Therefore, we set the required fill rate per article group on 98%.

Supply lead times

To determine the supply lead times of the components we use historical data from VivD. This data contains the expected lead times and actual lead times of the component deliveries. For our model, the supply lead time is the most uncertain input parameter. First, Hittech Multin treats the expected lead times of the components as if these are deterministic. In Section 2.6 we discussed that these expected lead times are by no means always correct. Second, we only use the supply data starting from the end of 2018 until the end of 2019 for the same reasons as with the demand calculations. This means that we only use historical data of the last year, so we have a limited amount of data available per component. We expect a supplier who delivers different components with the same expected lead time to perform equally for all of those components. We therefore group components from the same supplier with the same expected lead time. From the data and interviews with Purchasing we know that the data sometimes contains large outliers. These situations were exceptions that we do not want to take into account in our dataset. Therefore, we leave out all data points that are larger than the average plus two times the standard deviation. All data points of a component in our final model lie in the following interval: $[\mu - 2 * \sigma, \mu + 2 * \sigma]$

In Chapter 6 we discuss what Hittech Multin can do to improve the accuracy of the expected lead times. For Article group 1, the expected lead times range from 1 week up to 20 weeks. For Article group 2, the expected lead times range from 1 week up to 18 weeks.

Review period

Planning orders components once a week. The review period is therefore also one week.

4.2.2. Model assumptions

For EOQ – (*R,s,S*) model some assumptions are made, which might result in less realistic output. The output of this model however serves as input for the Simulation model. There the values are further improved to make sure the predefined fill rate is met, while the total costs are minimized. The Simulation model will reflect the real situation, so the improved values will also reflect the real situation.

The assumptions made are the following: (1) The (*R,s,S*) model assumes that the demand is normally distributed. In reality, this is not always the case. If we assume a different distribution, the calculations of the (*R,s,S*) model would become unnecessarily complex for our purpose. (2) The supply lead times are normally distributed. As we discussed in Section 3.3, during this thesis assignment, we assume that the lead times are normally distributed too. The calculations for the (*R,s,S*) model would become unnecessarily complicated if we assume a different distribution.

4.3. Simulation model

Both the simulation and the PSO are incorporated in one Excel model for Hittech Multin. The PSO algorithm tries to optimize the output when the inputs are adjusted. The PSO algorithm uses the simulation to determine the output if the input parameters are changed. Both the simulation and the PSO have their logic and parameters and we therefore discuss them separately. In Appendix G, we provide an overview of all input parameters, output parameters, and decision variables for the simulation model and the PSO algorithm. In this section, we discuss the parameters that are either unique for the Simulation model and need additional explanation or the parameters that we explained earlier, but for which we choose a different approach.

4.3.1. Simulation

Introduction of the simulation

The goal of the simulation is to determine what the outcomes are if we use a certain order policy or a combination of order policies. Therefore, we create a simulation model that mimics the reality of appearing customer orders on the demand side and the uncertainty in delivery on the supply side. The time steps in the simulation are weeks. The customer orders per week for each product are determined beforehand with a certain probability distribution. This means that the height of customer orders is stochastic, but the moment is deterministic, as discussed in Chapter 3. The customer orders result in demand for the individual components. When and how much of each component should be ordered depends on the order policy, the expected lead time, and the uncertainty in the lead time. In the simulation a production order that is not complete is delayed. Therefore, we measure the percentage of production orders that started on time and, which represents the percentage of complete production orders.

Demand

In the EOQ – (*R,s,S*) model we assumed that the demand is normally distributed, while we know this is not true in reality. For the simulation model we therefore use an empirical distribution to approximate the actual weekly demand. We briefly discuss how we determine the weekly demand in the simulation.

Each week the customer places a certain number of orders and each order contains several products. We have the historical demand data from the ERP system containing the number of orders per week and the number of products per order. In the simulation we determine what the minimum and the maximum number of orders placed have been during each week in the past year. Then we calculate the probability for each amount of orders in one week. We accumulate the probabilities and create probability intervals corresponding to a certain number of orders. In Table 3 we provide an example situation with the number of orders and corresponding probability. During the simulation, a random number between 0 and 1 is drawn for each product in each week. For example, in week 1, the number 0.667 is drawn. The interval in which the random number falls is the number of orders in that week of the simulation. In our example situation this would mean that 3 customer orders are placed in week 1.

Each order represents the demand for a certain number of products. We calculate the average height of an order and the standard deviation of the height with the historical data. During the simulation we draw a random height of each order based on a normal distribution with the calculated average and standard deviation. In each week of the simulation we repeat this procedure to determine the total demand in one simulation run.

Table 3: Example situation possible orders per week

Number of orders	Cumulative probability
0	0-0.5
1	0.51-0.65
3	0.66-0.9
5	0.91-1

Start inventory

For the components ordered with an inventory order policy, we pretend that we start at a random moment in time. This means that the start inventory is somewhere between the reorder level and the order-up-to-level. Therefore, the start inventory for each inventory component is calculated by the reorder point plus half the order size.

For the components ordered with a safety lead time, the goal is to have only as many components as is demanded and thus to have no excessive inventory. Therefore, we set the start inventory for the safety lead time components on zero.

Run length

The length of one run is expressed in number of years, which represents 52 weeks. On the one hand we want to keep the run length as small as possible, to reduce the run time of the simulation. However, we also want to make sure all components have at least one order cycle, meaning that each component must be ordered at least once during the simulation. Otherwise, the start inventory might be enough for a component to fill the complete demand and we do not test whether the reorder level is sufficient or too low. We determine that the run length of the simulation for Article group 1 needs to be at least ten years to make sure all inventory components fall below the reorder level at least once.

Warm-up length

The safety lead time components need to be ordered on the planned production date minus the expected lead time and a safety lead time. This means that the first orders in the first year can only occur in the week of the longest combination of expected lead time and safety lead time. If an order would occur before this week, we start the simulation with production orders with component shortage and this does not represent reality. Because all outputs are calculated on yearly basis, we cannot delete the first weeks of the simulation. Instead we must delete a complete year. Therefore, we use the first year of the simulation as the warm-up length and only start collecting the results from the second year.

Number of replications and runs

The number of runs per replication is a trade-off between run time and precision of the outcome per replication. To prevent the run time from becoming too long we set the number of runs arbitrarily per replication to three. If it turns out that the results are not precise enough, we will increase the number of runs.

The number of replications is a trade-off between relative error and confidence level on the one hand and the run time on the other hand. We calculate the number of replications with a relative error of 2% and a 95% confidence interval. This results in a minimum number of replications of four. We elaborate on the calculations in Appendix J.

When running the simulation, we use four replications containing three runs per replication and ten years per run. In total we simulate 120 years when testing a scenario.

Random number generator

To make sure one order policy does not get coincidentally more favourable demands and lead times, we use a pseudo-random number generator during the simulation. A pseudo-random number generator makes sure that the same stream of random numbers is generated for each order policy. A major disadvantage of Excel is that the build-in pseudo-random number generator is bad, which results in random numbers in a certain pattern instead of numbers that approximate true randomness. Therefore, we built our pseudo-random number generator in Excel. We use the linear congruential generator described by (Tang, 2007) that calculates a random number as follows:

$Z_i = (a * Z_{i-1} + c) \bmod m$
Integer i is the iteration
Integer m is modulus
Integers a (multiplier) and c (increment)
Starting value Z_0 (seed value), $0 < Z_0 < m$

The random number is calculated by:
$u = \frac{Z_i}{m}$, where u is the random number

We choose m large. Excel cannot process too large numbers, so we use trial and error to determine the m, a, and c. This results in $m = 33{,}554{,}431$, $a = 25$ and $c = 150$.

To test the settings, we draw 100 random numbers. An overview of the numbers is depicted in Figure 7. We are confident that this is random enough for the simulation.

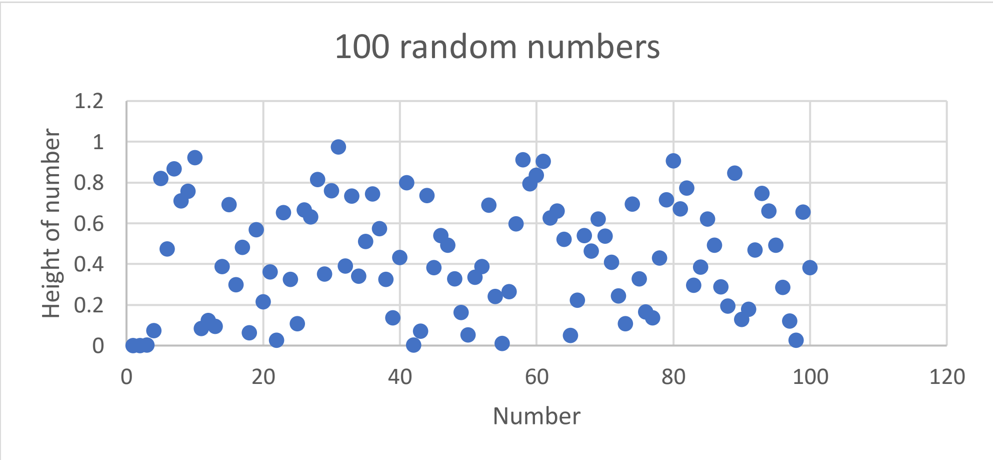

Figure 7: 100 random numbers

Model validation and verification

In this section we answer the second part of research question thirteen: "*How can the model be validated and verified?"*

The validation of the model will be done in Chapter 5, when we present and analyze the results of the models. In Chapter 5 one of the scenarios represents the current order policy of Hittech Multin. We will compare the results of the model with the historical data from the ERP system to check if the simulation accurately represents the real situation. We built the simulation using an incremental approach: we checked the correctness of every newly added step of the model. While programming, the values to be calculated were also recalculated by hand when possible.

The verification of the model is done in several steps. First, we discussed with the Planners and Purchasers what the current order policy of Hittech Multin is. Second, based on these discussions, we created a flowchart per order policy (which can be found in Appendix K) in which we show into detail every step that is taken in the simulation. The global logic per order policy is discussed in Section 4.4. Third, we implemented the logic into the simulation model. Finally, we discussed the logic and the outcomes of the model with the same planner to verify the decisions made in the model. When differences occurred in the approach of the planner and the model logic we determined if the planner made an exception for certain components or if the logic in the model was wrong. If the logic was wrong, we adjusted the model. If the planner made an exception for certain components, we kept the order logic that applied for most components and documented the differences in order approach.

4.3.2. Particle Swarm Optimization algorithm

Introduction of the PSO algorithm

We use the PSO algorithm to find the right reorder levels and order sizes of the components to make sure the percentage of complete orders in a simulation run meets the requirement. Further, the total costs should be minimized. The flowchart of the PSO algorithm can be found in Appendix I. In the rest of this section we will discuss some input parameters that need additional explanation.

Demand

The demand for each particle in each iteration is equal. We want to compare the output if we change the inputs but keep the rest of the situation the same. Therefore, we create one demand scenario for the PSO beforehand and use this for all particles and iterations. This results in reorder levels and order sizes that are tuned to one demand scenario. When inputting these values back into the simulation, the percentage of orders that started on time is often a bit lower than the required 98%. Therefore, we manually increase the reorder levels and order sizes of the components causing the component shortages until the required percentage orders on time is met. The simulation registers which components cause the delayed orders, so we know from which components we must increase the reorder levels and order sizes.

Number of particles

The number of particles is a trade-off between run length and the probability of finding the best solution. (Iwasaki, Yasuda, & Ueno, 2006) found that using about 20 particles results in good values. We will therefore also use 20 particles.

Number of iterations

The number of iterations is again a trade-off between the quality of the result and the run length of the algorithm. We experimented with the number of iterations by setting it to 100 and found for Article group 1 that after about 90 iterations the results did not improve anymore. Running such an experiment took us about 10 hours for this small article group. Therefore, we decide that it is not worth the time to search for better solutions with more iterations and we use 100 iterations as the standard for the Article group 1 experiments.

Inertial weight factor

As discussed in Chapter 3, a high inertial weight factor makes sure the PSO explores and a low inertial weight factor makes sure the PSO exploits. We start by exploring possible solutions first and exploit the found solutions in the end. Therefore, we start with an inertial weight factor of 0.99 and gradually decrease the factor as the number of iterations increases. This is done as follows:

$$Inertial\ weight\ factor\ (i+1) = Inertial\ weight\ factor(i) - \left(\frac{Start\ intertial\ weight\ factor}{Nr.Of\ Iterations}\right)$$

Cognitive and social weight factor

As discussed in Chapter 3, the ratio of cognitive/social weight factors determines how much a particle favours its own best-found solution or the global best found solution. In literature is suggested that the sum of the cognitive and social weight factor must be at least four (Barzegar & Seifbarghy, 2014). We favour the global best more than the local best and therefore set the cognitive weight factor to one and the social weight factor to three.

4.3.3. Model assumptions

The assumptions for the complete Simulation model are the following: (1) If components are delivered, the complete order is delivered simultaneously. In reality a delivery sometimes arrives in parts on different days to make sure no components are short during production. This is officially against company policy, so this does not occur in our simulation. (2) We assume that production orders only start when all components are available. In reality production orders sometimes start with shortages on some components. Hittech Multin has a goal that no production order starts while having shortages, so we only start complete production orders in the simulation. (3) We assume that each article has a flat BOM. In reality some BOMs contain components that are sub-assemblies, which are also produced by Hittech Multin. The production of such a sub-assembly is most often done right before the production of the end product. We consider this as part of the complete production of an end product and therefore do not make the situation unnecessarily complex for the simulation. (4) We assume that no repairs of products returned by the customer are done by Hittech Multin. In reality this is done and costs some of the components that are either in stock or need to be ordered again. This also means that the yearly demand for components, in reality, is a bit higher than in our simulation. (5) A part of the components, delivered by the suppliers, does not meet quality requirements, and can therefore not be used for production. However, in the simulation we assume that all components delivered meet the quality requirements, so this problem never occurs.

4.4. Scenarios

In this section we discuss the scenarios we test in the simulation and the sensitivity analysis we perform. We first discuss the KPIs we focus on during the experiments and then discuss the scenarios. All scenarios are run both for Article group 1 and Article group 2.

4.4.1. Key Performance Indicators

During the simulation we focus on eight KPIs, which are the following:

- Holding costs
- Order costs
- Purchase costs
- Total yearly costs (sum of the three above)
- Value of initial inventory. This is a one-time investment that must be made to get the components on the right inventory level.
- Average inventory value.
- Inventory throughput time: The height of the inventory measured in months.
- Percentage of production orders that start on time.

As discussed earlier, the goal of our research is to minimize the total costs while meeting a predefined percentage orders that start on time. The percentage on time production orders should not be lower than a rounded 98%. This means that 97.5% is still acceptable, but anything lower is not. We consider the percentage on time production orders a hard constraint which the solution must meet to be feasible. The inventory throughput time has a maximum of two months. As discussed, we consider this a soft constraint. We keep in mind the inventory throughput time, but the solution is not obligated to meet the two months.

4.4.2. Simulation scenarios

Scenario 1: Current order policy

In the first scenario we test the current order policy that is used by Hittech Multin. The flowchart of this order policy that describes in detail all the steps taken in the simulation can be found in Appendix K. Here we explain the logic of the order policy. In the current order policy, we have two kinds of components: the floorstock components and the regular components. Floorstock components are small components that may never be short and are therefore ordered in bulk the moment the inventory level position falls below a certain level. In reality there are no fixed rules for ordering floorstock components, only that these may never be short. Therefore, in the simulation we set the order size of a floorstock component to the expected yearly demand and we order when the inventory position falls below half the expected yearly demand. Regular components are ordered when demand occurs and there is not enough stock available to cover demand. Components are ordered on the planned production date minus the expected lead time and one-week safety lead time. The order size is equal to the demand unless the component has a MOQ. Then the MOQ is ordered. Production orders that lack one or more components are postponed to the next week. Then will be checked again if the components short have been delivered and production can begin.

As discussed earlier, the distribution of the lead times is the most uncertain input in our simulation. Therefore, we perform a sensitivity analysis on the uncertainty in the lead time. For each article group, we test the current policy six times. Each time the standard deviation of the lead time per component is decreased by 20% to reduce supply uncertainty. We start with a 100% standard deviation of the lead time, then 80%, 60%, 40%, 20% and we end with a 0% standard deviation of the lead time, so no uncertainty in lead times at all.

Scenario 2: All components ordered based on the inventory order policy

In the second scenario, we calculate the KPIs when all components are ordered with an inventory order policy. The flowchart of this order policy that describes in detail all the steps taken in the simulation can be found in Appendix K. Here, we explain the logic of this order policy and approach in the scenario. We start by calculating the reorder levels and order sizes of all components individually. We use the output of this model as input for the simulation. In the simulation, a component is ordered if its inventory position falls below the reorder point. The number of components ordered is equal to the order-up-to-level minus the inventory position, unless the MOQ of this component is larger. Then, the MOQ is ordered. Production orders that lack one or more components are postponed to the next week. Then will be checked again if the components short have been delivered and production can begin. When the simulation has been run, we have a certain percentage of orders that started on time and a certain total cost.

Subsequently, we use the PSO algorithm to determine what the reorder levels and order sizes should be for the components combined to meet the required percentage orders started on time. The PSO determines these values for one ten-year-long run.

Now, we want to know if the found values result in the required percentage orders on time. Therefore, we perform one complete simulation (four repetitions with three runs per repetition) with the reorder levels and order sizes found by the PSO as input. We check if the required percentage orders on time is met. If the percentage is not met, we manually increase the reorder levels of the components causing postponed production orders. Then we run a complete simulation again and check the percentage orders on time again. We repeat this until the percentage of complete production orders meets the required 98%. An overview of the approach can be found in Figure 8.

Again, we perform a sensitivity analysis on the uncertainty in the lead time similar to scenario 1. We start with a 100% standard deviation of the lead time and reduce the standard deviation of the lead time each time with 20% until we have no uncertainty in lead times at all. This means that we run six experiments for this scenario.

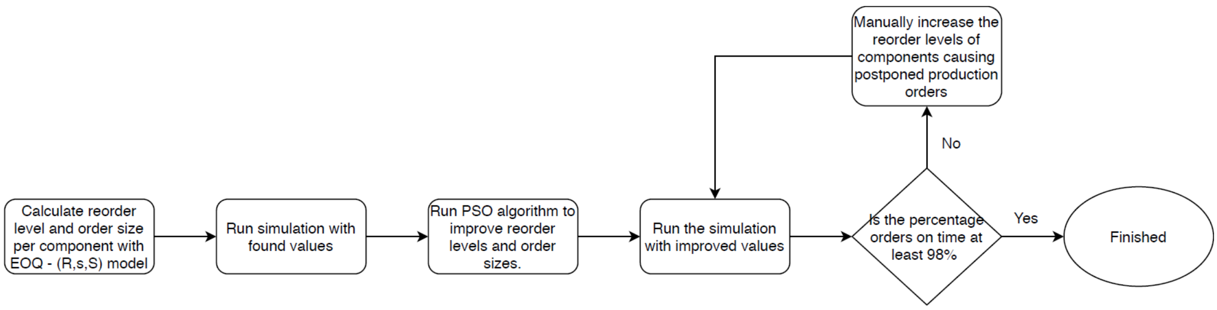

Figure 8: Approach scenario 2

Scenario 3: All components ordered with a safety lead time

In the third scenario we calculate the KPIs when all components are ordered with a safety lead time order policy. The flowchart of this order policy that describes in detail all the steps taken in the simulation can be found in Appendix K. Here we explain the logic of this order policy. All components are ordered with a safety lead time to make sure the required number of on-time orders is met. We discussed in Chapter 3 how we calculate the safety lead time for each component. We order a component on the production date minus the expected lead time minus the calculated safety lead time. The order size is equal to the demand unless the component has a MOQ. Then the MOQ is ordered. Production orders that lack one or more components are postponed to the next week. Then will be checked again if the components short have been delivered and production can begin.

Again, we perform a sensitivity analysis on the uncertainty in the lead time similar to scenario 1. We start with a 100% standard deviation of the lead time and reduce the standard deviation of the lead time each time with 20% until we have no uncertainty in lead times at all. This means that we run six experiments for this scenario.

Scenario 4: Combination inventory – safety lead time order policy

In the last scenario we test the combination of both order policies. The flowchart of this order policy that describes in detail all the steps taken in the simulation can be found in Appendix K. Here, we explain the logic of this order policy.

In this scenario, we determine a good combination of components ordered with either the inventory order policy or the safety lead time order policy. We use the Pareto principle again to determine which components should be ordered with which order policy. We determine what the 20% components are that account for 80% of the total average inventory value and account for 80% of the holding costs. The high-value components are ordered with the inventory order policy and the rest with a safety lead time order policy. Inventory components ordered in the same way as is done in scenario 2. The safety lead time components are ordered in the same way as is done in scenario 3. Production orders that lack one or more components are postponed to the next week. Then, there is another check if the components short have been delivered and production can begin.

Because we use the Pareto rule, several components around the 20th percentile belong just with the inventory components or the safety lead time components. These components around the breakpoint fall in the so-called “grey area”. These components might be better off with either a safety inventory or a safety lead time. Therefore, we run this scenario seven times for Article group 1. The first time, all the components in the grey area are assigned to the inventory order policy. Each iteration we add one of the uncertain components extra to the safety lead time components until all components to the safety lead time policy. Then, we can compare the possible combinations and compare the combined order policy to the other possible policies.

We choose one of the combinations and again perform a sensitivity analysis on the uncertainty in the lead time similar to scenario 1. We start with a 100% standard deviation of the lead time and reduce the standard deviation of the lead time each time with 20% until we have no uncertainty in lead times at all. This means that we run six experiments for this scenario.

4.5. Conclusions

In Section 4.1 we discussed that both the EOQ – (*R,s,S*) model and the Simulation model are created in Excel VBA to make sure Hittech Multin can keep using the model after the thesis assignment is completed. Furthermore, the models must be easy in usage and the interface of both models must be clear. Finally, both models must incorporate stochastic demand and lead times.

In Section 4.2 we discussed the parameters of the EOQ – (*R,s,S*) model. We discussed that the lead times of the components are the most uncertain input in our models. Due to too few delivery data points per component, we decided to group components from the same supplier with the same expected lead time when calculating the average lead time and standard deviation of the lead time. Further, we assume normally distributed demand to prevent the calculation from becoming too complex.

In Section 4.3, we discussed the parameters of both the simulation and the PSO algorithm. The normal approximation of demand is not accurate enough, so in the simulation we use an empirical distribution to determine the number of orders per week. The order size is drawn from a normal distribution. For the PSO, we create one demand scenario for all particles in all iterations and use this scenario to improve the output by changing the input values. The results of the PSO are used as input in the simulation model where we manually improve the values until the required percentage order on time is met. Finally, we determined the input parameters of the PSO algorithm either with the help of literature or by experimenting.

In Section 4.4, we discussed the four different scenarios we run in the simulation, which are the following: (1) the current order policy of Hittech Multin, (2) all components are ordered with an inventory order policy, (3) all components are ordered with a safety lead time and (4) a scenario in which one part of the components is ordered with an inventory order policy and the rest is ordered with a safety lead time. Previously, we determined that the supply performance is the most uncertain input in the model. Therefore, we perform a sensitivity analysis on the lead time uncertainty in each scenario.

5. Results and analysis

In this chapter we present and analyze the results. We start with Article group 1. Then discuss changes we made in the experimental design for Article group 2 based on the experiences of the Article group 1 experiments. Finally, we present and analyze the results of Article group 2. For each article group, we validate the model by comparing the simulation results with reality and discuss the differences.

5.1. Article group 1

5.1.1. Model validation

In scenario 1 we attempt to model the current order policy. In Table 4 an overview of the results is presented. The overview contains the results of the simulated current order policy, the combined order policy, and reality, which we calculated with historical data from the ERP system. The data we used and the calculations we made can be found in Appendix L.

Table 4: Simulation results vs reality Article group 1

	Holding costs	Order costs	Purchase costs	Total costs	Average inventory value	Percentage orders late	Inventory throughput time (months)
Current order policy	€ 8,300	€ 4,500	€ 154,000	€ 166,800	€ 34,600	19.1%	1.52
Combined order policy	€ 22,300	€ 3,000	€ 142,300	€ 167,600	€ 61,900	2.0%	3.73
Reality	€ 8,700	€4,800	€179,200	€ 192,700	€36,100	45.0%	0.92

As can be seen in the table, the results of the current order policy and reality do not match. There are two main reasons why the results differ. First, as input for the simulation we used the historical data from the former ERP system. Hittech Multin switched from ERP system at the beginning of November. It turns out that the historical data of the months November and December were not up to date in the former ERP system. This means that the demand in those two months is higher than our historical data shows. Our simulation, therefore, on average underestimates the demand with eight customer orders per year for Article group 1. In addition, one of these orders was much larger than the average order. Second, it turns out that this article group is ordered differently by this planner than is usual. The customer of this article group orders for two years ahead and the demand is very stable. Therefore, the planner knows with more certainty what the demand will be and does not want to run the risk of being leftover with components that cannot be sold anymore in the end. To benefit from quantity discounts, this planner orders for this article group in large amounts instead of only the amount that is needed for production. The order policy that is used for this article group approximates the combined order policy we tested in scenario 4. Still the results of the combined order policy and reality do also not completely match. In Appendix L we elaborate per KPI where the differences come from between reality and our simulation.

For now, we can conclude that, for this article group, the results do not match. We can therefore not implement the results of the model one-on-one in reality. Although the results do not match reality, we can compare the results of the different order policies. All scenarios have the same input data and programmed circumstance. Therefore, we can compare which order policies work best and what the impact of the lead time uncertainty is.

5.1.2. Scenario results Article group 1

In Table 5 we present an overview of the results of the four scenarios we simulated. For the fourth scenario (combined order policy), we present the results of one of the seven different combinations we tested. The results of the different divisions do not differ that much and adding all seven to the table would unnecessarily complicate the table. A complete overview of the results of all experiments can be found in Appendix M. In the combined order policy, the first number is the number of components ordered with an inventory order policy, and the second number the number of components ordered with the safety lead time order policy.

Table 5: Scenario results Article group 1

Order policy	**Holding costs**	**Order costs**	**Purchase costs**	**Total costs**
Current	€ 8,300	€ 4,500	€ 154,200	€ 167,000
Inventory	€ 37,100	€ 1,400	€ 138,300	€ 176,800
Safety LT	€ 8,200	€ 6,500	€ 154,000	€ 168,700
Combined (52 - 15 division)	€ 14,900	€ 3,000	€ 142,300	€ 160,200
Order policy	**Start value inventory**	**Average inventory value**	**Inventory throughput time (months)**	**Percentage orders late**
Current	€0	€ 34,600	1.52	19.1%
Inventory	€ 185,000	€ 154,700	9.76	2.1%
Safety LT	€0	€ 34,100	1.99	1.1%
Combined (52 - 15 division)	€ 37,000	€ 61,900	3.73	2.0%

We see that all order policies, except the current order policy, have a percentage of late orders of at most 2%. We briefly discuss the results of the KPIs that stand out, then determine which order policy Hittech Multin can best use and end with a discussion on the sensitivity analyses.

Average inventory value and holding costs

What stands out are the average inventory value and holding cost of the current order policy and the safety lead time order policy. An important argument of Hittech Multin to use a fixed one-week safety lead time instead of a longer safety lead time calculated with historical data is the fear of high inventories. As we see in Table 5, the differences in average inventory value and holding costs between the two order policies are small. This is caused by the high percentage of orders late in the current order policy. Because many production orders are delayed due to missing components, the present components stay in inventory for longer than one week. In the end the components are about as long in inventory as with a safety lead time order policy, but the percentage of orders late is much higher.

Inventory throughput time

The inventory throughput time of the current order policy is lower than that of the safety lead time order policy, although the average inventory and holding costs are similar. This is mainly caused by delayed customer orders. The throughput time of the inventory at a certain point in time is calculated by the inventory value divided by the expected turnover for the next month. When customer orders are delayed due to missing components, the orders are moved to the following week. Postponed customer orders are accumulated and the expected turnover for the next month increases. Therefore, it is better in our situation to compare the average inventory value instead of the throughput time of the inventory.

Comparison of order policies

When comparing the results in Table 5, we start by excluding the current order policy as a feasible solution. Although the total costs belong to the lowest and the throughput time of the inventory is below the required two months, the percentage orders late is far above the required 2%.

Next, we exclude the inventory order policy from potential best policies. Although the percentage of late orders meets the required 2%, the total costs and throughput time of the inventory are both too high. As expected, a few expensive components are responsible for the high average inventory value and holding costs. This means that we are left with the combined order policy and the safety lead time order policy.

The combined order policy has the lowest total costs and meets the requirement on percentage orders late. The expected throughput time of the inventory is higher than two months. This was a soft constraint, but it is almost twice as high as the two months that are allowed by Hittech Multin. One advantage of this policy is the low purchase costs. Currently, Hittech Multin does not focus on holding and order costs and only focuses on keeping the height of the inventory acceptable. When comparing the combined order policy and the safety lead time policy based on the purchase costs, the combined order policy would be the best option. However, in this research we focus on the total costs, but it is for Hittech Multin to decide if the purchase costs should be valued more or equal to the other costs. In our research the combined order policy can be considered as the second-best option, because of the high inventory throughput time.

The best order policy for Article group 1 is the safety lead time order in our opinion. This order policy meets all the requirements set by Hittech Multin. The total costs are low, the throughput time of the inventory is just below the two months and the percentage orders late is below the required 2%.

Sensitivity analysis

For each of the scenarios we performed a sensitivity analysis on the lead time uncertainty. All the results of the sensitivity analyses can be found in Appendix M. Here, we focus on the sensitivity analyses of the current order policy and safety lead time policy. In Table 6Table 9Figure 6Table 10 we present an overview of the sensitivity analysis of the current order policy. The purchase costs do not change when the lead time uncertainty changes, because the demand remains the same. These are therefore excluded from the tables. In Table 7Table 10: Sensitivity analysis current order policyTable 11 we present an overview of the sensitivity of the safety lead time order policy.

Table 6: Sensitivity analysis current order policy

Lead time uncertainty	Holding costs	Order costs	Total costs	Average inventory value	Percentage orders late	Inventory throughput time (months)
100%	€ 8,300	€ 4,500	€ 12,800	€ 34,600	19.1%	1.52
80%	€ 8,300	€ 4,500	€ 12,800	€ 34,700	13.0%	1.63
60%	€ 7,900	€ 4,500	€ 12,400	€ 33,000	5.4%	1.94
40%	€ 7,800	€ 4,500	€ 12,300	€ 32,400	1.4%	2.06
20%	€ 7,800	€ 4,500	€ 12,300	€ 32,400	0.3%	2.06
0%	€ 7,900	€ 4,500	€ 12,400	€ 33,100	0.0%	2.06

Table 7: Sensitivity analysis safety lead time order policy

Lead time uncertainty	Holding costs	Order costs	Total costs	Average inventory value	Percentage orders late	Inventory throughput time (months)
100%	€ 8,200	€ 6,500	€ 14,700	€ 34,100	1.1%	1.99
80%	€ 7,600	€ 6,600	€ 14,200	€ 31,600	1.8%	1.85
60%	€ 7,100	€ 6,500	€ 13,600	€ 29,300	1.5%	1.75
40%	€ 6,800	€ 6,600	€ 13,400	€ 28,400	1.2%	1.69
20%	€ 6,200	€ 6,600	€ 12,800	€ 25,600	1.4%	1.59
0%	€ 6,200	€ 6,600	€ 12,800	€ 25,800	0.0%	1.63

As discussed above, an important reason for Hittech Multin to use the fixed one-week lead time over safety lead time is the fear of high inventories. We already showed that, due to the high percentage orders late of the current order policy, the average inventories and the holding costs of both order policies are similar. Here, we discuss what happens if the uncertainty in the lead times decreases. In Chapter 3, we showed that the safety lead time is calculated by $z * \sigma_L$, where z is the safety factor determined based on the normal distribution and σ_L is the standard deviation of the lead time and is calculated with historical data.

When comparing both tables, we see that the average inventory value and holding costs of the safety lead time order policy are lower than those of the current order policy. As the lead time uncertainty decreases, the gap between both order policies increases in the advantage of the safety lead time order policy. The reason is that when the lead time uncertainty decreases, the components more often arrive according to the expectation. The components lie in the current order policy most of the time around one week in inventory in that situation. The length of the safety lead time is dependent on the uncertainty in the lead time, so when the uncertainty decreases, the safety lead time will also decrease. The components arrive more often according to expectation and will lie less than one week on inventory. This results in a lower average inventory value, lower holding costs, and lower inventory throughput time for the safety lead time order policy. We can thus conclude that regardless of the lead time uncertainty, the safety lead time order policy performs better than the order policy with a fixed one-week safety lead time.

5.2. Adjustments in experimental design

The large experiments for Article group 1 took about 12 hours per experiment. Article group 1 "only" contains 67 components, while Article group 2 contains 365 components. Performing the same experiments would take too long for Article group 2. Therefore, we adjust the experiments to reduce the calculation time of the simulation, while still gaining reliable outcomes. The adjustments we make are the following:

- Article group 2 consists of 115 floorstock components. In Article group 1 the floorstock articles only accumulate for a small part of the total costs and these components are never the reason a production order starts late. To simplify the experiments, we will leave the floorstock articles out of the simulation for Article group 2. Instead, we manually calculate the average costs on yearly basis. In this way, the simulation must perform fewer calculations, while the result remains similar.
- The number of repetitions is reduced to 3 and the number of runs is reduced to 2. This results in less precise outcomes. The relative error is still 2% and the confidence interval is still 95%. The run length is again 10 years. This means that we test 60 years instead of 120 years per scenario as for Article group 1. The calculations for the number of replications can be found in Appendix J. s
- We use 60 iterations instead of 100 in the PSO. This means that fewer possible solutions are explored. Further, this means that the inertial weight factor decreases faster, so the model does less exploration and goes faster to exploitation.
- When running the PSO algorithm we only change the reorder levels and leave the order sizes as calculated by the EOQ model. This reduces the number of possible solutions, so simplifies the situation for the PSO algorithm.
- During the sensitivity analysis of the safety lead time order policy we determine the safety factor less precise than for the Article group 1 components. For Article group 1 we reduced the safety factor with small steps and each step we had to perform a ten-year simulation run. The difference in outcome between a safety factor of, for example, 2.20 and a safety factor of 2.15 is small, but it takes a lot of time to test all possible safety factors. Therefore, we reduce the safety factor in larger steps to find a feasible, but slightly less precise solution for Article group 2.

5.3. Article group 2

5.3.1. Model validation

In scenario 1 we attempt to model the current order policy. In chapters 2 and 4 we discussed how this order policy works. Here we compare the results of our simulation with historical data from the ERP system. The elaborations on all calculated values can be found in Appendix L. Here, we briefly discuss what the differences are between the simulation and reality and where these differences come from. Important to note is that we excluded the floorstock components in our simulation to make the simulation less complex. The floorstock items are included in historical data. Therefore, we estimated the values of the floorstock to fill the gap between the simulation data and reality. An overview of the simulation results, the expected floorstock values, and actual numbers can be found in Table 8.

Table 8: Simulation results vs reality Article group 2

	Holding costs	Order costs	Purchase costs	Total costs	Average inventory value	Percentage orders late	Inventory throughput time (months)
Simulation	€ 110,000	€ 86,000	€ 3,156,000	€ 3,352,000	€ 457,000	89%	0.30
Floorstock	€ 7,000	€ 4,000	€ 30,000	€41,000	€30,000	0%	0.03
Reality	€ 167,000	€ 70,000	€ 3,501,000	€ 3,738,000	€ 696,000	74%	3.40

As can be seen in the table, the model results and reality do not completely match. There are three main reasons why the simulation results and the reality do not match. First, as input for the simulation we used the historical data from the former ERP system. Hittech Multin switched from ERP system at the beginning of November. It turns out that the historical data from the months November and December were not up to date. This means that the demand in those two months is higher than our historical data shows. Our simulation model on average underestimates the demand with 15 customer orders per year for Article group 2. Second, Hittech Multin wanted to make sure they would not lack too many components when problems during the implementation of the new ERP system. Therefore, they made sure an extra inventory was present. Such an extra buffer is not common in the order policy of Hittech Multin, so is therefore not present in the simulation model data. Thirdly, many components of Article group 2 have a longer supply lead time than the production lead time of the end product. Therefore, Hittech Multin orders components based on forecasts. Over the year the demand of one customer (cannot be named due to confidentiality) dropped dramatically for a few months. The forecasts were much higher and therefore large amounts were already ordered for many components. These orders could not be cancelled, which resulted in large inventories for Hittech Multin. In Appendix L we discuss in detail where all the differences come from per KPI.

For now, we can conclude that the simulation results and reality currently do not match for several reasons described above. We can therefore not implement the results of the model one-on-one in reality. Although the results do not match reality, we can compare the results of the different order policies. All scenarios have the same input data, so we can compare which order policies work best and what the impact of the lead time uncertainty is.

5.3.2. Scenario results Article group 2

In Table 9, we provide a complete overview of the results of the four scenarios we simulated. For the fourth scenario (combined order policy) we present the results of one of the five different combinations we tested. A complete overview of the results of all experiments can be found in Appendix M. In the combined order policy, the first number is the number of components ordered with an inventory order policy, and the second number of components ordered with the safety lead time order policy.

Table 9: Scenario results Article group 2

Order policy	Holding costs	Order costs	Purchase costs	Total costs
Current	€ 110,000	€ 86,000	€ 3,156,000	€ 3,352,000
Inventory	€ 315,000	€ 31,000	€ 3,070,000	€ 3,416,000
Safety lead time	€ 114,000	€ 86,000	€ 3,156,000	€ 3,356,000
Combined (206 – 44 division)	€ 158,000	€ 44,000	€ 3,070,000	€ 3,272,000
Order policy	**Start value inventory**	**Average inventory value**	**Inventory throughput time (months)**	**Percentage orders late**
Current		€ 457,000	0.30	89.1%
Inventory	€ 1,846,000	€ 1,312,000	3.79	2.1%
Safety lead time		€ 473,000	1.25	0.1%
Combined (206 – 42 division)	€ 403,000	€ 656,000	1.81	1.8%

What stands out is that, except for the current order policy, all order polices have a percentage orders late that meet the required maximum of 2%. We briefly discuss the results of the KPIs that stand out, then determine which order policy Hittech Multin can best be used and end with a discussion on the sensitivity analyses.

Average inventory value and holding costs

What stands out is that the difference in holding cost between the current order policy and the safety lead time policy is only €4,000. We would expect an order policy with a fixed lead time of one week to have significantly lower holding costs than an order policy with longer safety lead times. The reason for this small difference is in the percentage orders late. In safety lead time policy, the percentage order starting late is low, while in the current order policy this percentage is high. This means that most components are longer in stock than the planned one week, because one or multiple components are missing. The components in stock for so long that the total holding costs are only slightly lower than for the safety lead time policy. We also saw this in the results of Article group 1. The high percentage orders late also cause low inventory throughput time, because the expected turnover increases a lot due to delayed production orders. Again, this is the same as for Article group 1.

Purchase costs

In the purchase costs something unexpected occurs. As expected, the current and safety lead time order policies have the highest purchase costs. These policies do not use quantity discounts unless these are incorporated in the MOQs. We would expect the purchase costs of the inventory order policy to be the lowest of all, but the combined order policy results in the lowest purchase costs. The reason is as follows. About 40 components are ordered with a safety lead time instead of a safety inventory. When these components do not have quantity discounts or an MOQ so high that the components are automatically bought for the lowest price, the price per unit is equal for both order policies. When ordering with a safety inventory policy, always the EOQ is ordered, which is larger than the demand. The total amount bought in this order policy is larger than needed and thus more purchase costs are incurred than necessary. This results in a total purchase costs for the inventory order policy that exceed the total purchase costs of the combined order policy.

Comparison of order policies

In Chapter 2, we discussed that the objective is to create a decision-method to make sure that in 98% of the production orders all components are present, while the total costs are minimized. The extra (soft) constraint was that the throughput time of the inventory may not exceed two months. If we look at the result in Table 9, we see that all order policies, except the current policy, meet the required 98%. Therefore, we exclude the current order policy as an acceptable solution and we are left with the safety lead time, inventory, and combined order policies.

Of those three order policies, we can exclude the inventory order policy next. First, because the total costs are higher than for the other two polices. Second, and most importantly, the throughput time of the inventory is far too high. We discussed that the two months throughput time is a soft constraint, which we would be willing to violate if the costs could be significantly reduced. However, a throughput time that is almost twice as high as allowed is not an acceptable solution. Therefore, we are left with the safety lead time and combined order policies. We briefly discuss the benefits and drawbacks of both policies and then discuss which order policy we prefer.

We start with the safety lead time policy, which has the second-lowest costs of the four scenarios. This order policy has multiple advantages. First, a major advantage of this order policy is the low throughput time of the inventory. Even if extra components, needed for repair, are included in the inventory, the throughput time can be held below the desired two months. Second, this policy means only one way of ordering for all components, so it is quite easy to implement and use. Thirdly, it is quite like the way Hittech Multin currently orders the components, only with longer safety lead times. Therefore, implementing this order policy means a small change in the way of working for the planners. This order policy has also some drawbacks. First, the delivery of all components is critical. The planner must focus on all components, cheap or expensive, because one component delivered too late means that the production order will start late. Second, many orders must be placed each year. All components, cheap or expensive, are ordered in the amount needed. All these extra orders cost time of the planner that could be used for a different cause and all these extra orders run the risk of being delivered late.

Now, we turn to the combined order policy. We start with the advantages. First, it is the cheapest of the order policies. Second, far fewer orders must be placed compared to the safety lead time order policy. This means fewer orders in which mistakes can be made. Third, we can focus more on the important suppliers that supply the expensive components. Because the planners must place fewer orders, more time and energy is available for improving the supplier performance. This order policy also has some drawbacks. First, the inventory throughput time is near the two months. In the simulation, the extra components used for repairs are not considered. When using this policy, the probability of exceeding the two months is higher than for the safety lead time policy. Second, we use two different order policies for the components in one article group. This is more complicated in the beginning for the planners because this asks for a different way of working than they are used to. Thirdly, an initial investment is needed for this policy to bring the inventory levels to the right heights. However, currently extra inventory is present because of the switch to the new ERP system. This reduces the height of the initial investment. As expected, the components with high prices contribute most to the high holding costs and high start inventory value and must therefore be ordered with a safety lead time. The cheap components or components with low demand, so low safety inventory, are ordered with the inventory order policy.

Overall, we would recommend using the combined policy. This policy has the lowest yearly costs and meets the requirements on the percentage orders late and throughput time of the inventory. In addition, the advantage of having to place fewer orders and thus extra time left for improvement activities is a great benefit of this order policy.

Sensitivity analysis

For each of the scenarios we performed a sensitivity analysis on the lead time uncertainty. All the results of the sensitivity analyses can be found in Appendix M. Here, we focus on the sensitivity analyses of the current order policy and safety lead time policy. In Table 10, an overview of the sensitivity analysis of the current order policy is presented. In Table 11, an overview of the sensitivity of the safety lead time order policy is presented. The purchase costs remain the same for each level of lead time uncertainty because demand remains the same. Therefore, these costs are excluded from the tables.

Table 10: Sensitivity analysis current order policy

Lead time uncertainty	Holding costs	Order costs	Total costs	Average inventory value	Percentage orders late	Inventory throughput time (months)
100%	€ 110,000	€ 86,000	€ 196,000	€ 457,000	89.1%	0.30
80%	€ 94,000	€ 86,000	€ 180,000	€ 391,000	75.0%	0.38
60%	€ 84,000	€ 86,000	€ 170,000	€ 349,000	55.3%	0.49
40%	€ 74,000	€ 86,000	€ 160,000	€ 309,000	23.2%	0.64
20%	€ 70,000	€ 86,000	€ 156,000	€ 293,000	1.2%	0.74
0%	€ 70,000	€ 86,000	€ 156,000	€ 292,000	0	0.75

Table 11: Sensitivity analysis safety lead time order policy

Lead time uncertainty	Holding costs	Order costs	Total costs	Average inventory value	Percentage orders late	Inventory throughput time (months)
100%	€ 114,000	€ 86,000	€ 200,000	€ 473,000	0.1%	1.25
80%	€ 95,000	€ 86,000	€ 181,000	€ 395,000	1.0%	1.08
60%	€ 87,000	€ 86,000	€ 173,000	€ 364,000	2.5%	0.98
40%	€ 74,000	€ 86,000	€ 160,000	€ 309,000	0.7%	0.86
20%	€ 59,000	€ 86,000	€ 145,000	€ 247,000	0.2%	0.71
0%	€ 56,000	€ 86,000	€142,000	€ 233,000	0.0%	0.66

The main reason for Hittech Multin to use a fixed one-week safety lead time instead of a safety lead time based on historical data is the fear of high inventories. With the sensitivity analysis, we will show that our safety lead time model performs equal or better than the current order policy, especially when the lead time uncertainty decreases. In Chapter 3, we showed that the safety lead time is calculated by $z * \sigma_L$. Here, z is the safety factor and is determined with the normal distribution and σ_L is the standard deviation of the lead time and is calculated with historical data.

When looking at Table 10 and Table 11, we see that for the 100% lead time uncertainty case, the holding costs of both order policies only differ by €4,000. This, while the percentage orders late of the current order policy is 89% and of the safety lead time policy is 0.1%. When we reduce the lead time uncertainty, we see that the performance of the holding costs and average inventory value of both policies remain similar until 40% lead time uncertainty. From that moment the safety lead time order policy not only performs better on percentage orders late, but also on holding costs and average inventory value. The reason for this is in the calculation of the safety lead time, as was also the case for Article group 1. When lead time uncertainty decreases both the safety factor and the standard deviation of the lead time decrease until the safety lead time is zero. In the current order policy, we work with a fixed one-week safety lead time. This means that, when we have no lead time uncertainty at all, all components stay in inventory one week for the current order policy. For the safety lead time order policy this is zero weeks when there is no uncertainty in lead time. On average this results in higher holding costs and average inventory value for the current order policy. In our simulation, the tipping point is reached around 40% lead time uncertainty. This means that the safety lead time order policy performs equal or better than the current order policy, regardless of the lead time uncertainty.

5.4. Conclusions

In Section 5.1 we presented the results of the different order policies for Article group 1. First, during the model validation we concluded that the model results did not match reality for several reasons. Implementing the model results one-on-one into reality is therefore not yet possible. The different order policies can be compared however in the simulation because the input data are similar. Second, we concluded that the safety lead time order policy can best be used by Hittech Multin for this article group. The percentage of late orders is reduced from 19.1% to 1.1%, while total costs only increase from €167,000 to €168,700. The inventory throughput time meets with 1.99 the required 2 months. The combined order policy is the second-best option. Here, the percentage of late orders is 2.0% and the total costs are €167,700. The inventory throughput time is 3.73 months however, so this is not the best option. Based on holding costs of each component and with the help of the Pareto principle, we determined which components were ordered with a safety inventory and which with a safety lead time. Third, we concluded that regardless of the supply uncertainty the safety lead time order policy performs equal or better than the current order policy. Regardless of the supply uncertainty, the costs of the safety lead time policy are similar or lower than those of the current order policy. The percentage orders late of the safety lead time order policy always meet the required 2%. This percentage for the current order policy only meets the requirement when supply uncertainty is 40% or lower.

In Section 5.2, we concluded that running the Article group 2 experiments in the same experimental setting as for Article group 1 will take too long due to a large number of components. Therefore, we discussed all the adjustments we make in the experimental design for Article group 2.

In Section 5.3 we presented the results of the different order policies for Article group 2. First, during the model validation we concluded that the model results did not match reality for several reasons. Implementing the model results one-on-one into reality is therefore not yet possible. The different order policies can be compared however in the simulation because the input data are similar. Second, we concluded that the combined order policy can best be used by Hittech Multin for this article group. The percentage of late orders is reduced from 89.1% to 1.8%, while the total costs are reduced from €3,352,000 to €3,272,000. The inventory throughput time remains below the required two months. Again, we determined with the holding costs and Pareto principle, which components should be ordered with a safety inventory and which with a safety lead time. The safety lead time order policy is the second-best option. Here, the percentage order late is 0.1% and the total costs are €3,356,000. Third, we concluded that regardless of the supply uncertainty the safety lead time order policy performs equal or better than the current order policy.

6. Implementation plan

After this thesis assignment, we want the decision-making model to be implemented in reality. Therefore, we draft an implementation plan for a pilot to determine what needs to be done to successfully implement the results of our thesis assignment. We discuss the activities for the technical implementation, but also what change management is necessary to make the implementation a success. Finally, we discuss what specifically can be done to improve the supplier performances by improving supplier relationships and how the quality of the historical lead time data can be improved. Although, it is not completely certain the project will be implemented, we draw the implementation plan up as if it was the preparatory phase of the implementation.

6.1. Project definition

As described in this thesis assignment, many production orders are delayed due to missing components on the planned production date. In the thesis, we created a decision-making tool to ensure that the percentage of complete production orders is 98%. Unfortunately, we were not able to thoroughly validate and verify the model due to various reasons. Therefore, our primary focus in the implementation is to validate and verify the decision-making model.

The objective of the implementation of the pilot is therefore as follows: “Implement the decision-making model for a certain article group and monitor during four months if the results in reality are similar to the results in the decision-making model.”

We also define three sub-objectives to ensure that the main objective is reached without violating the constraints we formulated during the thesis assignment. The sub-objectives are the following:

- The percentage complete production order of the chosen article group must meet the required 98%.
- The average inventory throughput time may not exceed a predefined number of months. The number of months is dependent on the chosen article group.
- The supply uncertainty of the three most important suppliers of the chosen article group should be reduced by 20% by the end of the year.

6.2. Project scope

The implementation pilot will consist of two phases.

Phase one is the pilot phase. In this phase we choose one article group for which we implement the model and order policies. The article group should contain a limited number of components, so that we must deal with a limited number of suppliers. However, there should be enough improvement potential for this article group. Because the article group is small, we can implement the project with a small group of motivated project members. Further, we choose three large suppliers for which we try to improve the supply performances. Important is that the suppliers are enthusiastic about the project and are willing to cooperate. We would not recommend using one of the two article groups we used in our thesis. Article group 1 is ordered differently from the rest of the article groups. When we choose this article group it would not be a representative pilot for the other article groups. Article group 2 is a large article group, which would cause too many problems for a pilot. We recommend discussing with the supply chain manager which article group meets the characteristics of our ideal article group and choose that article group for the pilot.

Only when the implementation of the pilot is finished successfully, we start with phase two. In phase two, we expand on the number of article groups for which we use the model and new order policies. Based on the experiences in phase 1, we adjust the implementation plan. We add one article group at the time until all article groups are included.

6.3. Project organisation

For the implementation of the project, we have the following project team:

- Project owner: the project owner is the person assigning the project. He is responsible for approving the budget, project objectives, planning, and composition of the project group.
- Project leader: the project leader has the responsibility to make sure that the implementation follows the planning and stays within budget. Further, he is responsible for the quality of the project results. Finally, he has the responsibility to make sure that all team members can perform their assigned tasks. He helps team members when they encounter problems.
- Project team members. The project team consists of at least of the following persons:
  - A purchaser: the purchaser is responsible for the agreements with the most important suppliers. His main responsibility is to improve the reliability of the supplier's performance.
  - A planner: the planner is responsible for executing the new order policy.
  - ERP/IT team member: this person is responsible for providing all the historical and real-time data we need out of the ERP system. The available data should be as accurate as possible.

During the implementation pilot we have a couple of stakeholders that should be considered and be informed. Without the consensus and cooperation of these stakeholders the pilot cannot become a success. The stakeholders of the project are the following:

- Direction of Hittech Multin
- Project owner
- Purchasing
- Planning
- ICT department
- Finance department
- The person responsible for the ERP system
- The suppliers

6.4. Approach and planning

In Table 12 we provide the terms used in the Work Breakdown Structure (WBS). In Table 13, we provide a rough planning of the implementation pilot. In Table 14, we provided the expected number of days needed for the implementation pilot per function.

Table 12: Work Breakdown Structure

Work Breakdown Structure	
Project Phase	**Phase**
P	Preparation
C	Mapping current status
M	Model finalization and meet with suppliers
I	Implementation
E	Evaluation
G	General

Table 13: Planning implementation project

Planning implementation pilot					
WBS	Phase	Activity	Responsible	Working days	Week
P1	Preparation	Set-up meeting for the preparation of the implementation.	Project leader	2	1
P2		Project set-up meeting	Project members (5 x 0,5 day)	2,5	1
P3		Create a Project Initiation Document (PID) including a detailed project planning	Project leader	4	1/2
P4		Review + Approve PID	Project owner	1	2
G1		Project management + communication + change management (1 day/week)	Project leader	2	1/2
C1	Mapping current status	Map the current status of the objectives	Project leader	3	3/4/5
C1		Map the current status of the objectives	ERP/IT person	1,5	3/4/5
C2		Gather input data	Project leader	3	3/4/5
C2		Help gather input data	ERP/IT person	1,5	3/4/5
C3		Complement missing input data	Project leader	1	3/4/5
C3		Help complement missing input data	Planner	1	3/4/5
C4		Define the three most important suppliers	Project leader	0,5	3/4/5
C4		Define the three most important suppliers	Purchaser	0,5	3/4/5
C5		Define new agreements with suppliers	Project leader	1,5	3/4/5
C5		Define new agreements with suppliers	Purchaser	1	3/4/5
G1		Project management + communication + change management (1 day/week)	Project leader	3	3/4/5
M1	Model finalization and meet with suppliers	Solve last mistakes and make model ready to use during the pilot project	Project leader	10	6/7/8
M1		Solve last mistakes and make model ready to use during the pilot project	ERP/IT person	2	6/7/8
M2		Prepare and meet with suppliers to adjust agreements	Project leader	4	7/8
M2		Prepare and meet with suppliers to adjust agreements	Purchaser	4	7/8
G1		Project management + communication + change management (1 day/week)	Project leader	3	6/7/8
I1	Implemen-tation	Determine which components to order with which order policy	Project leader	2	9
I2		Determine reorder level, order-up-to-level, order moment and order size	Project leader	1	9
I3		Implement and use new order policy (0,5 day/week)	Project leader	2	9/11/13/15
I3		Implement and use new order policy (0,5 day/week)	Planner	2	9/11/13/15
I4		Monitor results (1 day/week)	Project leader	4	9/11/13/15

I5		Monitor supplier performance (0,5 day/week)	Project leader	2	9/11/13/15
I5		Monitor supplier performance (0,5 day/week)	Purchaser	2	9/11/13/15
G1		Project management + communication + change management (1 day/week)	Project leader	4	9/11/13/15
E1	Evaluation	Evaluation meeting	Project members (5 x 0,5 day/week)	10	9/11/13/15

Table 14: Nr. of days implementation pilot

Nr. Of days for implementation pilot	
Function	**Days**
Project owner	3,5
Project leader	55
ERP/IT person	8
Purchaser	10
Planning	5,5
Total	82

6.5. Project risks

During the implementation and after implementation, we run certain risks. During the preparation, we will do a risk analysis with the complete project group to make sure everyone is aware of the problems that can occur. Here, we already name some of the project risks and what we can do to prevent or mitigate them.

The risks that occur during the implementation are the following:

- Unmotivated group project members fall back into the old behaviour. How we deal with this risk will be explained in section 6.7, where we discuss change management.
- Delays in the project. Before the start of the project we will do a risk analysis to discuss possible problems that can occur during implementation. We will include these in the planning and make sure we plan in enough slack to make sure the project is not delayed.
- The suppliers are not motivated to adjust their way of working. We try to prevent this by only selecting the suppliers with which Hittech Multin already has a good long-term relationship. For the unmotivated suppliers we build in extra safety lead time or safety stock to cover for the uncertainty in supply.
- Historical data is not available in the new ERP system. We try to prevent this by mapping out beforehand what data we need and what data is available in the ERP system. If we lack data in the new ERP system, we use the historical data from the former ERP system and make sure we can measure the desired data with the new ERP system.
- Data conversion from the old ERP system is not done correctly. All kinds of data are conversed into the new ERP system, like supplier numbers or article numbers. Data conversion will be done with the conversion tables at first. Together with the responsible planner we will manually check if all the data is conversed right to make sure no mistakes in conversion are made.
- Project members have less time for the project than thought of. We try to prevent this by making a good planning beforehand where we estimate the time each task will take, so everyone knows how much time the project will take. Further, we will plan enough slack for activities.

The risks that occur after the implementation are the following:

- The risk of blindly accepting the output of the model. Although the model reflects reality, multiple assumptions are made. Furthermore, the quality of the input data (historical data) is dependent on the quality of data measuring and certain assumptions. The output data of the model should always be reflected on by someone who knows the end product to make sure no mistakes are made.
- Wrong interpretation of output data. The output of the simulation model is, among others, the safety lead time and reorder level. Before inputting these into the ERP system we need to make sure that the definitions of the output data of the simulation are the same as the input data for the ERP system. For example, we order an inventory component when the inventory position is below the reorder level. We need to make sure the definition of inventory position of the ERP system is equal to the definition of inventory position of the simulation. Otherwise, Hittech Multin still orders at the wrong moment.
- People fall back in the old behaviour. We need to make sure that the planners fully understand what the new order method yields for the company. This risk will be discussed in section 6.7.
- History is not a perfect predictor for the future. The planners should also consider the forecasts of the customers to adjust the expected demand for the simulation. If the planners just assume that the historical data is equal to the future demand, we can still end of with bad results. It is therefore important that the planners are made aware of this during the implementation pilot.

6.6. Communication

During the project we, as a project group, have to communicate with all the other stakeholders. With the project group we will meet once every two weeks to discuss the progress of the project and potential problems. At the beginning of the project, we make an elaborate list of stakeholders. Then, we also discuss how often we inform every stakeholder.

6.7. Change management

Implementing the model does not only mean using an extra tool, but also a different way of working. What we often see is that everyone wants change, but nobody wants to change. Therefore, we discuss in this section what change management we will do during the implementation of the project. We use the 8 steps of Kotter (Kotter, 1997) for this.

1. Create a sense of urgency

The first step is to create a sense of urgency. We create this using this thesis assignment and by addressing the experience and emotions of the planners and purchasers. A lot of time is spent by the purchasers and planners to find out why the deliveries are late or incomplete and to determine when the components will arrive. This takes a lot of time and costs a lot of energy. We gathered data and visualized the problem along with a possible solution. We will give a presentation to all stakeholders to make them aware that, together with them, we can solve their problem.

2. Form a powerful coalition

In section 6.3 we described the composition of our project group. When selecting the project members, we choose those persons who have to deal with the problem on a daily basis and who are enthusiastic to invest time in the implementation. This helps us mitigate the risk of unmotivated group members who fall back into old behaviour.

3. Create a vision for change

The vision of the project is described in section 6.1. When we start with the implementation pilot, we will dedicate one meeting to specify vision, the objectives, and the constraints of the implementation to make sure everyone is on the same page.

4. Communicate the vision

Each member of the project group belongs to a department of the company. We will make sure that they communicate the vision, objectives, and constraints of the implementation pilot to the rest of their departments.

5. Remove obstacles

The obstacles we can encounter during and after the implementation and how we deal with them can be found in section 6.5.

6. Create short-term wins

This is in our opinion particularly important for the success of the project. We ask for the team members to change their way of working. Only by showing positive results, we can convince members to keep going. Therefore, we will monitor the KPIs and emphasis on the gain we make every period. The ultimate goal is to make sure in 98% of the production orders all components are available before the planned production date. However, this will not be possible at once, but will take some steps. Each time the percentage has improved, this is considered a win and will be shared to ensure everyone stays energized to work for improvements.

7. Build on the change

Even after our goal is achieved, we will keep on meeting once every period to make sure the good results remain. The project is about changing a way of working. We will have to keep reminding people of this until it is the new standardized way everyone works.

8. Anchor the changes in corporate culture

This is in line with the previous step. We must make sure that the changes we want to implement now become the new normal. Only then the possible improvements become structural.

6.8. Improving supplier performance

During this thesis assignment, we mentioned several times that, in our opinion, the supplier performances can be improved by improving supplier-buyer relationships. In Section 2.5 we discussed the agreements Hittech Multin has with the suppliers and in Section 3.4 we performed a literature research about what can be done to improve the supplier-buyer relationship. In this section, we describe what Hittech Multin can do to improve supplier performance. We base these recommendations on our observations supported by the findings in the literature. Important to note is that these recommendations apply for important suppliers for which Hittech Multin is a large customer. As discussed in section 3.4 economic factors are an important part of dedicated suppliers and this applies mainly for the important suppliers. Furthermore, improvements with these suppliers have a greater impact than improvements for smaller suppliers. We define improvement in supplier performance as supplying more according to expectation than is currently done. We have the following recommendations:

- Our most important recommendation is to change the mindset when making agreements with the supplier. Currently, the focus of Hittech Multin is on performance and outcomes, while suppliers focus on relationship atmosphere and development as discussed by (Hüttinger , Schiele, & Veldman, 2012). We recommend a change in mindset from competition focused to cooperation focused. In our opinion the mindset should be 'How can we together make sure that the supplier supplies according to expectation?' instead of 'What can, and should the supplier do for me?'. This means that not only is demanded how the supplier should supply Hittech Multin, but also the supplier is asked what he needs to be able to supply according to expectation.
- In addition to the previous recommendation, we recommend sharing forecasts and customer information with the supplier. This is already done for some of the suppliers, but we recommend doing this for all large suppliers. It helps the supplier manage its production and increases the trust of the supplier towards Hittech Multin.
- Make clear agreements between the supplier and Hittech Multin of what is expected from each other including consequences if one of both parties does not keep his end of the agreement. Make sure the content of the agreement can be interpreted in only one way and that the consequences are feasible.
- Make clear agreements on what to do if the supplier has conflicting expedited orders from Hittech Multin. Should the supplier decide which order has priority or discuss with Hittech Multin which order should be supplied first.
- Let the supplier keep inventory in exchange for a guarantee that at least a certain percentage of that inventory will be bought by Hittech Multin. In the thesis assignment, only series production is in the scope. This means that demand dropping to zero without any warning is small. The risk of being leftover with components that cannot be sold anymore is therefore small. The benefit of inventory at the supplier is that the supplier can supply with a smaller lead time, with a more reliable lead time and often for a lower price.

6.9. Reliability lead times

We discussed that besides reducing the lead time, improving the reliability of the lead time has a large impact on the performance of all order policies. Currently, the quality of the historical lead time data is low. This is a bottleneck in our research and already in reality. In this section, we discuss what needs to be done to improve the quality of the historical lead time data, which is the following:

- Make a clear definition of what lead time is together with the supplier. Currently, for example, some suppliers start measuring when they confirm an order, while Hittech Multin starts measuring while when they place the order. Both parties must agree when they start measuring lead time and when they finish measuring lead time of a delivery. Only then, the actual lead time can be reviewed.
- Let the supplier check if the expected lead times in the ERP system correspond to their expectation of the lead time. When interviewing a few suppliers, we found out that the expected lead times in the ERP system do often not correspond to the expectation of the supplier.
- In addition to the previous recommendation, make sure the supplier provides the true expected lead time instead of the desired expected lead time. Hittech Multin aims for a maximum lead time for many components and expects the supplier to deliver according to this maximum. When not taking no for an answer, you run the risk of a supplier agreeing to this maximum while they know this is infeasible.
- Decide if one or two extra days need to be added to the expected lead time for booking in the component by Warehousing.
- Decide how lead time is measured if the planner communicated to the supplier that he has more time to deliver than the expected lead time. A supplier has more time than is needed to produce our order. Often a supplier does not start directly with production, because other production orders have priority for him. When he starts later with our production order and there is a delay, he delivers our product later than planned. The complete time until delivery does not give an accurate overview of the real lead time, because he did not start producing right away. Therefore, measuring the complete lead time would decrease the quality of the historical data measurement. Determine how to prevent this problem or how this lead time should be measured.
- Discuss how the lead time is measured if the supplier can provide a part of the delivery, but not all components. Currently, the lead time measurement is stopped if the last component is delivered. Even if no production problems occurred because enough components arrived on time, the system considers the complete delivery as too late.

6.10. Conclusions

The primary focus of the implementation project is to validate the decision-making model created during the thesis assignment. Three sub-objectives are also defined to ensure that the main objective is reached without violating the constraints formulated during the thesis assignment.

The implementation project consists of two phases. Phase one is the pilot phase where we implement the model for one article group. In phase two we expand on the number of article groups for which the model is implemented.

The project team responsible for the implementation consists of the project owner, the project leader, a purchaser, a planner, and an ERP/IT team member.

We created a rough planning of the implementation and determined that we need about four months for the implementation of the pilot project.

We concluded that we must deal with two kinds of risk. The risks during the implementation of the pilot and the risks after the implementation of the pilot. We already listed several potential risks. Furthermore, we will perform a complete risk analysis with the complete project group during the preparation phase of the pilot project.

During the implementation pilot, the complete project group meets every two weeks to evaluate the course of the implementation.

We use the eight steps of Kotter as help for change management.

When improving the relationship with the suppliers the most important recommendation is a change of perspective from ‘What can and should the supplier do for me?’ to 'How can we together make sure that the supplier supplies according to expectation?’.

Finally, improvement of the quality of the historical lead time data can be achieved by making clear agreements with the suppliers about the definition of lead time and how lead times are measured. Furthermore, it is important to check if the expectation of the lead time per component by Hittech Multin corresponds to the expectation of the supplier.

Chapter 7 – Conclusions and discussion

We start this chapter with the conclusions of this thesis. Here, we answer all the research questions we posed in Chapter 1. Subsequently, we provide a discussion on our research.

7.1. Conclusions

In this thesis assignment we formulated the following research objective: *"Develop a decision-making model to ensure that in 98% of all production orders all components are delivered on or before the planned production date by the suppliers, while minimizing the total costs and keeping in mind inventory requirements."* We created the decision-making model by analysing the current situation, choosing a root cause, and based on the literature review, created the model to meet the requirements of the objective. In this section, we will provide the conclusions per research question.

The main root cause for delayed production orders due to missing components is that components are delivered later by the suppliers than expected. In 59% of the delayed production orders due to missing components, this is the reason.

59% of the components used for series production have always been delivered on time. The remaining 41% are the components that potentially contributed to the chosen core problem. During this thesis assignment we focussed on these 41% so-called "unreliable components".

Only 15% of the unreliable components account for 80% of the value of the unreliable components. This means that many (relatively) cheap components contribute to missing components at the start of production.

Only 20% of the suppliers, supplying the unreliable components, are responsible for the supply of 78% of the unreliable components. This means that supply improvement of a few suppliers greatly improves overall supply performance.

Only a small part of the suppliers has a contract and receive a six-month rolling non-binding forecast. All suppliers are evaluated every month, but there are few consequences for suppliers that perform poorly.

The current order policy does not result in the desired percentage of production orders for which all components are present on or before the planned production date. Components are ordered with a fixed one-week safety lead time in the amount needed to fulfill the demand unless the supplier requires a minimum order quantity. The expected lead times do often not correspond to the actual lead times.

Hittech Multin requires that the height of the inventory may not exceed two months' worth of inventory. In other words, the inventory throughput time may not exceed two months. However, these two months are chosen arbitrarily.

When creating a good supplier-buyer relationship, suppliers greatly value social factors like communication and early involvement. Not only economic factors are important, but social factors are equally important to improve the relationship and therefore the supply performance.

When validating the decision-making model, model results and reality did not match for various reasons. Therefore, the results cannot be implemented one-on-one in reality right now. However, we were able to compare the results of different order polices, because they all use the same input data and face the same circumstances.

For Article group 1, all components can best be ordered with a safety lead time, called the "safety lead time order policy". Compared to the current order policy, the percentage of late orders is reduced from 19.1% to 1.1%, while total costs only increase from €167,000 to €168,700. The inventory throughput time meets with 1.99 the required 2 months. The combined order policy is the second-best option.

For Article group 2 a part can best be ordered with a safety lead time and a part can best be ordered with a safety inventory, called the "combined order policy". Compared to the current order policy, the percentage of late orders is reduced from 89.1% to 1.8%, while the total costs are reduced from €3,352,000 to €3,272,000. The inventory throughput time remains below the required two months. The safety lead time order policy is the second-best option.

Regardless of the supply uncertainty, the safety lead time order policy performs similar or better than the current order policy for both Article group 1 and Article group 2. The percentage of production orders that start on time always meets the required 2% for the safety lead time policy, while this is not always the case for the current order policy. Furthermore, the total costs of the safety lead time order policy are similar or lower than the total costs of the current order policy.

When implementing the decision-making model in reality the mindset when making agreements with suppliers should be changed from 'What can and should the supplier do for me?' to 'How can we together make sure that the supplier supplies according to expectation?'. In this way the supplier-buyer relationship can be improved and with that the supply performance.

Currently, the quality of the historical lead time data is poorly. Therefore, the measurements of the historical lead time data should be changed to improve the quality. Better quality then results in more accurate expectations of the delivery time of each component.

7.2. Discussion

We start this discussion with the three main limitations of the research and then provide our final recommendations for Hittech Multin.

The first limitation is that validation of the decision-making model is currently difficult, mainly for two reasons. First, we often lacked data or lacked data of good quality. Hittech Multin keeps track of a lot of data, especially in the new ERP system. Most of the data is not yet suited to answer the research questions of our research in detail. For example, we could only determine the percentage production orders delayed because components were missing, but not the production orders that started on time, but with component shortages. This meant that we were only partially able to map the actual problem. We believe that the data needed to map the problems can be measured with the new ERP system as long as is clear what needs to be measured specifically. Then, the model can be thoroughly validated. The second reason that made validation difficult was the unexpected circumstances like the implementation of the new ERP system or the sudden demand drop of one customer (cannot be named due to confidentiality) in 2019. This resulted in that planners and purchasers made different decisions than they would do under normal circumstances.

The second limitation is the limited computational power of Excel VBA in comparison to other programming programs. We deliberately choose Excel, because Hittech Multin knows this program, so the final model can be used by the company after we leave. The disadvantage is that running an experiment takes long (up to 24 hours), especially when the article group contains a lot of components. Because we had limited time and experiments took so long, we were not able to perform a sensitivity analysis on other inputs than the lead time. For example, a sensitivity analysis with a different fixed cost per order placed or holding cost percentage would have been a strong addition to the research. Also, we were limited in the number of divisions we could try out for the combined order policy. We may have missed a better division of components ordered with a safety lead time and components ordered with a safety inventory than we currently have found.

The third limitation is the small dataset we used to find the root causes and the impact of each root cause. Although the impact of the main root cause was the largest in our dataset, we always have the probability that this root cause is in reality smaller than in our dataset. Implementing the created decision-making model will have less impact than expected if the small dataset indeed turns out to be a poor representation of reality.

Our first and primary recommendation is to change the way Hittech Multin orders. In all experiments we performed, the current order policy did not meet the requirements set by Hittech Multin themselves. Furthermore, the total costs of other order policies were similar or better than those of the current order policy. The best order policy depends differs per article group, but in all experiments the current order policy was certainly not the best.

Our second recommendation is to improve the quality of the historical lead time data. In Section 6.9, we provided a detailed overview of how to do this. In general, we recommend the following. On the one hand make sure the expectations of the lead time of Hittech Multin correspond to the expectations of the supplier. On the other hand, make sure there is one clear way of measuring lead time without all kinds of exceptions which decreases the quality of the historical data.

Our final recommendation is to make the KPIs, used for this thesis assignment, better measurable. As discussed in the first limitation, the ERP keeps track of a lot of data. This research makes clear what KPIs should be measured and in which detail to solve the research objective. When implementing this thesis assignment, start by making the KPIs measurable. Then, it will be possible to determine with more certainty the impact of the main root cause and the improvement potential of the model we created.

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Appendix A – Organizational chart

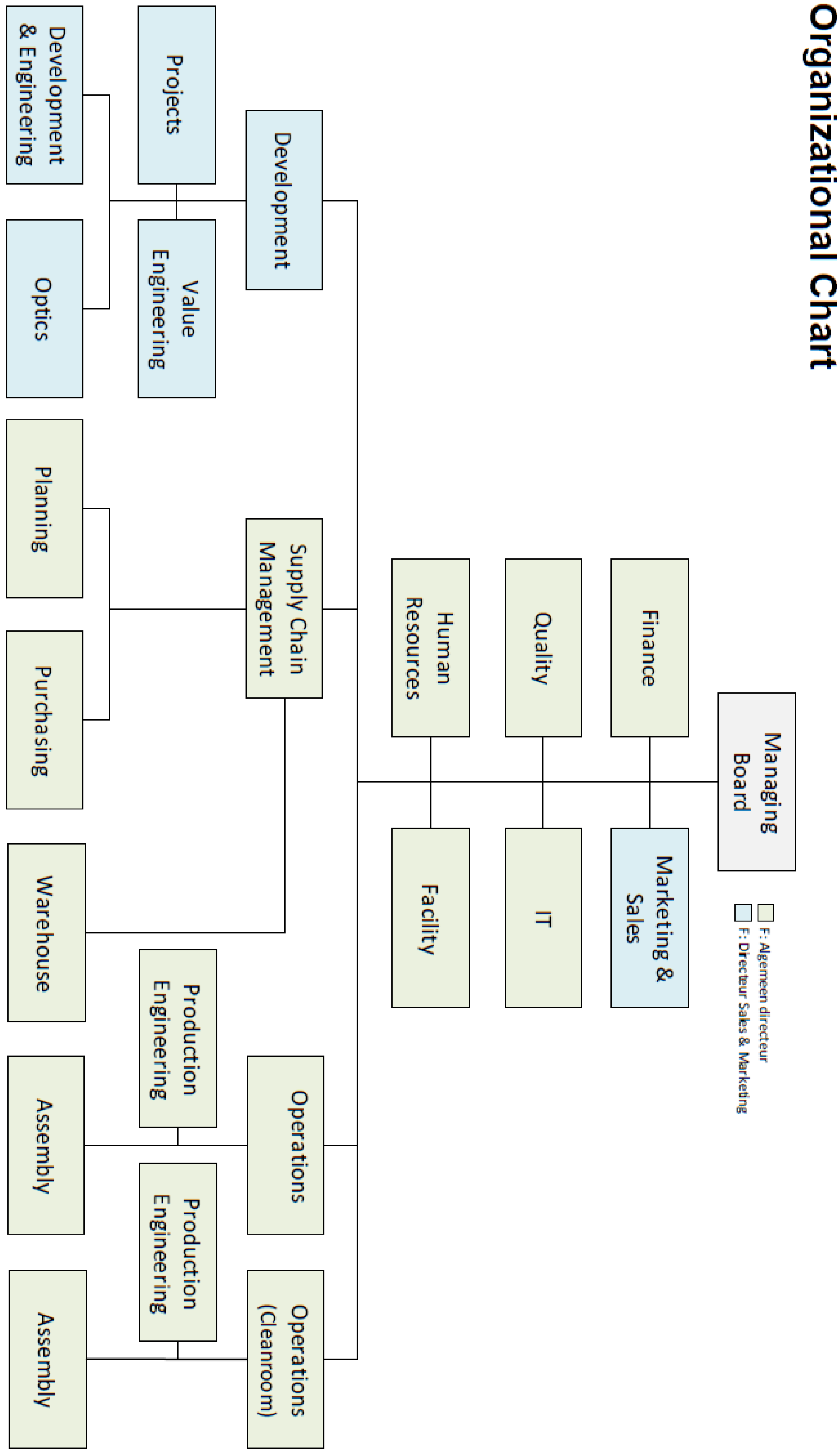

Figure 9: Organizational chart

Appendix B – Data used for calculations in chapters 1 and 2

In this appendix we elaborate on the data used and the calculations done in chapters 1 and 2.

Delayed production orders

In Section 1.3 we describe that 88% of all production orders start on time. Unfortunately, no historic data is available about postponed production orders and corresponding causes. Therefore, we calculated this percentage with the help of our own created (small) dataset. We kept track of all production orders for five weeks. We aimed for a larger dataset than only five weeks of data. However, after these five weeks Hittech Multin switched to a new ERP system. It was uncertain for everyone in the company whether the root causes of delayed production orders could be identified in the new system. Further, and most importantly, the switch of ERP system had such an impact on the company that many of the company processes were disturbed. The data we could have gathered was not a good representation of the common situation. The data we gathered until the switch of ERP system showed one root cause with such a big impact that we would always have chosen this as our core problem. Therefore, we decided to work with this data set and did not try to gather extra data differently.

This results in a five-week data set, containing 36 delayed production orders out of a total of 290 production orders. This means 12% of production orders starting too late and thus 88% of production orders starting on time. An important note is that this 88% also contains production orders that started on time, but with a shortage of certain components. Officially this is not allowed by Hittech Multin, but multiple planners admitted that this happens frequently. This means that the percentage of production orders in which all components are present is even lower than 88%. Unfortunately, it is not possible to determine the percentage of orders that started on time but with a component shortage with the historical data.

Root causes components missing at production site

In Section 2.1 we discuss the root causes of the delayed production orders. As discussed above we have a dataset containing 36 delayed production orders. For each of these 36 production orders we discussed with the planners what the root cause was. Further, to determine more root causes that can occur but did not occur in our dataset, we interviewed the planners. When possible, we gathered historical data indicating the impact of a root cause when this cause lacked in our dataset.

Total number of production orders

In Section 2.1.1 we said that there are about 3700 production orders per year. We found this number in the former ERP system by checking all production orders from the past year. We only took into account the series production article groups.

Suppliers deliver components later than expected

In Section 2.1.3 we calculated the percentage components delivered later than expected. The calculation is based on a dataset containing the supply performances of all purchases from January 2018 till August 2019 out of ViVD. We only considered the components used in series production.

To determine if a delivery was delivered too late or on time, we use the requested delivery date, the date the supply should be delivered according to the lead time registered in the ERP system and the actual delivery date. We distinguish three different situations: (1) the date of delivery is earlier than or equal to the date requested by Hittech Multin. The delivery is considered on time. (2) The date of delivery is later than the requested delivery date, but on or before the delivery date according to the lead time. The delivery is still considered on time because the order is delivered within the agreed lead time. (3) The date of delivery is later than the requested delivery date and later than the delivery date according to lead time. Now, the delivery is considered late, because the supplier was not able to deliver on or before the date according to the lead time. To clarify the three possibilities we formulated three example situations in Table 15.

Table 15: Example situations

Situation	Requested date	Delivery date according to lead time	Delivery date	Working days late/early	On time/Too late
1	02-01-2018	08-12-2017	02-01-2018	0 working days late	On time
2	05-01-2018	16-01-2018	11-01-2018	3 working days early	On time
3	12-01-2018	16-01-2018	18-01-2018	2 working days late	Too late

Reliability component deliveries

In Section 2.2 we calculate the reliability of the component deliveries. We used the same supply dataset as in 2.1.3. Here we calculated per component what the average lead time was and how many days late the latest delivery was per component. Again, only the components that belong to series production were considered.

Value of components

In Section 2.3 we discuss the value price of the components. The price of each component was found in the former ERP system.

Reliability suppliers

In Section 2.4 we discuss how reliable each of the suppliers from the unreliable components is. We already composed the dataset of unreliable components earlier in Chapter 2. The list of suppliers was found in the former ERP system.

Appendix C – planning

Date	2-sep	9-sep	16-sep	23-sep	30-sep
Week	1	2	3	4	5
Activities	Get familiar with the ERP data.	Analyse data ERP system.	Analyse data ERP system.	Skype meeting with both supervisors.	Keep track of the number of times too few components are delivered (during the next months).
	Literature review just in time policy.	Rewrite chapter 1.	Work on chapter 2.	Process the feedback on chapter 1.	Analyse the data about the returns to the suppliers.
	Analyse current company processes.	Analyse current company processes.	Analyse current company processes.	Write preliminary version of chapter 1.	Analyse data about components that are broken during production.
	Analyse current order policy.	Analyse current order policy.	Find critical components --> will be done later.	Analyse the data about reparations of finished products.	Find out if data exists about components in inspection, planning mistakes and mistakes in the warehouse.
	Analyse current supplier lead time estimation.	Analyse current inventory costs.	Complete next version of chapter 1.	Analyse the data about the supplies of 2018 and 2019.	Write Sections 2.1.5, 2.1.6, 2.1.7 and 2.2.
	Meeting with tutors from University.	Analyse current supplier lead time estimation.		Analyse data about returns from the customers	Determine component availability
	Work on planning.	Start with chapter 2.		Write Sections 2.1.1 and 2.1.6.	Meeting about the EOQ computation of the company
		Find out what kind of contracts there are with suppliers.			
		Work on planning.			

7-okt	14-okt	21-okt	28-okt	4-nov
6	7	8	9	10
Analyse the data about components	Write Sections 2.5, 2.6, 2.7, 2.8	Literature review about component classification.	Literature review about methods to improve component availability.	Finish chapter 3.
Write Sections 2.1.2, 2.1.3, 2.1.4 and 2.3 and 2.4.	Finish chapter 2.	Literature review about inventory order policies for assembly systems.	Literature review about causes for good and bad supplier performance.	Send chapter 3 to Matthieu in the middle of the week.
	Send chapter 2 to Matthieu in the middle of the week.	Write Sections 3.1 and 3.2.	Write Sections 3.3. and 3.4.	Start with chapter 4.
	Start with chapter 3.		Rewrite chapter 2.	
	Analyse the inventory related costs data.			
		Meeting with Matthieu about chapter 2 (preferably at the beginning of the week).		

11-nov	18-nov	25-nov	2-dec	9-dec
11	12	13	14	15
Determine what the requirements are for the inventory order model.	Determine how each class can be integrated in the model.	Build the model.	Build the model.	Validate and verify the model.
Write Section 4.1.	Determine what input data is used and how to collect those data.	Write chapter 4.	Finish chapter 4 .	Write Section 5.1 about the validation and verification.
	Determine what output data should be obtained from the model	Determine what output data should be obtained from the model	Send chapter 4 to Matthieu in the middle of week.	
	Write Sections 4.3 and 4.4.	Write Sections 4.3 and 4.4.	Start with chapter 5.	
	Rewrite chapter 3.			
Meeting Matthieu about chapter 3 (preferably at the beginning of the week).				**Meeting Matthieu about chapter 4 (preferably at the beginning of the week).**

16-dec	23-dec	30-dec	6-jan	13-jan
16	17	18	19	20
Validate and verify the model.	Christmas holiday.	Christmas holiday.	Calculate the new inventory related costs .	Determine what the effects are of the improved component availability.
Write Section 5.1 about the validation and verification.	Christmas holiday.	Christmas holiday.	Write Section 5.2 about the new inventory related costs.	Write Section 5.3 about these effects.
Rewrite chapter 4.	Christmas holiday.	Christmas holiday.		

20-jan	27-jan	3-feb	10-feb	17-feb	24-feb
21	22	23	24	25	26
Write the reccomendations to succefully implement the model (Chapter 6).	Green light conversation.	Process the feedback and rewrite the master thesis.	Process the feedback and rewrite the master thesis.	Hand in final version on paper.	Prepare presentation for the master colloquium.
Write the conclusion and discussion.	Write the implementation plan.	Send implementation plan to Matthieu for feedback.	Complete the lay-out of the thesis.	Prepare presentation for the master colloquium.	Master colloquium.
Send chapters 5, 6 and 7 to Matthieu (at the end of the week).					
	Meeting Matthieu for green light conversation. Also to discuss chapter 5 and 6. Probably end of the week.				

Appendix D - 20% suppliers supplying the late delivered components

Due to confidentiality reasons the content of this appendix is not shown. In the confidential version a list is provided of all suppliers supplying the unreliable components.

Appendix E - KPIs for supplier evaluation

The KPIs on which suppliers are evaluated are the following:

- Reliability lead time.
- Reliability of the first confirmation of the delivery date. The supplier is expected to communicate about the time of delivery. It is measured how well the supplier delivers based on the first confirmation.
- Reliability of the last confirmation of the delivery date. The supplier is expected to communicate about the time of delivery. It is measured how well the supplier delivers based on his last confirmation.
- Confirmed orders. The percentage orders that is confirmed at all by the supplier.
- Average number of days delivered late.
- Percentage of products that do not meet the quality requirements.
- Amount of open/past defect analyzes. When the product does not meet quality requirements a defect analysis is requested with a certain due date. This KPI measures the number of requested defect analyzes that are not reported (in full) to Hittech Multin before the due date.

Appendix F – The Economic Order Quantity model

Harris (1913) was the first to present a formula to calculate the optimal order quantity, called the Economic Order Quantity. The EOQ formula as described by (Winston & Goldberg, 2004) is the following:

$Q^* = \sqrt{\left(\frac{2DK}{h}\right)}$

D: Annual demand
K: Fixed cost per order
h: Holding cost per unit
Q^*: Economic Order Quantity

The formula follows from the fact that the Total Costs (TC) are calculated as follows: $TC = \frac{D*K}{Q} + \frac{Q}{2} * h + pD$
p: Purchase price per unit
Q: Order quantity

In the EOQ formula, the quantity discounts are not yet incorporated. (Winston & Goldberg, 2004) describe a method to include quantity discounts. The goal is to find the Q minimizing the TC. Per price class the EOQ is calculated. Figure 10 illustrates an example situation from (Winston & Goldberg, 2004). In the figure TC(q) is the solid portion of the curve. The dashed portion of each curve represents unattainable costs. As can be seen the EOQ_1 belonging to $TC_1(q)$ is not admissible, because $EOQ_1 > b_1$, where b_1 is the price breakpoint.

In the figure the EOQ_3 would result in the lowest costs but are unattainable due to the minimum amount that must be ordered to attain such a low price. The lowest $TC_3(q)$ that can be attained therefore lies on b_2. In the figure the lowest TC(q) are attained at EOQ 2 and are attainable because these lie on the solid part of the TC_2 line. The minimum TC_1 lies on b_1 and minimum TC_3 lies on b_2.

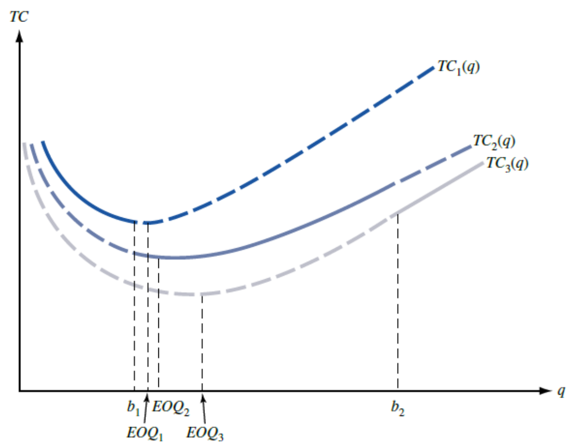

Figure 10: Illustration of TCi(q) and EOQi

Appendix G – Parameters models

In this appendix we discuss all the input parameters, output parameters and decision variables of the different models.

EOQ – (R,s,S) model

Table 16: Parameters EOQ – (R,s,S) model

Parameter	Category
Products to make	Input parameter
Components per article group	Input parameter
Avg. demand and St. Dev. of demand per component per week	Input parameter
Unit price per order size per component	Input parameter
Fixed cost to place an order per component	Input parameter
Holding cost as percentage of component value per year	Input parameter
Minimum order quantity per component	Input parameter
Required fill rate	Input parameter
Avg. lead time and St. Dev. of lead time per component	Input parameter
Review period	Input parameter
Order size per component (for the (R,s,S) model)	Input variable
Order size per component (of the EOQ model)	Output
Safety factor k per component	Output
Expected fill rate per component	Output
Reorder level per component	Output
Order-up-to-level per component	Output

Simulation

Table 17: Parameters simulation

Parameter	Category
Products to make	Input parameter
Components per article group	Input parameter
Required percentage production orders that start on time	Input parameter
Fixed cost to place an order	Input parameter
Holding costs as percentage of the component value per year	Input parameter
Avg. demand and St. Dev. of demand per component per week	Input parameter
Avg. lead time and St. Dev. of lead time per component	Input parameter
Per component the unit price per order size	Input parameter
Minimum order quantity	Input parameter
Review period	Input parameter
Reorder level per component	Input parameter
Order-up-to-level per component	Input parameter
Number of years to simulate over	Input parameter
Total holding costs per run	Output parameter
Total order costs per run	Output parameter
Total purchase costs per run	Output parameter
Total costs per run	Output parameter
Percentage production orders that started late per run	Output parameter
Average inventory throughput time	Output parameter
Average per output parameter per repetition	Output parameter

PSO algorithm

Table 18: Parameters PSO algorithm

Parameter	Category
Products to make	Input parameter
Components per article group	Input parameter
Required percentage production orders that start on time	Input parameter
Fixed cost to place an order	Input parameter
Holding costs as percentage of the component value per year	Input parameter
Avg. demand and St. Dev. of demand per component per week	Input parameter
Avg. lead time and St. Dev. of lead time per component	Input parameter
Per component the unit price per order size	Input parameter
Minimum order quantity	Input parameter
Review period	Input parameter
Start reorder level per component	Input parameter
Start order-up-to-level per component	Input parameter
Number of years to simulate over	Input parameter
Number of repetitions	Input parameter
Number of runs	Input parameter
Number of particles	Input parameter
Number of iterations	Input parameter
Inertial weight factor	Input parameter
Cognitive learning factor	Input parameter
Social learning factor	Input parameter
Reorder level per component	Decision variable
Order size per component	Decision variable
Reorder level per component	Output parameter
Order size per component	Output parameter

Appendix H – Calculation holding cost percentage and order cost

General

Table 19: General information

General	
Number of work weeks per employee	43
Hours per work week	40
Weighted Average Cost of Capital (WACC)	8.1%
Holiday pay	8%
Profit-sharing	8%
Extra costs or Hittech Multin on top of gross salary	50%
New suppliers per year	80
Time to register a new supplier (hours)	0.17
Surface warehouse (m^2)	850
Number of order lines per year	14,270
Average inventory value	€ 3,692,000

In Table 19 we present all the general information needed for the calculations. We determine the number of workweeks by deducing the total amount of workweeks minus the vacations and free days, like Easter, in a year. The WACC we used is an industry average calculated by KPMG (Castedello & Schöniger, 2018). The holiday pay and profit-sharing percentages come from the financial department of Hittech Multin. The extra costs on top of gross salary include for example employee insurance and tax contributions, but also materials of employees like computers. The percentage is an estimation done also by the financial department of Hittech Multin. The number of new suppliers each year is the average of the number of new suppliers over the past years. The time to register a new supplier is an estimation done by Purchasing. The surface of the warehouse is a calculation based on the floor plan. Each order line represents the order of a component and is registered in the ERP system. The average inventory value is based on the weekly inventory value of the past year.

Cost per position

Table 20: Cost per function

Cost per function				
Position	**Average gross salary**	**Gross costs per month for Multin**	**Yearly costs (1FTE)**	**Hourly costs**
Warehouse	€ 2,544.50	€ 4,451.86	€ 53,422.29	€ 31.06
Planner	€ 3,435.00	€ 6,009.88	€ 72,118.51	€ 41.93
Buyer	€ 3,435.00	€ 6,009.88	€ 72,118.51	€ 41.93
Financial	€ 3,435.00	€ 6,009.88	€ 72,118.51	€ 41.93

Holding cost percentage

According to (Chopra & Meindl, Supply Chain Management: Strategy, Planning and Operation, 2013) the holding costs exist of:

- Cost of capital. This is the opportunity cost of making a specific investment. This is the dominant component in our case. Money that is invested in inventory cannot be used for production. For Hittech Multin the production costs mainly consist of material costs.
- Obsolescence (or spoilage) costs.
- Storage costs.
- Miscellaneous costs. These are relatively small other costs that include theft, security, risk, damage, tax, and additional insurance charges that are incurred.

Table 21: Holding cost information

Holding costs		
Category	**Costs**	**Total**
Cost of capital	€ 299,043.59	€ 299,043.59
Inventory revaluation	€ 208,626.00	€ 208,626.00
Inventory differences	€ 173,464.00	€ 173,464.00
Scrap of inventory	€ 125,388.00	€ 125,388.00
Cost of space (per m^2)	€ 100,00	€ 85,000.00
Total		€ 891,522

The holding cost percentage is calculated by dividing the total holding costs by the average inventory value. Holding costs = $\frac{891{,}522}{3{,}692{,}000} = 24\%$.

Order costs

Each time an order is placed certain costs are incurred. According to (Chopra & Meindl, Supply Chain Management: Strategy, Planning and Operation, 2013) the cost per order consists of:

- The time it cost the buyer to place the order. The planners must determine which components should be ordered and in which amount. This costs time and therefore money.
- Transportation costs. A fixed transportation cost is incurred regardless of the order size. In our situation these costs are included in the price.
- Receiving costs. These are the costs of receiving the components and storing them in the warehouse. Also, inventory record updating and inspection of goods when they arrive belong to this cost category.
- Other costs. Other costs can be thought of, for example time to call the supplier when components are delivered late.

Table 22: Time per planner to order components

Time per planner to list the to be ordered component	
Name	**Hours**
Planner 1	6
Planner 2	4
Planner 3	6
Planner 4	4
Planner 5	5
Total	25

Table 23: Order cost information

Yearly order costs				
Category	**Costs**	**Units**	**Total**	**Remarks**
Warehouse employee	€ 31.06	Hour	€ 53,422.29	1 FTE
Planners	€ 41.93	Hour	€ 45,074.07	See Table 19
Transport costs	€ 230,000.00		€ 230,000.00	
Check up on suppliers	€ 41.93	Hour	€ 72,118.51	1 FTE
Financial administration	€ 41.93	Hour	€ 36,059.26	0,5 FTE
Registering new suppliers	€ 41.93	Hour	€ 559.06	See Table 19
Total			€ 437,233	

Cost per order is calculated by dividing the total order costs by the number of order lines. $\text{Cost per order} = \frac{437{,}233}{14{,}270} = €31.$

Appendix I – Flowchart PSO algorithm

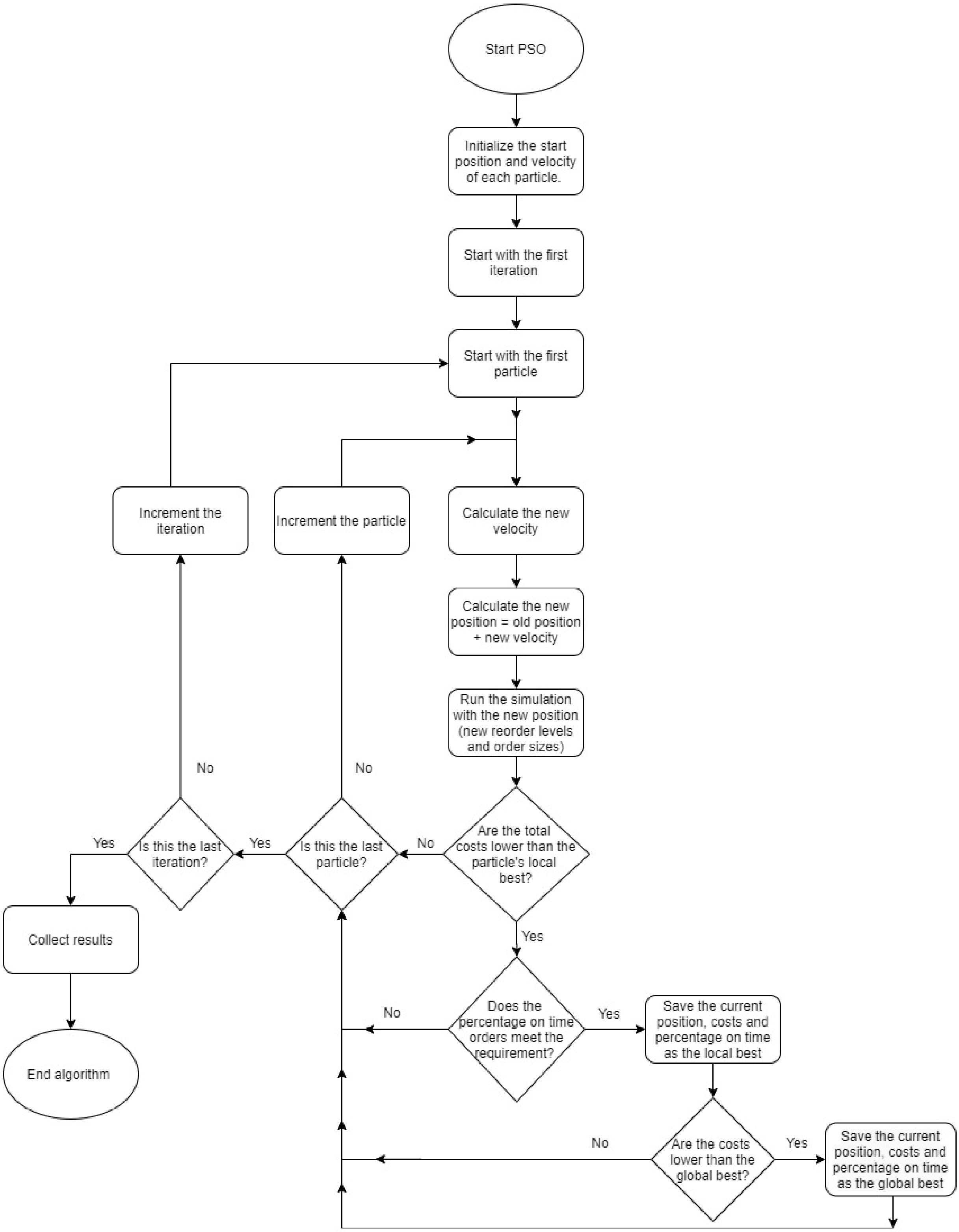

Figure 11: Flowchart PSO algorithm

Appendix J – Calculations number of replications

To determine the number of replications a run length of 10 years is used, which is the same run length as in the experiments of the simulation. As KPI we use the average inventory value. For both article groups we run sufficient replications until the confidence interval, relative to the average, is sufficiently small.

The confidence interval is calculated as follows:

$$Confidence\ interval = \bar{X}_n \pm t_{n-1,1-\frac{\alpha}{2}} * \sqrt{\frac{S_n^2}{n}}$$

$$\bar{X}_n = \frac{1}{n}\sum_{j=1}^{n} X_j$$

$$S_n^2 = \frac{1}{n-1}\sum_{j=1}^{n}\left[X_j - \bar{X}_n\right]^2$$

N: Number of replications
$\bar{X}_n$: Sample average until replication n
S_n^2: Sample variance until replication n
α: The likelihood that the true population parameter lies outside the confidence interval
$t_{n-1,1-\frac{\alpha}{2}}$: t-value linked to the repetition number and alpha. This value can be found in a standard normal t-table or with the help of the t.inv function in Excel.

We increase the repetitions until the width of the confidence interval is smaller than the corrected relative error, which is calculated as follows:

$$\gamma' = \frac{\gamma}{1+\gamma}$$

γ: Relative error
γ': Corrected relative error

We set the relative error arbitrarily to 2%, which results in a corrected relative error of 1,96%, and we set the alpha to 5%. An alpha of 5% means that with 95% certainty the average will fall into the confidence interval. We calculate the width of the confidence interval for each replication until it is smaller than the corrected relative error. We calculate this with the following formula:

$$\frac{t_{n-1,1-\frac{\alpha}{2}}\sqrt{\frac{S_n^2}{n}}}{\bar{X}} < \gamma'$$

In Table 24 we provide an overview of the calculations of Article group 1 for all replications. After 4 replications the width of the confidence interval is smaller than the corrected relative error, so we will use 4 replications for the experiments of Article group 1 in our simulation.

In Table 25 we provide an overview of the calculations of Article group 2 for all replications. Article group 2 is larger than Article group 1, so running one replication takes much longer. Therefore, we only ran the number of replications until the width of the confidence interval was small enough. After 3 replications the width of the confidence interval is smaller than the corrected relative error, so we will use 3 replications for the experiments of Article group 2 in our simulation.

Table 24: Calculation number of replications Article group 1

Repetition	Mean inventory value	Mean till repetition n	Variance until run n	Standard deviation	t-value	Width confidence interval
1	74,414.65	74,414.65	0.00	0.00	0.00	0.00000
2	75,549.15	74,981.90	321,772.23	567.25	12.71	0.06797
3	74,061.14	74,674.98	402,913.70	634.75	4.30	0.02112
4	74,825.01	74,712.49	306,405.52	553.54	3.18	0.01179
5	75,684.83	74,906.95	396,396.55	629.60	2.78	0.01044
6	75,345.26	74,980.01	357,012.82	597.51	2.57	0.00836
7	74,691.51	74,938.79	316,202.39	562.32	2.45	0.00694
8	75,332.07	74,987.95	293,593.79	541.84	2.36	0.00604
9	76,454.31	75,150.88	473,338.25	688.00	2.31	0.00704
10	75,424.56	75,178.25	432,745.32	657.83	2.26	0.00626
11	74,775.89	75,141.67	406,784.52	637.80	2.23	0.00570
12	75,451.60	75,167.50	380,223.38	616.62	2.20	0.00521
13	74,766.70	75,136.67	362,381.94	601.98	2.18	0.00484
14	75,165.31	75,138.71	336,551.95	580.13	2.16	0.00446
15	75,922.99	75,191.00	352,387.79	593.62	2.14	0.00437

Table 25: Calculations number of replications Article group 2

Repetition	Mean inventory value	Mean till repetition n	Variance until run n	Standard deviation	t-value	Width confidence interval
1	458,884.83	458,884.83	0	0		
2	454,169.66	456,527.25	1,389,550.79	1,178.79	12.71	0.0232
3	458,923.97	457,326.15	958,436.59	979.00	4.30	0.0053

Appendix K – Logic flowcharts order policies

In this appendix we provide the logic flowcharts of each scenario described in Section 4.4.

Current order policy

We split the flowchart into three parts to make sure it remains readable. Due to the size we start on the next page.

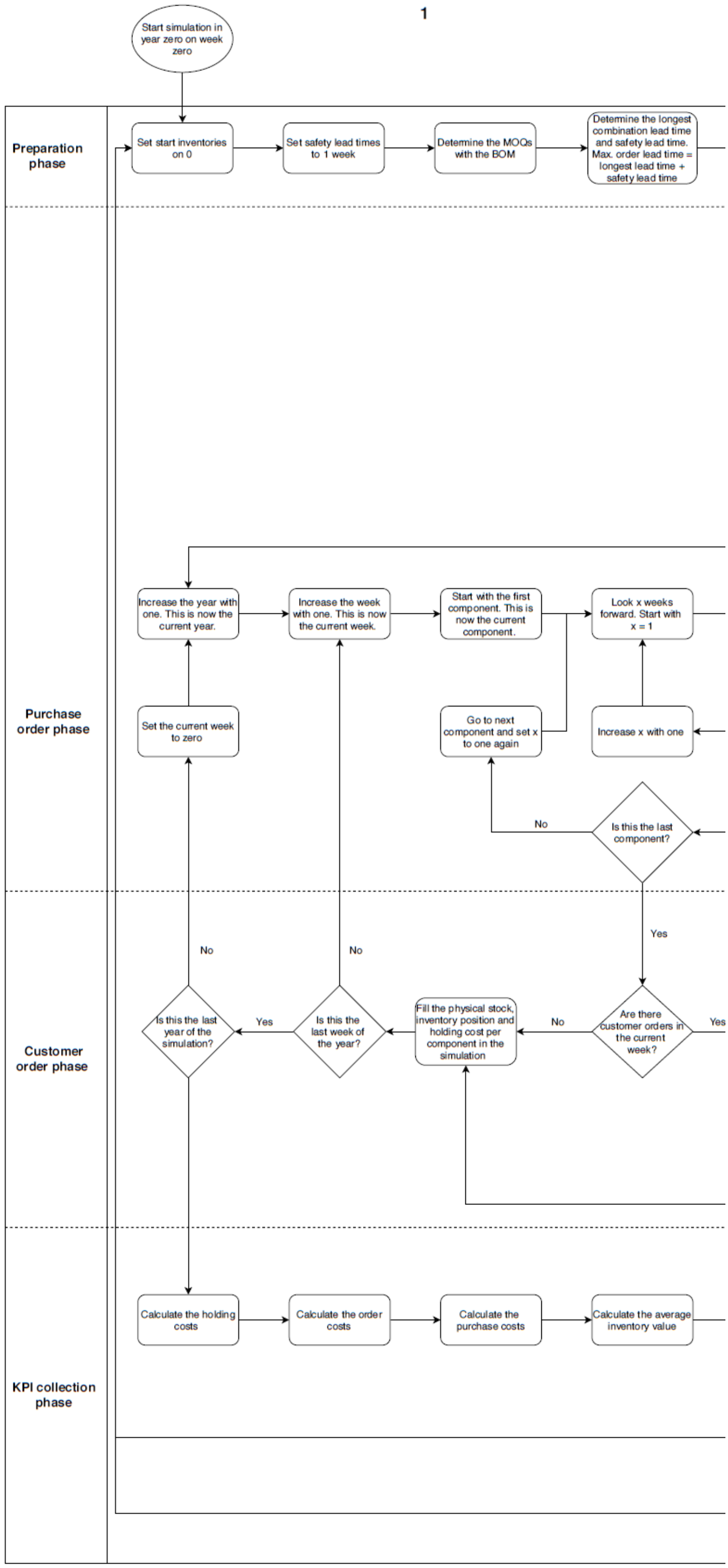

Figure 12: Flowchart current order policy part 1

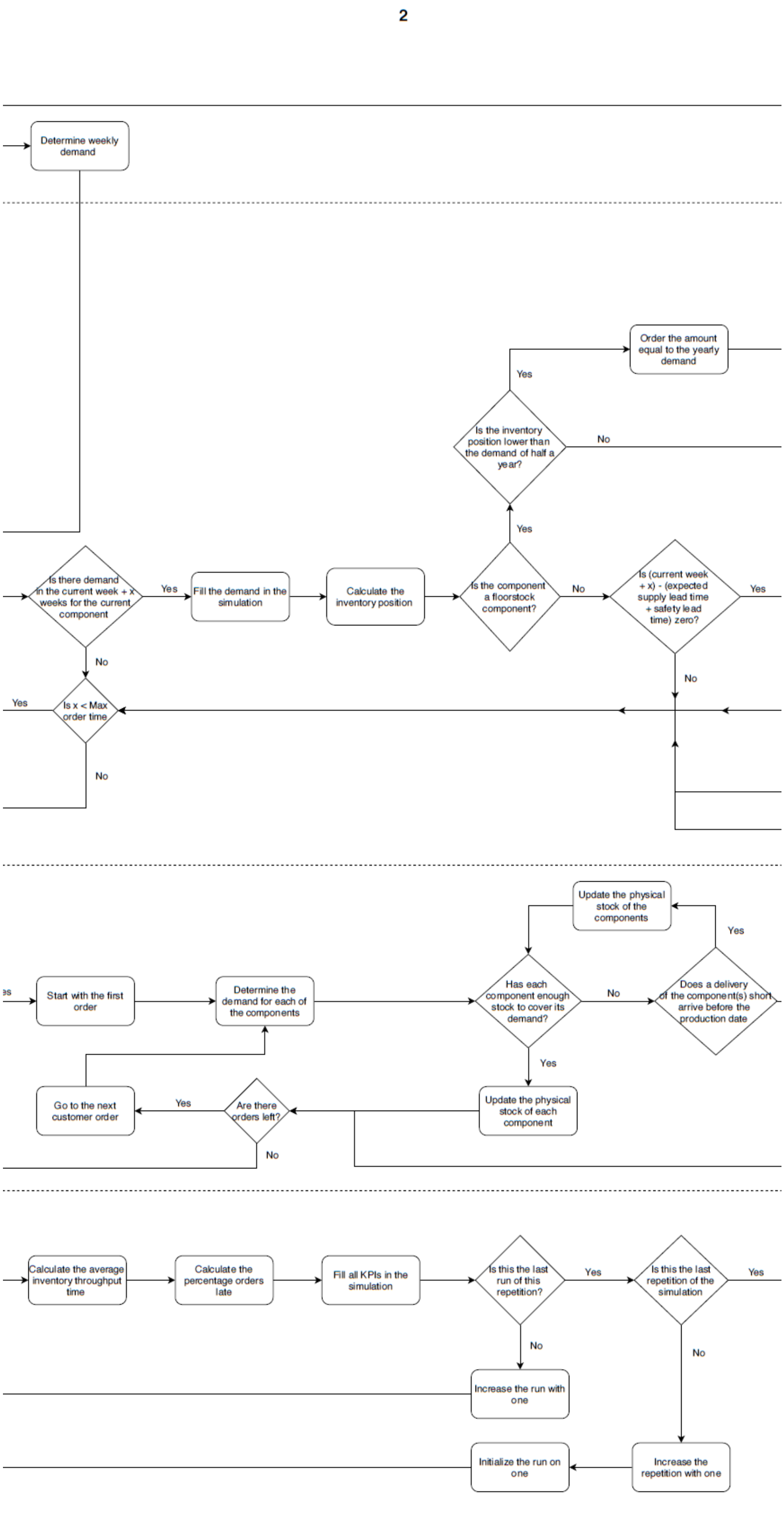

Figure 13: Flowchart current order policy part 2

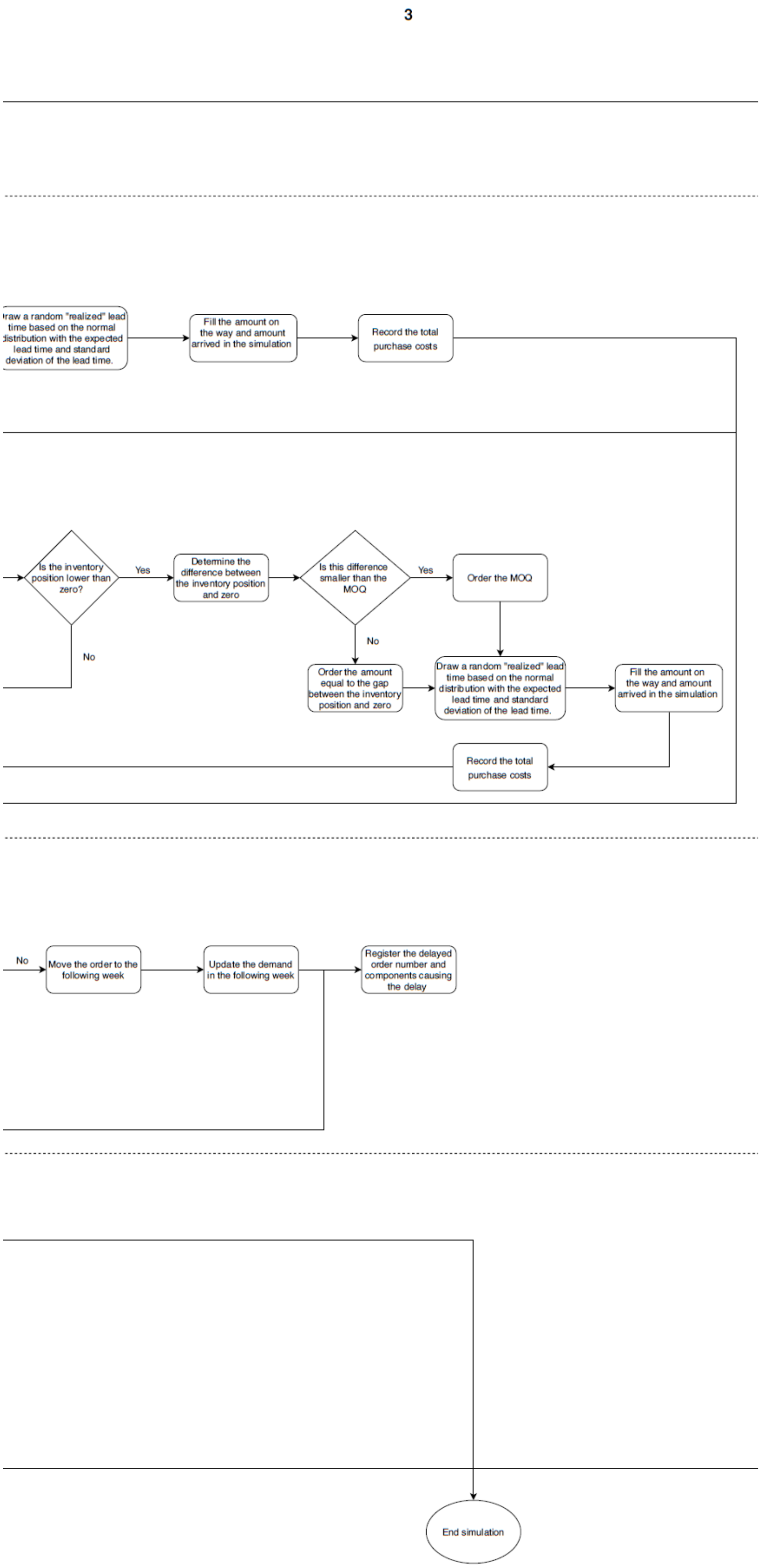

Figure 14: Flowchart current order policy part 3

Inventory order policy

We divide this flowchart in four parts.

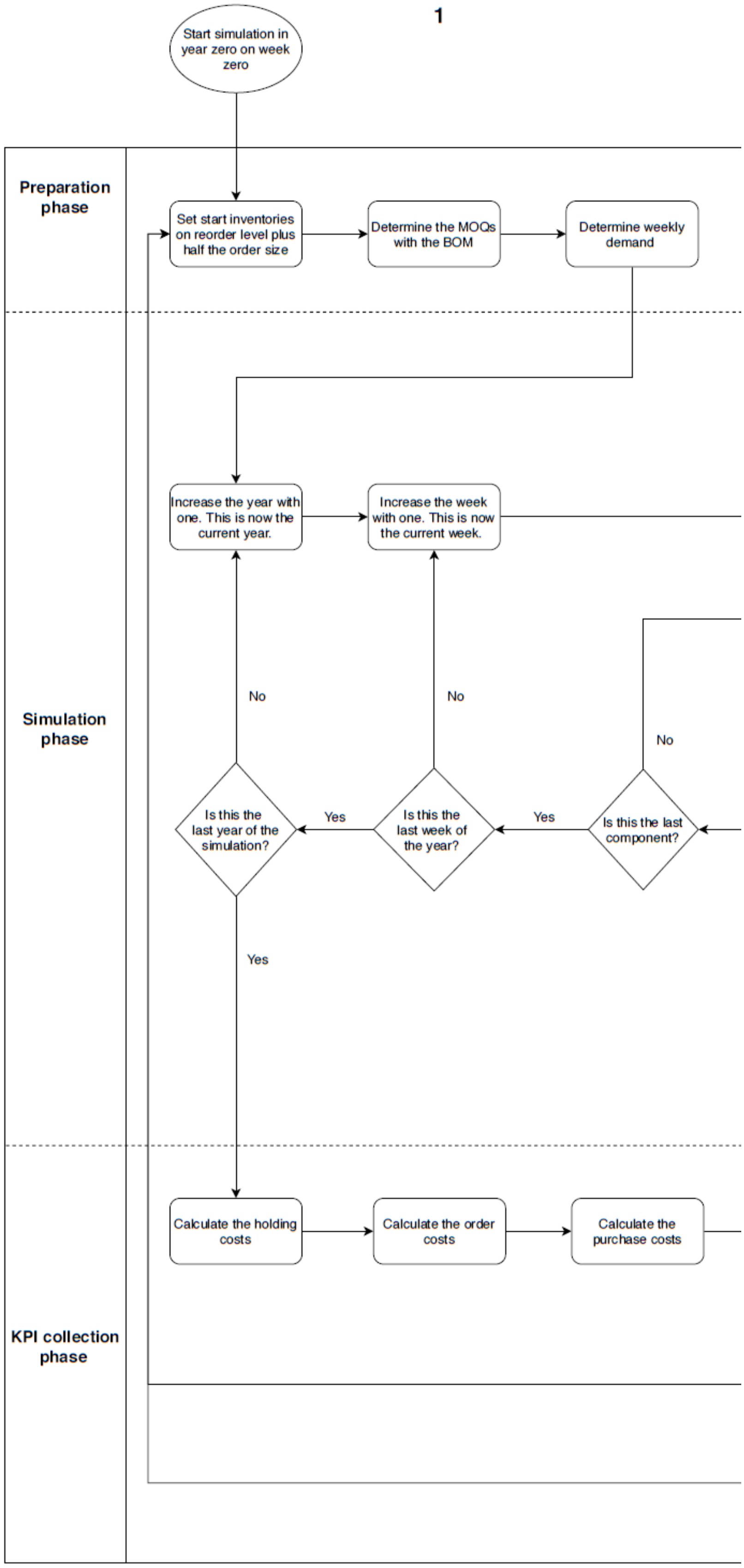

Figure 15:Flowchart inventory order policy part 1

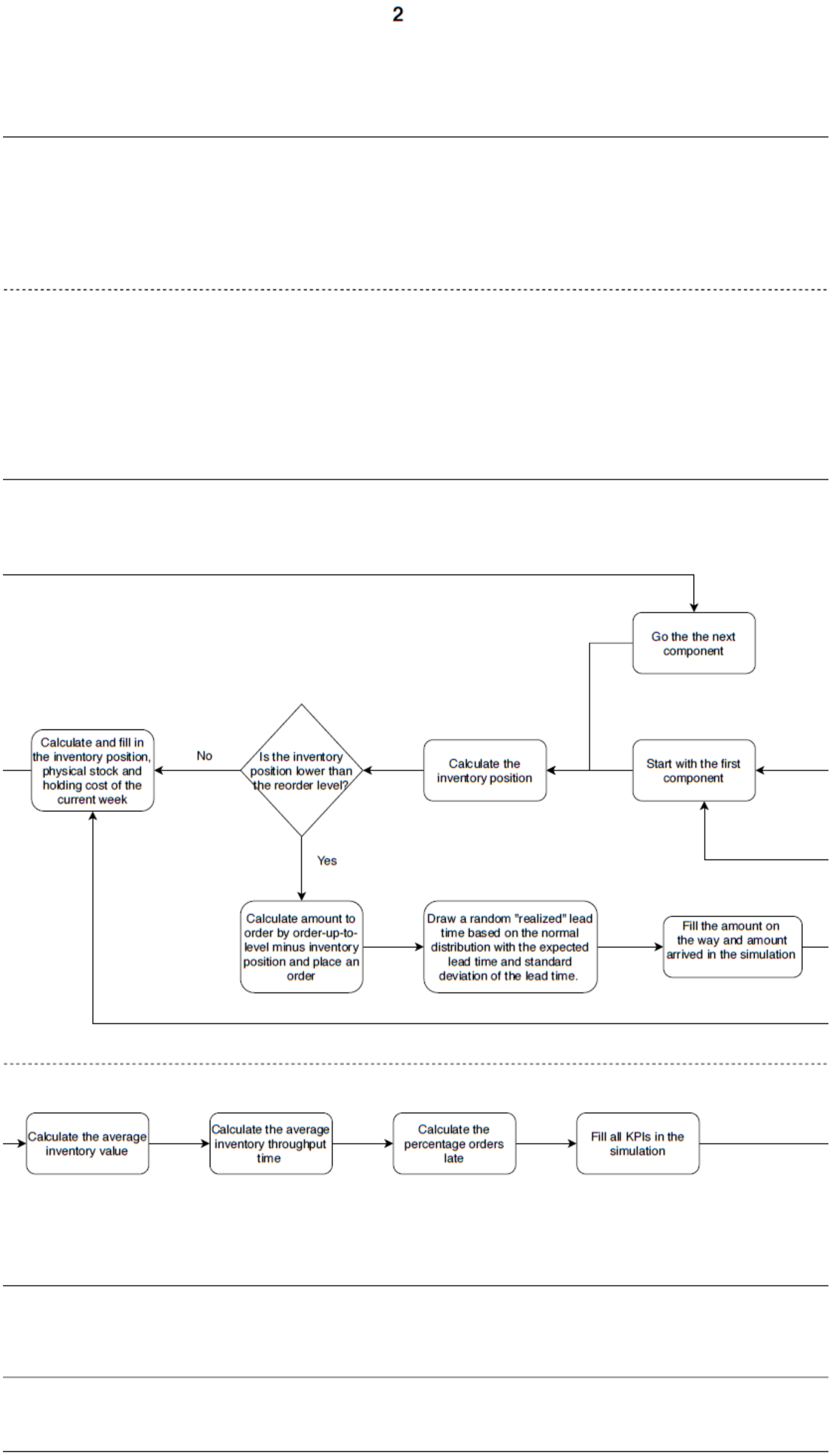

Figure 16: Flowchart inventory order policy part 2

3

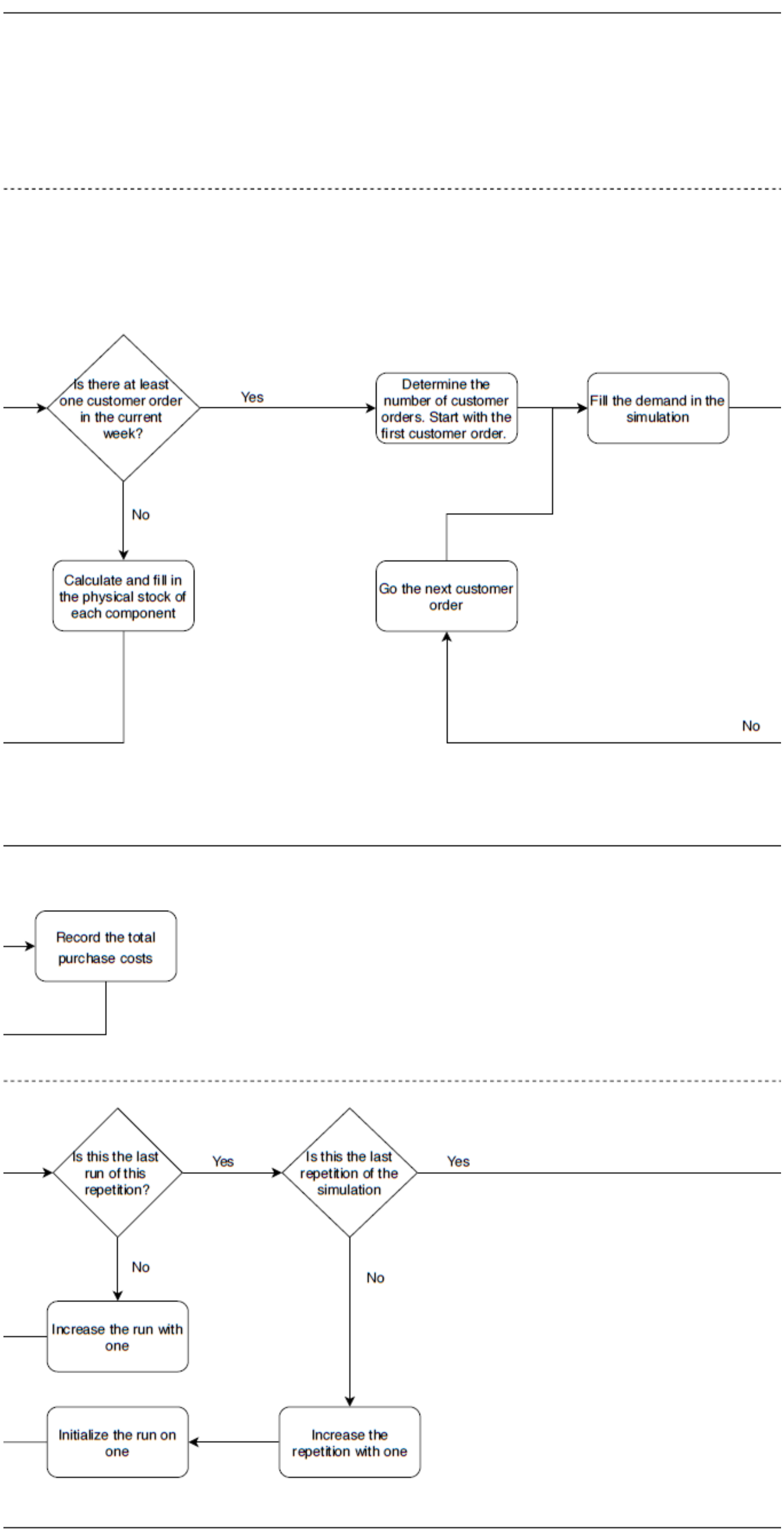

Figure 17: Flowchart inventory order policy part 3

4

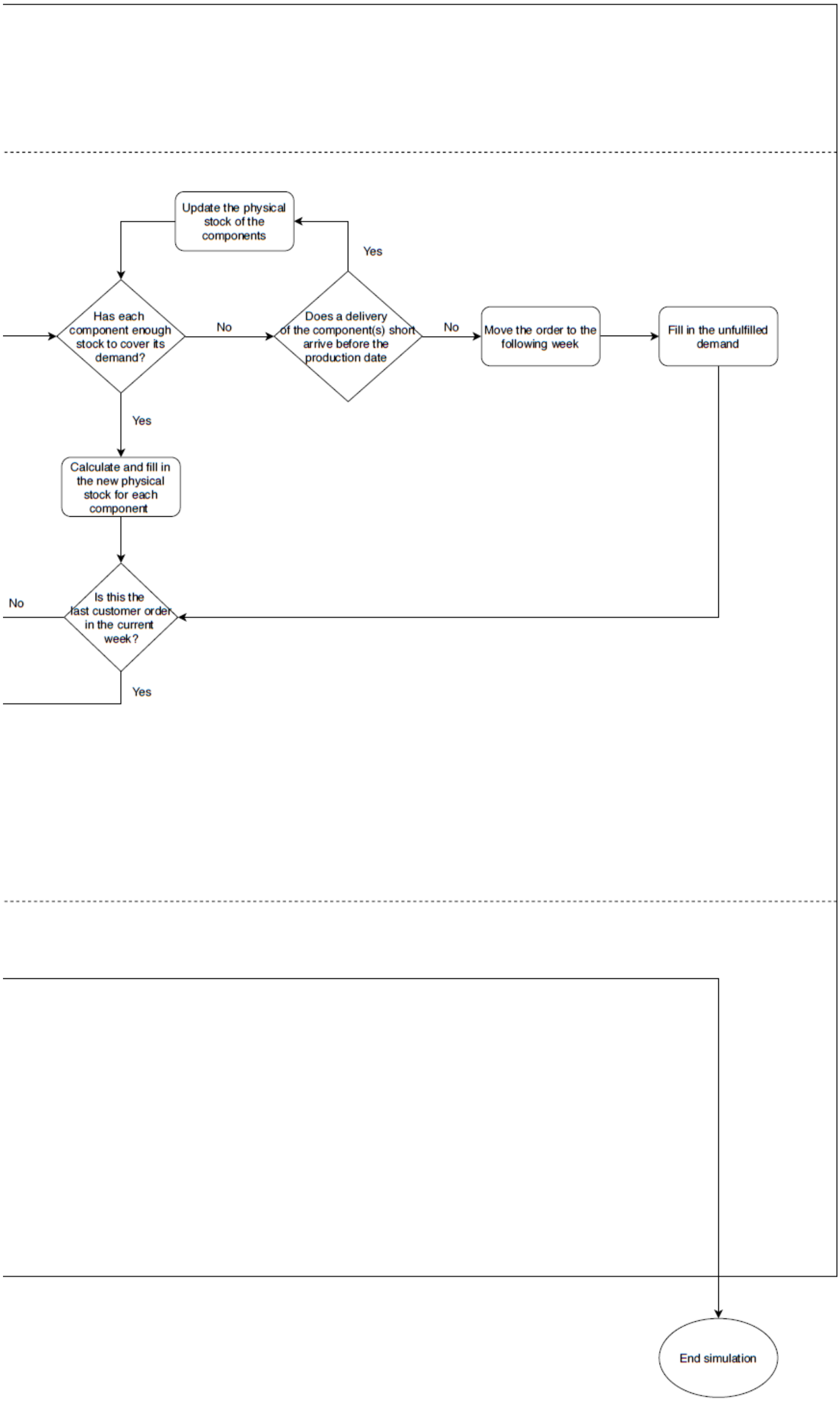

Figure 18: Flowchart inventory order policy part 4

Safety lead time order policy

We divide this flowchart in three parts.

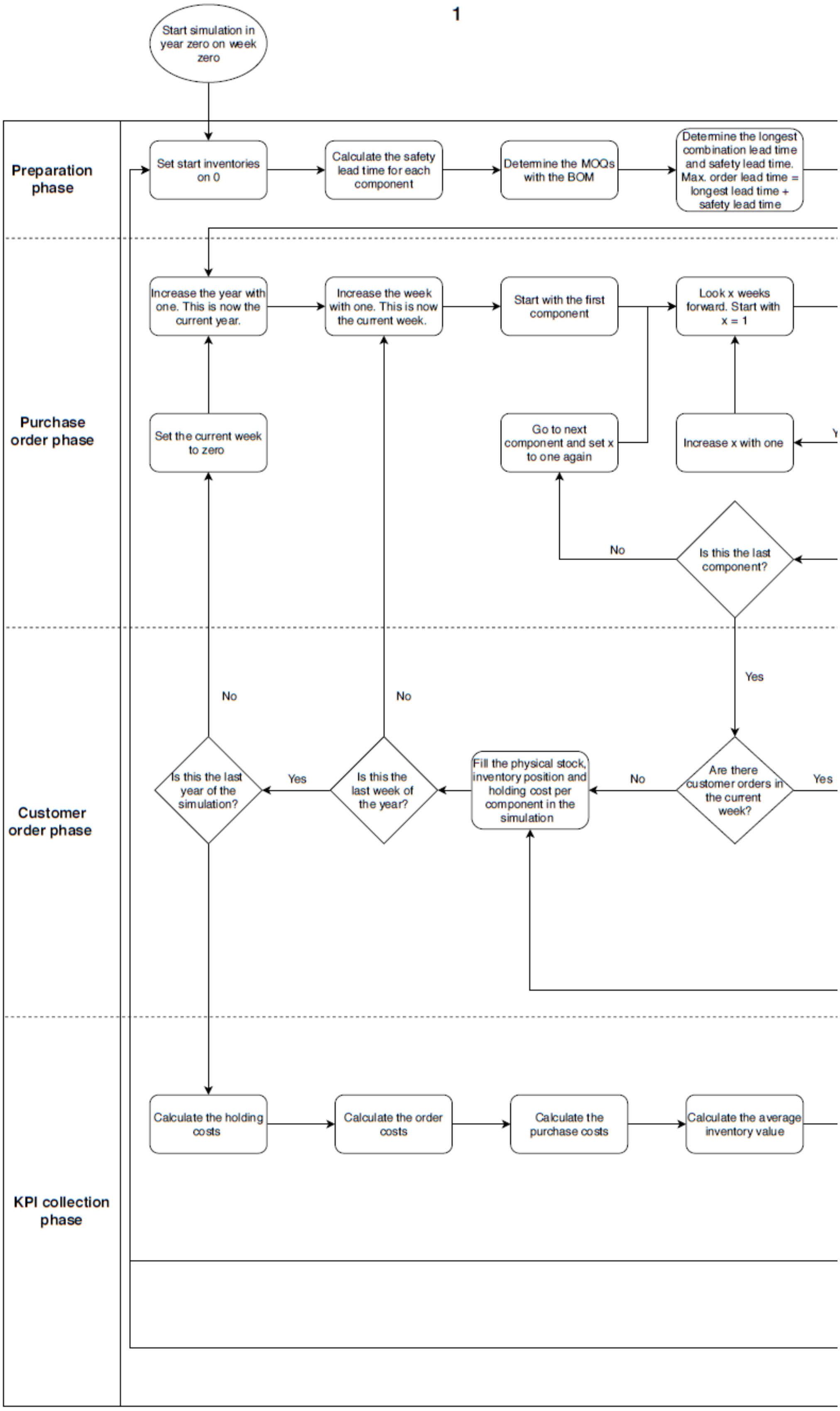

Figure 19: Flowchart safety lead time order policy part 1

2

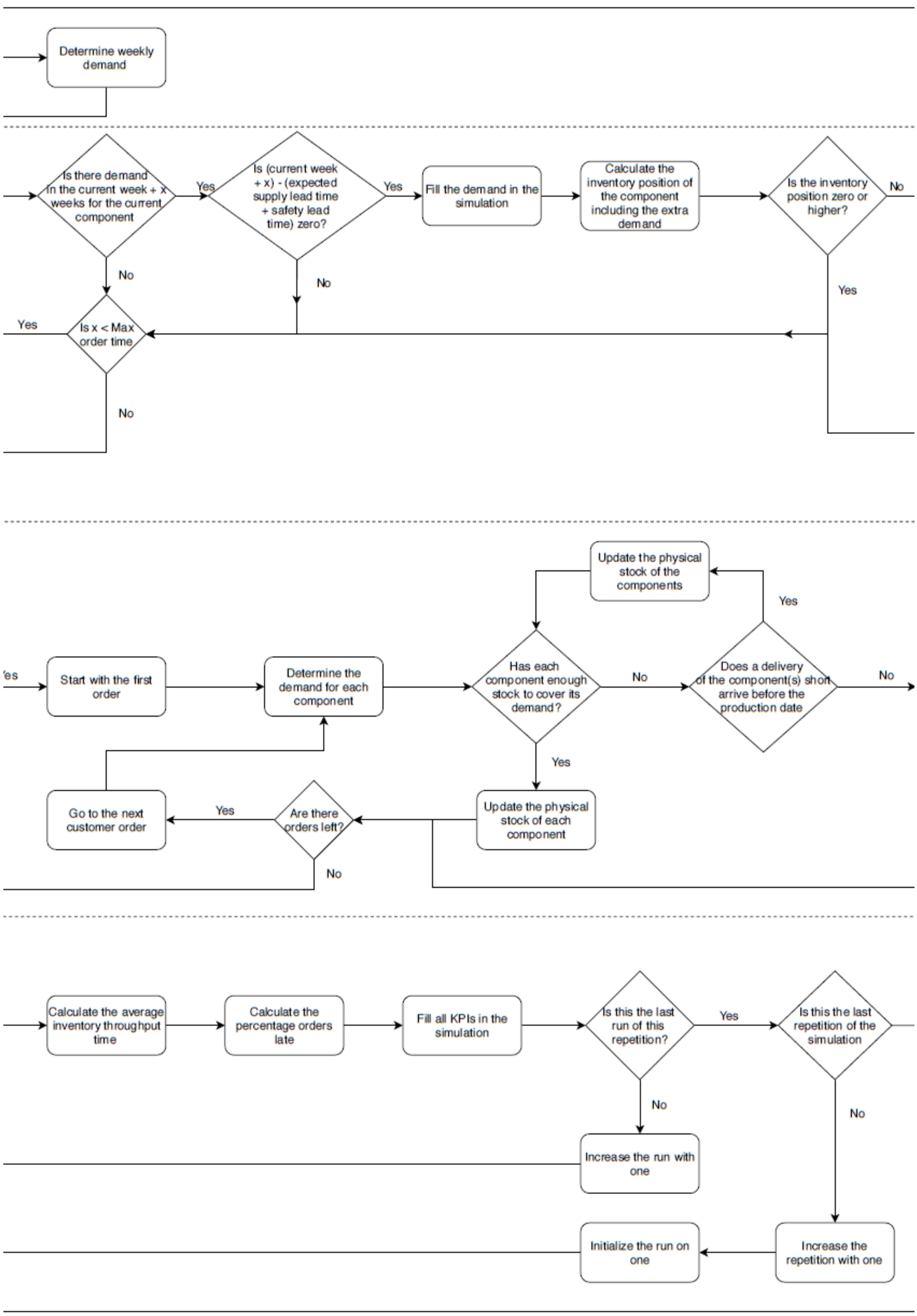

Figure 20: Flowchart safety lead time order policy part 2

3

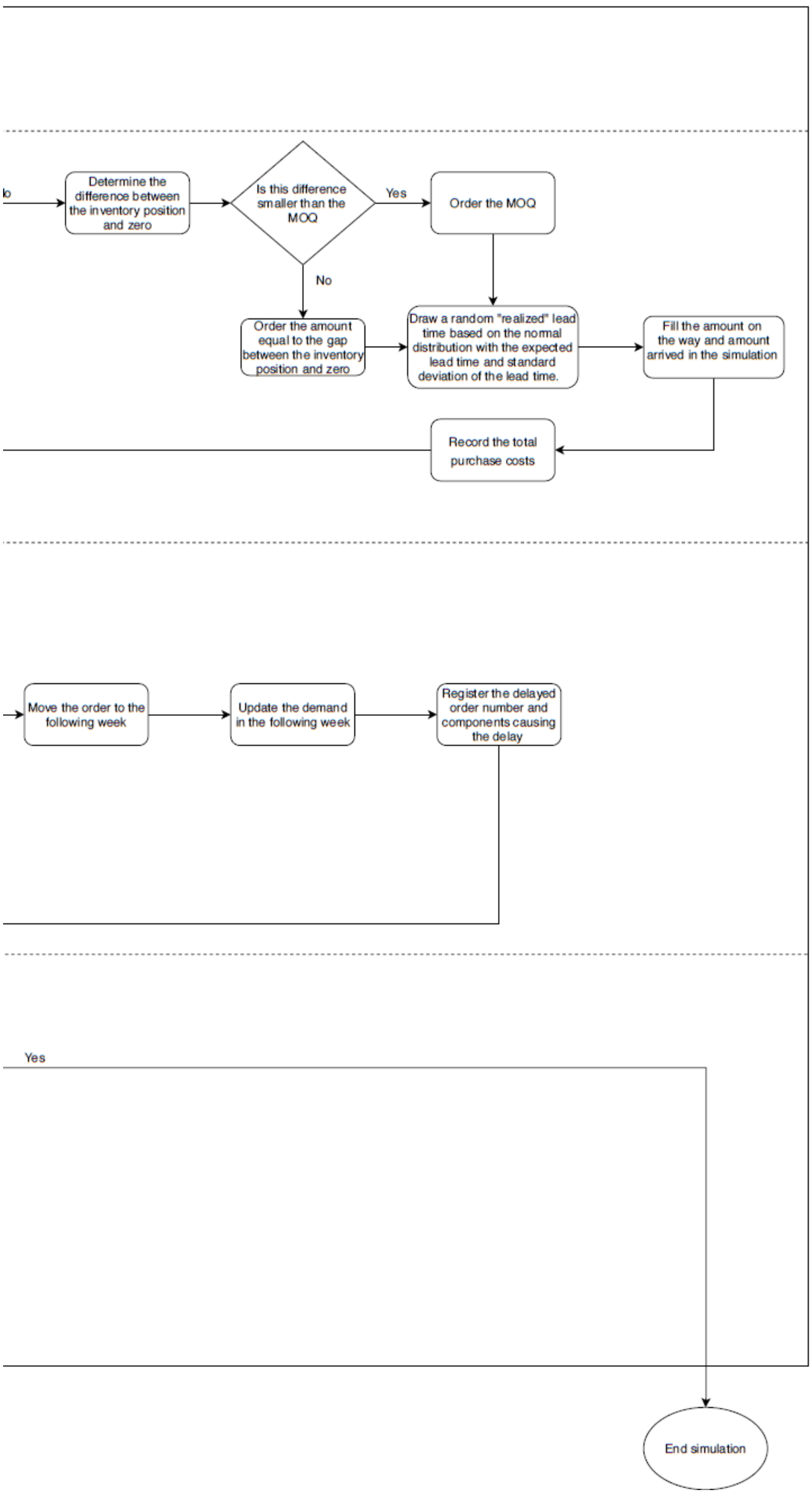

Figure 21: Flowchart safety lead time order policy part 3

Combined order policy

We divide this flowchart in six parts.

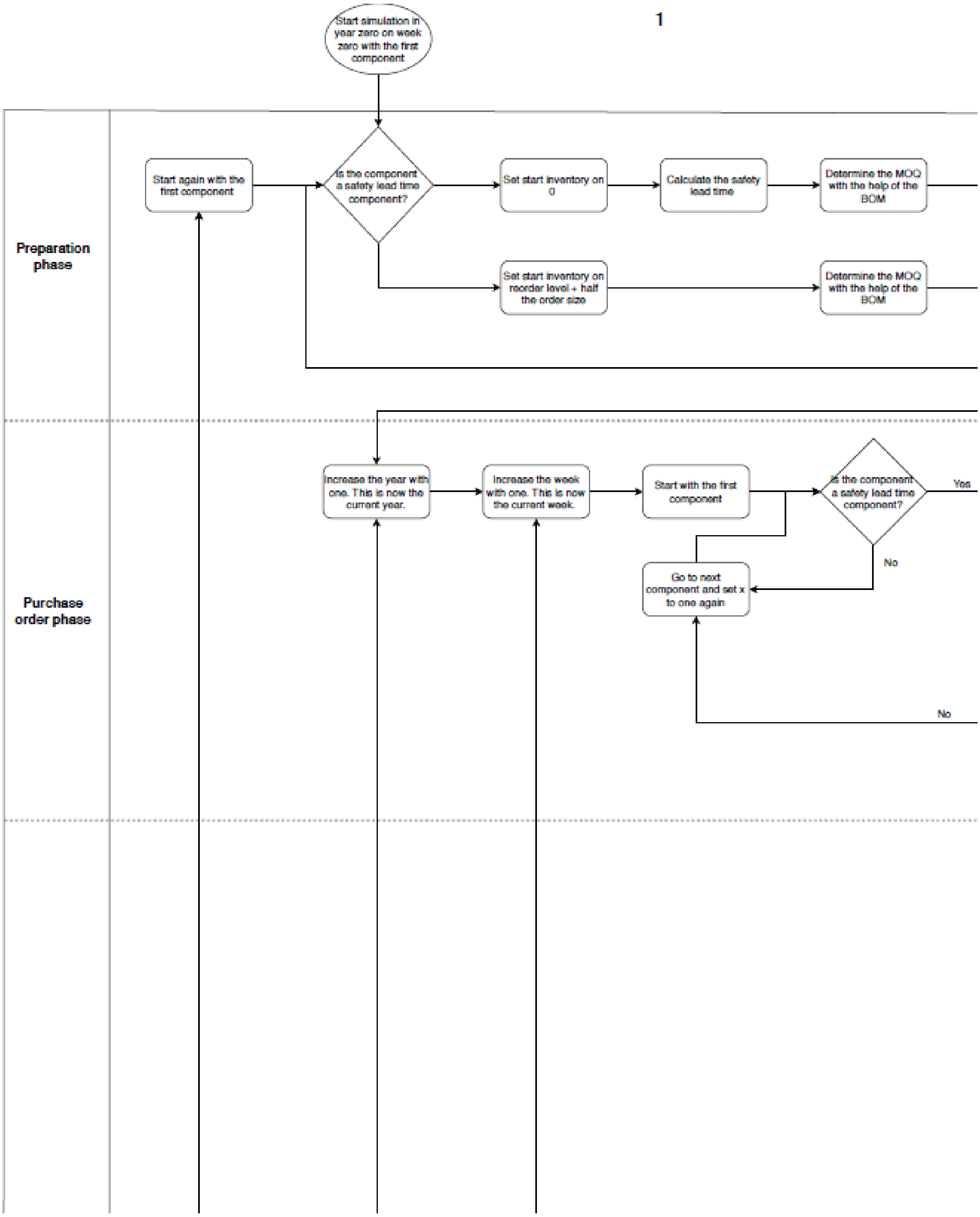

Figure 22: Flowchart combined order policy part 1

2

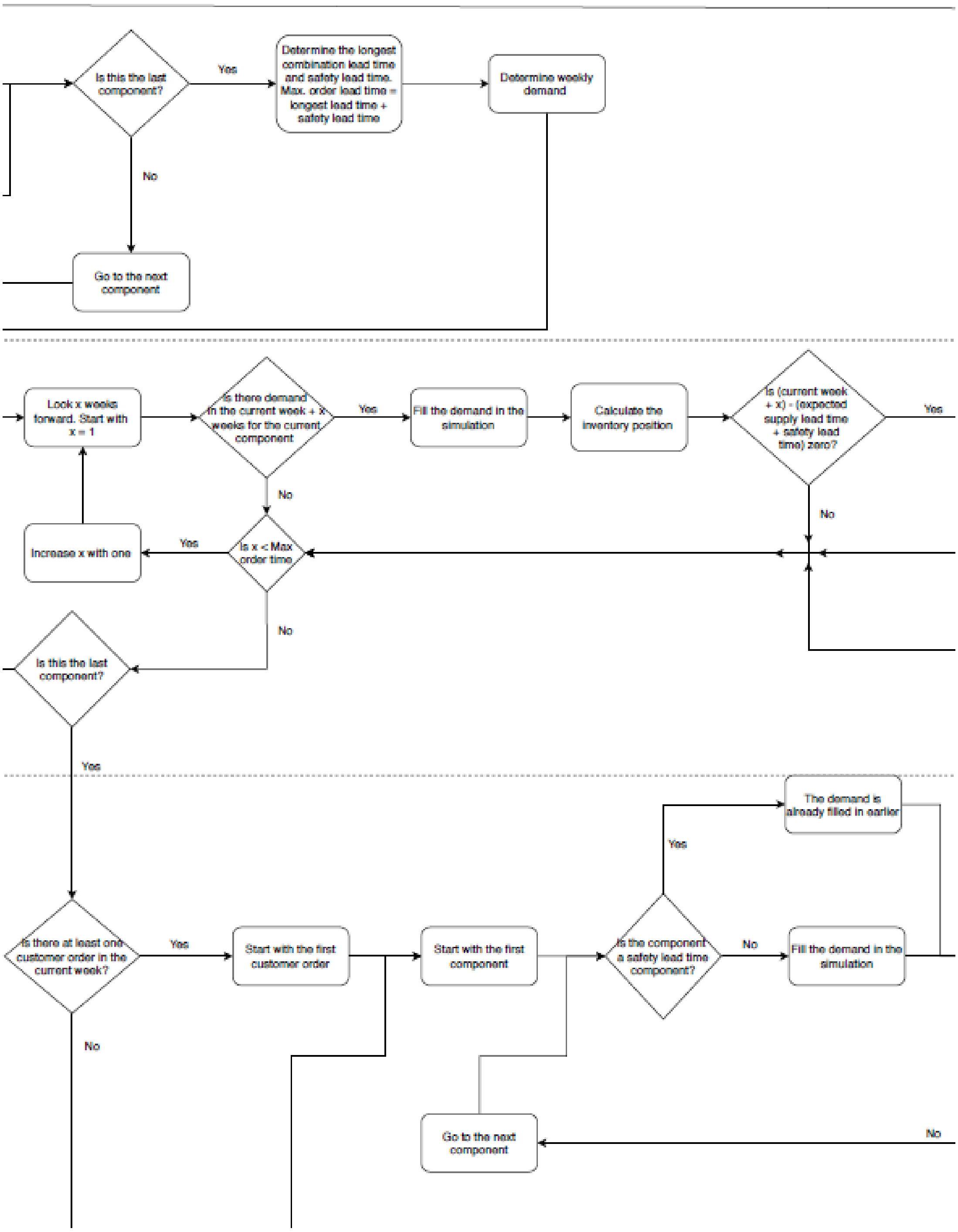

Figure 23: Flowchart combined order policy part 2

3

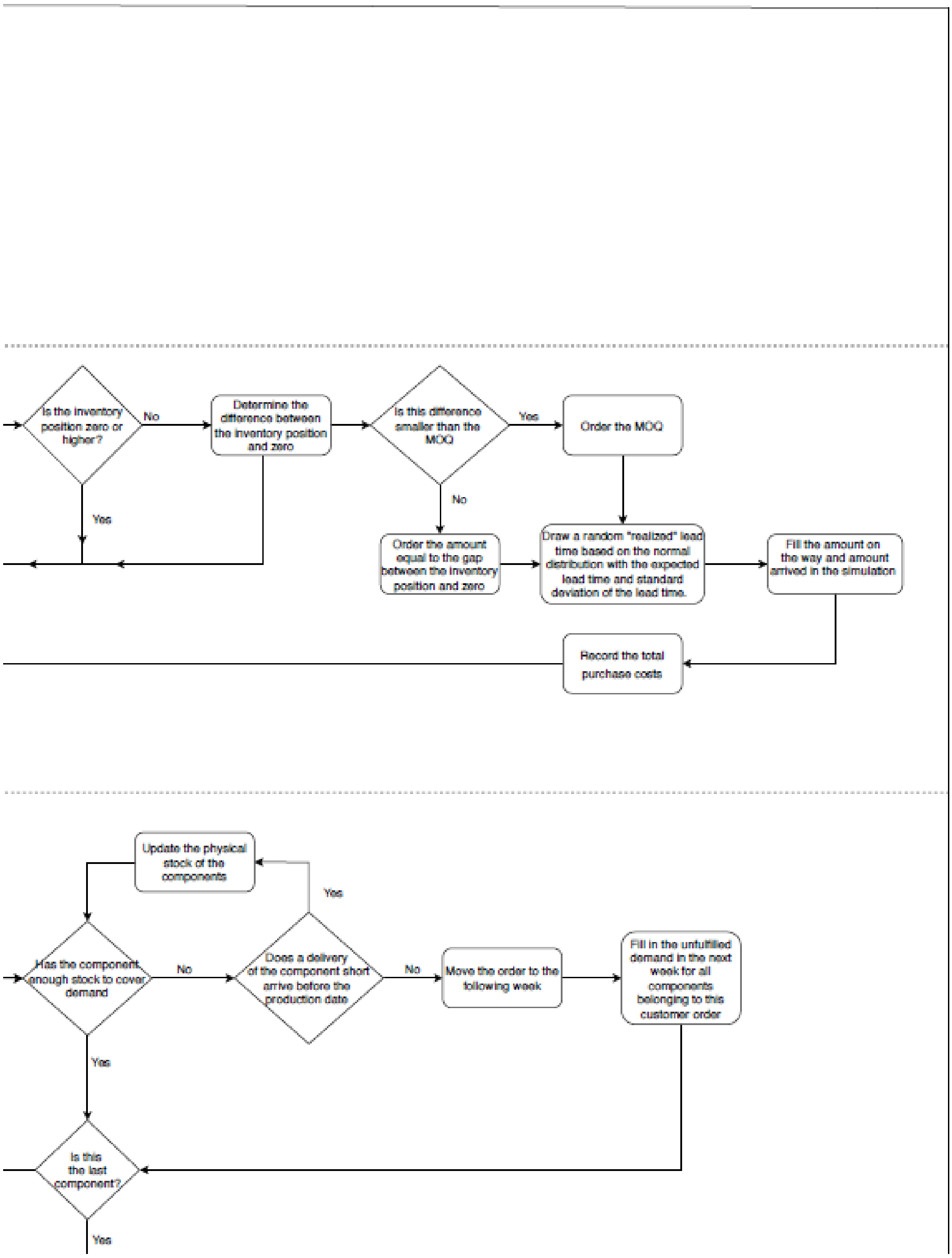

Figure 24: Flowchart combined order policy part 3

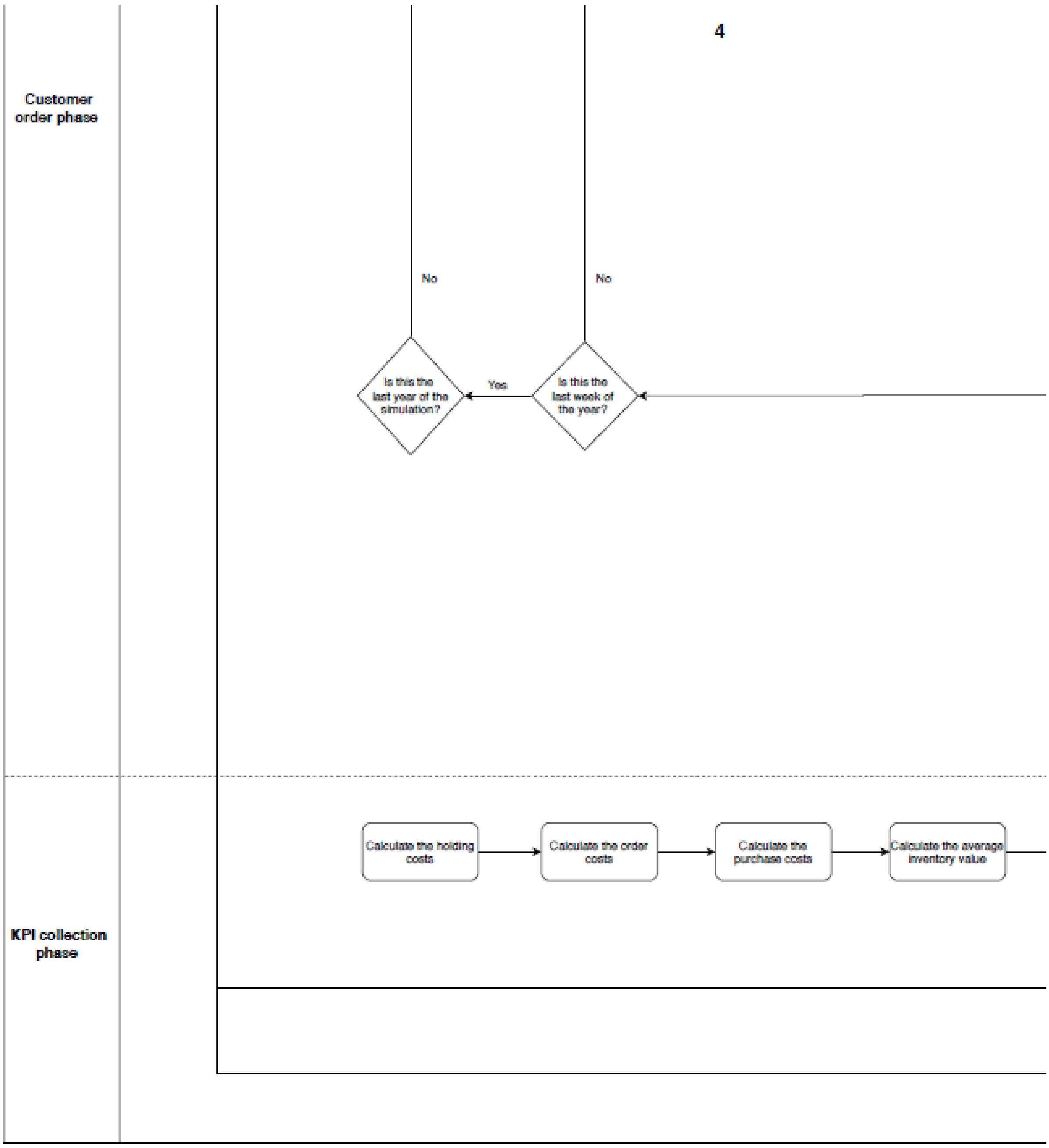

Figure 25: Flowchart combined order policy part 4

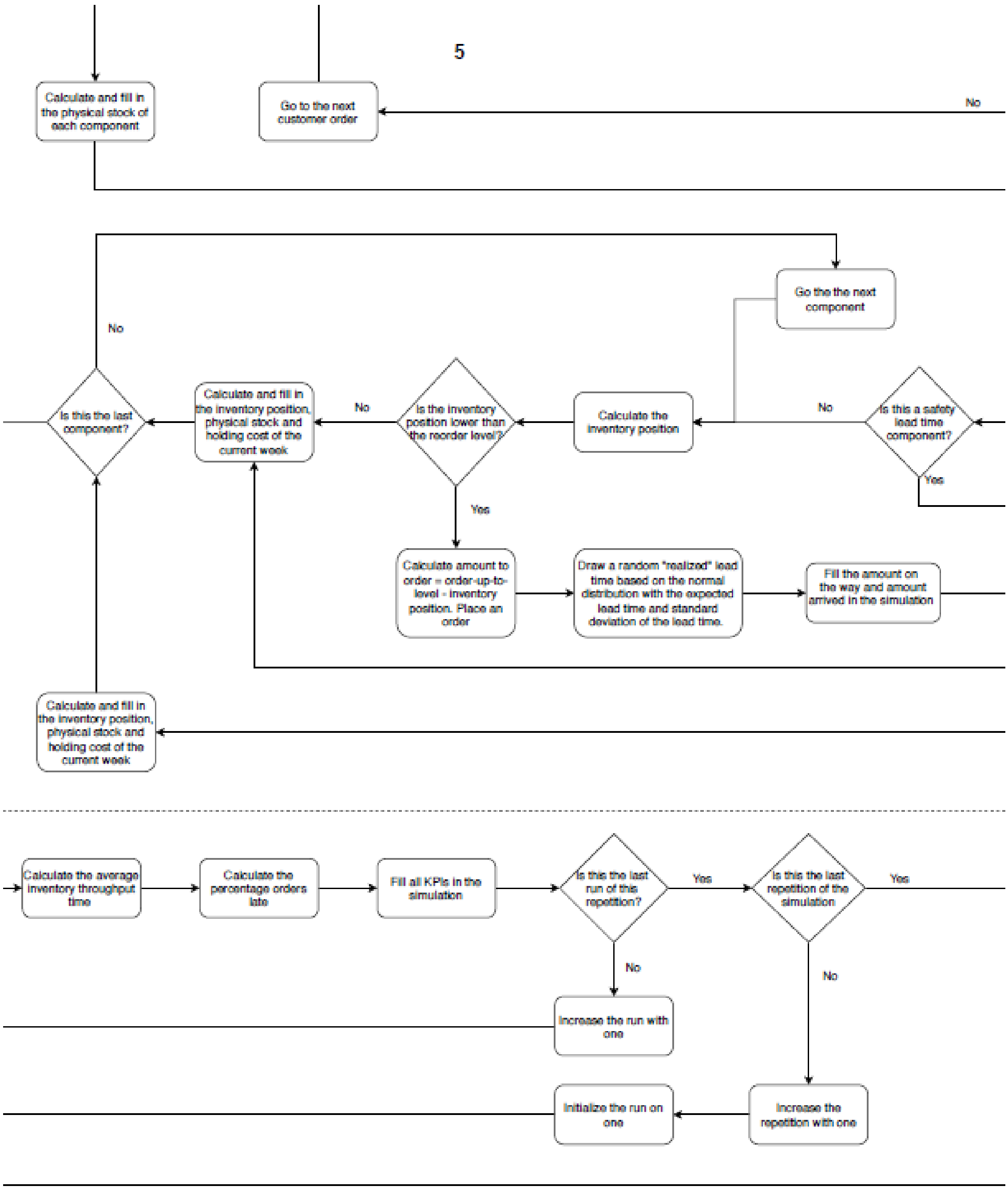

Figure 26: Flowchart combined order policy part 5

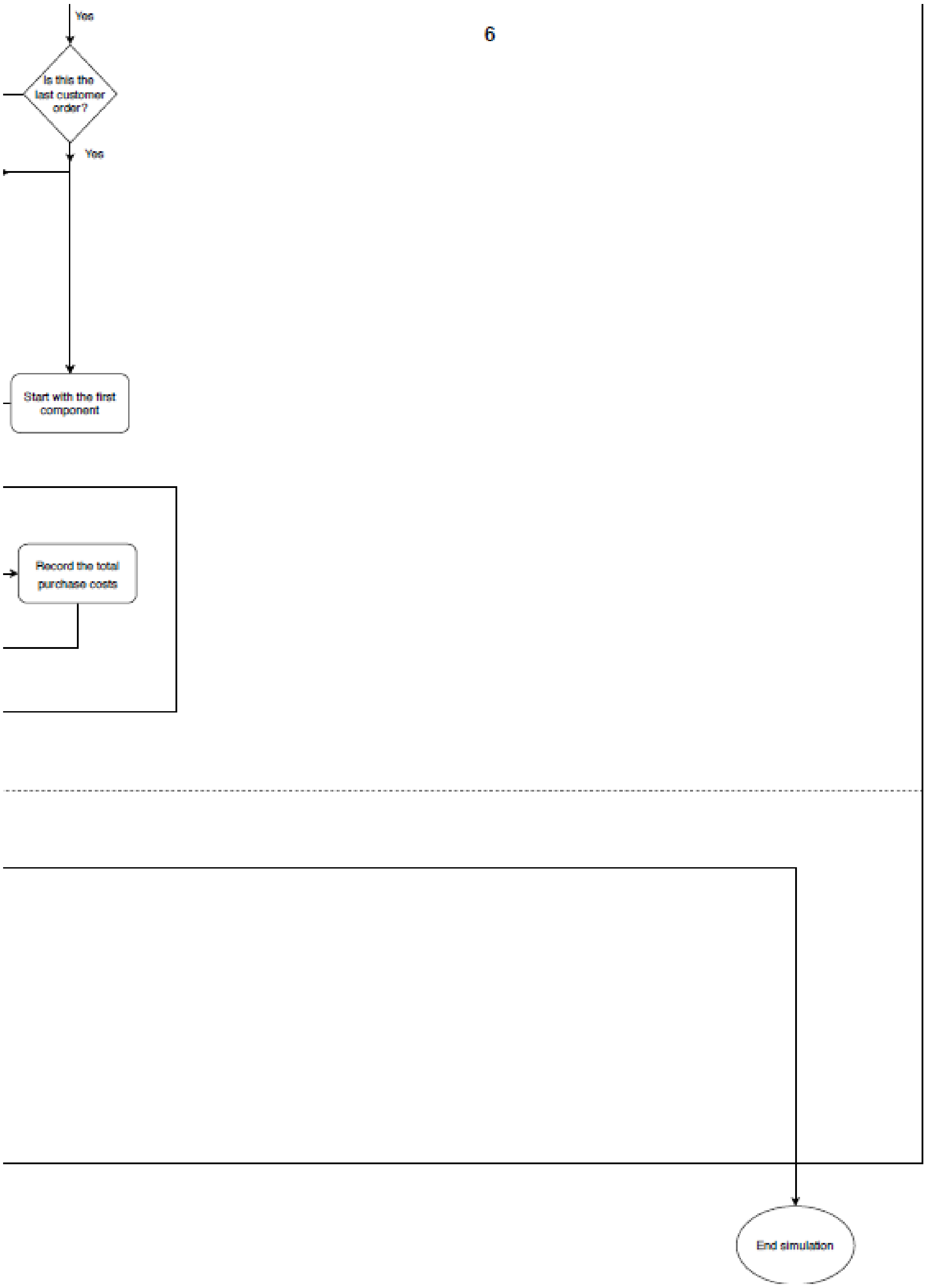

Figure 27: Flowchart combined order policy part 6

Appendix L – Model validation and historical data

In this appendix we elaborate on the model validation and especially on the differences between the model results and reality. We start with the Article group 1 validation followed by an elaboration on the data used for Article group 1. Then we discuss the validation of Article group 2, which is also followed by an elaboration on the used data for Article group 2.

Validation simulation Article group 1

We start with the validation of Article group 1. The results of the current order policy according to the simulation, the combined order policy, and the number in reality are presented in Table 26. As discussed in the report, reality and both order policies do not match. We first discuss why the current order policy as simulated does not match reality. Then we will per KPI compare the combined order policy and numbers from reality and discuss where the difference comes from.

Table 26: Simulation results vs reality Article group 1

	Holding costs	Order costs	Purchase costs	Total costs	Average inventory value	Percentage orders late	Inventory throughput time (months)
Current order policy	€ 8,300	€ 4,500	€ 154,000	€ 166,800	€ 34,600	19.1%	1.52
Combined order policy	€ 14,900	€ 3,000	€ 142,300	€ 160,200	€ 61,900	2.0%	3.73
Reality	€ 8,700	€4,800	€179,200	€ 192,700	€36,850	45.0%	0.92

In the report we already discussed two main reasons for the mismatch between the current order policy from Table 26 and the numbers in reality. First, the input data lacks input data from the months November and December due to the transition to a different ERP system. Second, it turns out that this article group is an exception in the way components are ordered. To benefit from quantity discounts, this planner orders for this article group in large amounts instead of only the amount that is needed for production. The order policy that is used by the planner approximates the combined order policy we tested in scenario 4. Therefore, we compare the combined order policy with numbers from reality, because this is the best approximation of reality. Next, we will per KPI discuss where the differences between the simulated values and reality come from.

We start with the total purchase costs, because these influence the other values too. As discussed, the model underestimates the real purchase costs, because we lacked demand data from November and December. We calculate the extra components needed and multiply the number of extra components with the corresponding price. This results in a total of €46,000 missing purchase costs. When adding this to our found purchase costs we have €188,300 purchase cost. This is higher than in reality, which can be explained by the order quantities. In the simulation model always the EOQ is ordered, but the EOQ values are larger than the order sizes that in reality are ordered. This results in higher purchase costs in the simulation than in reality.

This is also the reason the order costs are higher in reality. Although the planner buys in larger than needed, he still buys in lower quantities than the EOQs. This results in more orders placed in reality than in our simulation. Further, the missing orders in our input data mean fewer components needed, so fewer orders placed for extra components.

The lower average inventory value and holding costs in reality can be explained by Figure 28. As can be seen the value of the inventory was low until month six and then steeply increased. The reason is as follows: as discussed above Hittech Multin receives for about two years ahead of new orders from this customer. Halfway 2019 the new orders came in and the responsible planner bought in large quantities. This resulted in a low inventory value until month six. The average inventory was therefore low but is significantly higher in 2020. The same applies to the holding costs, which are a percentage of the inventory value. Furthermore, we miss historical data about the inventory of the last two months. During this period, the inventory value was high, so the average inventory value would have been higher if we had a complete year of inventory data.

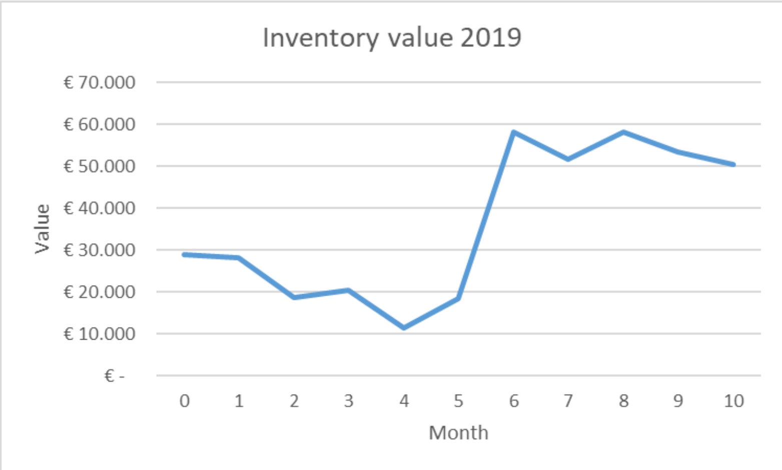

Figure 28: Inventory value 2019

The difference in percentage orders late can be explained by a few very poorly performing suppliers. Where these suppliers used to deliver reliable, they delivered poorly in the last year. The responsible planner estimated that before the supply performance decreased, the percentage order late was at a maximum of 3%. This makes sense, because the planner kept inventories for most components, so we expect a low percentage of delayed production orders. The 45% in Table 26 is therefore not a representative value.

The last KPI is the inventory throughput time, which is much lower in reality than in our model. This has two reasons. First is the low inventory value until month six, which results in half a year of low inventory throughput time. Second is the overestimation of the expected turnover. The total turnover of 2019 was about €320,000 which is an average monthly turnover of about €27,000. The average expected monthly turnover in the historical data was about €36,000 and much higher in the last months of the year. The combination of both causes ensures that the throughput time of the inventory is much lower in the historical data than in our simulation.

Article group 1 historical data calculations

Average inventory value, inventory throughput time and holding costs

We use the historical inventory data to calculate the holding costs. We look at the average inventory once every four weeks. We multiply this amount by the holding cost percentage of keeping four weeks inventory. The holding cost percentage per year is 24%, so the holding cost percentage per four weeks is $\frac{24\%}{52\ weeks} * 4\ weeks = 1.85\%$.

An overview of the inventory value, expected turnover, and throughput time of the inventory can be found in Table 27. We only have data until week 44. Then the new ERP system went live, and the data needed was not recorded. For the missing eight weeks of inventory and missing holding cost we add twice the average holding cost for holding four weeks of inventory.

We calculate a total average inventory value of €36,850, an inventory throughput time of 0.92 months, and a total holding cost of €8,000.

Table 27: Historical inventory and expected turnover Article group 1

Week	Inventory	Expected turnover	Inventory throughput time (months)
4	€ 29,000	€ 36,100	0.80
8	€ 28,100	€ 38,100	0.74
12	€ 18,600	€ 15,900	1.17
16	€ 20,500	€ 22,700	0.90
20	€ 11,400	€ 16,100	0.71
24	€ 18,300	€ 34,700	0.53
28	€ 58,100	€ 59,300	0.98
32	€ 51,600	€ 39,900	1.29
36	€ 58,100	€ 59,300	0.98
40	€ 53,300	€ 54,500	0.98
44	€ 50,500	€ 49,400	1.02
Average	€ 36,850	€ 38,990	0.92

Order and purchase costs

To calculate the order and purchase costs over 2019 we use the historical purchase data out of Navision (the former ERP system). The historical data displays all purchase orders related to Article group 1. Unfortunately, the real order date of each purchase order is not available. Therefore, we use the demanded delivery date. This delivery date falls in the year 2019. This means that we include some orders from 2018 and exclude some orders placed in 2019, but it is a good approximation.

With the historical data we calculate that a total of 155 orders are placed, which equals €4,800 order costs. The total purchased amount is €179,200.

Percentage orders late

To calculate the percentage orders late we use the historical pick data of production orders. Important to note is that this data is only available since the new ERP system went live. The historical data is therefore from 2020 instead of 2019. We will use this historical data as the best approximation for the period we simulated for. We calculate the percentage orders late due to lacking material by comparing the pick dates of the components and the planned production date. All production orders that are picked later than planned contribute to the percentage orders late. The reason the order started late cannot be found in the historical data. This means that a part of the calculated percentage will be due to a different reason than components that arrived later than expected. However, the main part is caused by late arrival of components, as discussed in chapter 2, and we do not have any other historical data. Therefore, we use this as the best approximation we have. The calculated percentage orders that started late was 45%.

Validation simulation Article group 2

Here we discuss per KPI the difference between the simulation result and reality. In the report we already provided the following three main reasons. First, the input data lacks input data from the months November and December due to the transition to a different ERP system. Second, before the switch to the new ERP system, Hittech Multin made sure extra inventory was available in case problems occurred during the transition. Thirdly, the customer (cannot be named due to confidentiality) started with a high demand for Article group 2, but demand suddenly dropped. Many components with long lead times were already bought in by Hittech Multin. This resulted in high inventories. In Table 28 the overview of the results and reality can be found. The calculations of the numbers in reality can be found in the next section.

Table 28: Simulation results vs reality

	Holding costs	Order costs	Purchase costs	Total yearly costs	Average inventory value	Percentage orders late	Inventory throughput time (months)
Simulation	€ 110,000	€ 86,000	€ 3,156,000	€ 3,352,000	€ 457,000	89%	0.30
Floorstock	€ 7000	€ 4000	€ 30,000	€41,000	€30,000	0%	0.03
Reality	€ 167,000	€ 70,000	€ 3,501,000	€ 3,738,000	€ 696,000	74%	3.40

The average inventory value is mainly higher in reality than in our simulation due to the last two above-mentioned reasons. Further, the model does not consider repairs of end products that are returned by the customer to Hittech Multin. These repairs also need replacement components, which are held in stock.

The holding costs are higher in reality due to the higher average inventory value.

The order costs are lower in reality than in our simulation. Because the forecasted demand of the customer was so high at the beginning of the year, large orders were placed. When demand suddenly dropped the inventory was enough to cover much of the demand. Until the moment the demand rose again almost no components were ordered. In the end this resulted in less, but larger orders.

The higher purchase costs in reality are due to two causes. First, the underestimated customer demand in the simulation. We calculate that the extra purchase costs of the 15 customer orders are about €253,000. This is calculated by the extra components needed for the missing production orders times the price. When we sum up the purchase costs of the model, the floorstock, and the extra customer orders we end up with €3,448,000. We expect that the remaining difference with the reality is caused by components used for repairs of end products from customers. This is out of the scope of our simulation but does occur in reality.

The difference in percentage orders late can be explained by the high inventory held by Hittech Multin, which is not present in the simulation. Further, the planner indicated that he often used longer safety lead times than the official one week.

The difference in inventory throughput time has two reasons. On the one hand is the high average inventory value in reality, which increases the throughput time. On the other hand, is a difference in the calculation of the throughput time between reality and the simulation. In the simulation, when a customer order cannot be produced, the order is moved to the next week. The expected turnover for the following month increases because the amount of customer orders increases. Because so many customer orders are produced late, the expected turnover becomes large. In reality, the turnover of a customer orders that should have been fulfilled in the past is not considered as expected turnover. The expected turnover remains reasonable and the throughput time does not become as small as in the simulation.

Article group 2 historical data calculations

Average inventory value, inventory throughput time and holding costs

We use the historical inventory data to calculate the holding costs. We look at the average inventory once every four weeks. We multiply this amount by the holding cost percentage of keeping four weeks inventory. The holding cost percentage per year is 24%, so the holding cost percentage per four weeks is $\frac{24\%}{52\ weeks} * 4\ weeks = 1.85\%$.

An overview of the inventory value, expected turnover, and throughput time of the inventory can be found in Table 29. We only have data until week 44. Then the new ERP system went live, and the data needed was not recorded. For the missing eight weeks of inventory and thus holding cost we add twice the average holding cost for holding four weeks of inventory.

We calculate a total average inventory value of €696,000, an inventory throughput time of 3.40 months, and a total holding cost of €167,000.

Table 29: Historical inventory and expected turnover Article group 2

Week	Inventory	Expected turnover	Inventory throughput time (months)
4	€ 830,000	€ 371,000	2.24
8	€ 711,000	€ 290,000	2.45
12	€ 757,000	€ 277,000	2.73
16	€ 722,000	€ 256,000	2.82
20	€ 894,000	€ 103,000	8.68
24	€ 845,000	€ 207,000	4.08
28	€ 630,000	€ 216,000	2.92
32	€ 717,000	€ 154,000	4.66
36	€ 630,000	€ 216,000	2.92
40	€ 479,000	€ 201,000	2.38
44	€ 438,000	€ 295,000	1.48
Average	€ 696,000	€ 235,000	3.40

Order and purchase costs

To calculate the order and purchase costs over 2019 we use the historical purchase data out of Navision (the former ERP system). The historical data displays all purchase orders related to Article group 2. Unfortunately, the order date is of each order is not available. Therefore, we use the demanded delivery date. This date should fall in the year 2019. This means that we include some orders from 2018 and exclude some orders placed in 2019, but it is a good approximation.

With the historical data we calculate a total of 2,259 orders are places, which equals €70,000 purchase costs. The total purchased amount is €3,501,000.

Percentage orders late

To calculate the percentage orders late we use the historical pick data of production orders. Important to note is that this data is only available since the new ERP system went live. The historical data is therefore from 2020 instead of 2019. The responsible planner indicated that the performance over the past year has been stable, so we will use this historical data as the best approximation. We calculate the percentage orders late due to lacking material by comparing the pick dates of the components and the planned production date. All production orders that are picked later than planned contribute to the percentage orders late. The reason the order started late cannot be found in the historical data. This means that a part of the calculated percentage will be due to a different reason than components that arrived later than expected. However, the main part is caused by late arrival of components, as discussed in chapter 2, and we do not have any other historical data. Therefore, we use this as the best approximation we have. The calculated percentage orders that started late was 74%.

Floorstock calculations

The floorstock components are left out of the simulation because these components do not contribute to delayed production orders but make the simulation considerably more complex. In the historical data these components are included however, so we estimated the KPIs for the floorstock components. Here we briefly discuss how we estimated the KPIs.

We apply the same floorstock rules as we did for the Article group 1 components. We order a floorstock component when the inventory position is below half a year of demand for this component. We order the amount for one year of demand. In this way we are never short floorstock components.

We calculate the average inventory value for each component as follows: $\frac{reorder\ level + order-up-to-level}{2}$, which results in an average inventory value for floorstock components of €30,000.

The holding costs per component are calculated by multiplying the yearly holding cost percentage and the average inventory value. This results in a holding cost of €7,000.

On average, each component is ordered once a year, so the total order cost is the number of components time the cost to place an order. This results in an order cost of €4,000.

The purchase costs per component are calculated by multiplying the price of one component times the yearly demand (order size of the component). This results in a total purchase cost of €30,000.

The inventory throughput time is calculated by the average inventory value divided by the expected turnover. This results in an average throughput time of 0.03 months.

Appendix M – Results and sensitivity analyses

In this appendix we provide an overview of all results and all sensitivity analyses we performed. We start with Article group 1 and then show the results of Article group 2.

Article group 1

Overview results Article group 1

Table 30: Scenario results Article group 1

Order policy	Holding costs	Order costs	Purchase costs	Total costs
Current	€ 8,300	€ 4,500	€ 154,200	€ 167,000
Inventory	€ 55,700	€ 1,400	€ 138,300	€ 195,400
Safety LT	€ 8,200	€ 6,500	€ 154,000	€ 168,700
Combined (55 - 12 division)	€ 25,500	€ 2,900	€ 141,400	€ 169,800
Combined (54 - 13 division)	€ 25,600	€ 2,900	€ 141,000	€ 169,500
Combined (53 - 14 division)	€ 25,600	€ 2,900	€ 143,900	€ 172,400
Combined (52 - 15 division)	€ 22,300	€ 3,000	€ 142,300	€ 167,600
Combined (51 - 16 division)	€ 21,700	€ 3,100	€ 144,100	€ 168,900
Combined (50 - 17 division)	€ 21,000	€ 3,200	€ 148,400	€ 172,600
Combined (49 - 18 division)	€ 20,500	€ 3,300	€ 149,900	€ 173,700
Order policy	**Start value inventory**	**Average inventory value**	**Inventory throughput time (months)**	**Percentage orders late**
Current	€0	€ 34,600	1.52	19.1%
Inventory	€ 185,000	€ 154,700	9.76	2.1%
Safety LT	€0	€ 34,100	1.99	1.1%
Combined (55 - 12 division)	€ 51,750	€ 70,800	4.41	1.8%
Combined (54 - 13 division)	€ 49,100	€ 71,100	4.38	1.8%
Combined (53 - 14 division)	€ 47,800	€ 71,100	4.56	1.1%
Combined (52 - 15 division)	€ 37,000	€ 61,900	3.73	2.0%
Combined (51 - 16 division)	€ 34,200	€ 60,300	3.67	1.7%
Combined (50 - 17 division)	€ 31,900	€ 58,500	3.46	2.3%
Combined (49 - 18 division)	€ 29,400	€ 56,900	3.38	2.1%

Sensitivity analysis current order policy

Table 31: Sensitivity analysis current order policy Article group 1

Lead time uncertainty	Holding costs	Order costs	Purchase costs	Total yearly costs	Average inventory value	Inventory throughput time (months)	Percentage orders late
100%	€8,300	€4,500	€ 154,200	€ 167,000	€ 34,600	1.52	19.1%
80%	€8,300	€4,500	€ 154,200	€ 167,000	€ 34,700	1.63	13.0%
60%	€7,900	€4,500	€ 154,200	€ 166,500	€ 33,000	1.94	5.4%
40%	€7,800	€4,500	€ 154,200	€ 166,500	€ 32,400	2.06	1.4%
20%	€7,800	€4,500	€ 154,200	€ 166,500	€ 32,400	2.06	0.3%
0%	€7,900	€4,500	€ 154,200	€ 166,600	€ 33,100	2.06	0.0%

Sensitivity analysis inventory order policy

Table 32: Sensitivity analysis inventory order policy Article group 1

Lead time uncertainty	Holding costs	Order costs	Purchase costs	Total yearly costs
100%	€ 55,700	€ 1,400	€ 138,300	€ 195,400
80%	€ 49,800	€ 1,400	€ 138,800	€ 190,000
60%	€ 44,100	€ 1,400	€ 139,100	€ 184,600
40%	€ 43,700	€ 1,500	€ 139,000	€ 184,200
20%	€ 42,900	€ 1,500	€ 139,000	€ 183,400
0%	€ 42,200	€ 1,600	€ 138,400	€ 182,200
Lead time uncertainty	**Value start inventory**	**Average inventory value**	**Percentage orders late**	**Inventory throughput time (months)**
100%	€ 185,000	€ 154,700	2.1%	9.76
80%	€ 168,500	€ 138,300	2.1%	8.75
60%	€ 152,300	€ 122,600	2.3%	7.67
40%	€ 151,000	€ 121,400	2.5%	7.60
20%	€ 148,500	€ 119,100	2.4%	7.41
0%	€ 145,600	€ 117,200	2.0%	7.41

Sensitivity analysis safety lead time order policy

Table 33: Sensitivity analysis safety lead time order policy Article group 1

Lead time uncertainty	Holding costs	Order costs	Purchase costs	Total yearly costs
100%	€ 8,200	€ 6,500	€ 154,000	€ 168,700
80%	€ 7,600	€ 6,600	€ 154,000	€ 168,200
60%	€ 7,100	€ 6,500	€ 154,000	€ 167,600
40%	€ 6,800	€ 6,600	€ 154,000	€ 167,400
20%	€ 6,200	€ 6,600	€ 154,000	€ 166,800
0%	€ 6,200	€ 6,600	€ 154,000	€ 166,800
Lead time uncertainty	**Average inventory value**	**Inventory throughput time (months)**	**Percentage orders late**	**Safety factor**
100%	€ 34,100	1,99	1.1%	2.05
80%	€ 31,600	1,85	1.8%	1.64
60%	€ 29,300	1,75	1.5%	1.55
40%	€ 28,400	1,69	1.2%	1.10
20%	€ 25,600	1,59	1.4%	0.00
0%	€ 25,800	1,63	0.0%	0.00

Sensitivity analysis combined order policy

The sensitivity analysis for the combined order policy is performed for the 52 inventory – 15 safety lead time combination.

Table 34: Sensitivity analysis combined order policy Article group 1

Lead time uncertainty	**Holding costs**	**Order costs**	**Purchase costs**	**Total yearly costs**
100%	€ 22,300	€ 3,000	€ 142,300	€ 167,600
80%	€ 20,000	€ 3,000	€ 142,000	€ 165,000
60%	€ 19,400	€ 3,000	€ 142,700	€ 165,100
40%	€ 18,700	€ 3,000	€ 142,600	€ 164,300
20%	€ 18,400	€ 3,000	€ 142,800	€ 164,200
0%	€ 17,800	€ 3,000	€ 143,000	€ 163,800
Lead time uncertainty	**Value start inventory**	**Average inventory value**	**Percentage orders late**	**Inventory throughput time (months)**
100%	€ 37,000	€ 61,900	2.3%	3.74
80%	€ 36,200	€ 55,600	2.1%	3.48
60%	€ 36,300	€ 54,000	1.8%	3.41
40%	€ 35,500	€ 52,000	2.5%	3.25
20%	€ 35,600	€ 51,000	1.5%	3.24
0%	€ 35,600	€ 49,500	1.8%	3.12

Article group 2

Overview all results Article group 2

Table 35: Scenario results Article group 2

Order policy	Holding costs	Order costs	Purchase costs	Total costs
Current	€ 110,000	€ 86,000	€ 3,156,000	€ 3,352,000
Inventory	€ 315,000	€ 31,000	€ 3,070,000	€ 3,416,000
Safety lead time	€ 114,000	€ 86,000	€ 3,156,000	€ 3,356,000
Combined (208 – 42 division)	€ 159,000	€ 44,000	€ 3,071,000	€ 3,274,000
Combined (207 – 43 division)	€ 159,000	€ 44,000	€ 3,068,000	€ 3,271,000
Combined (206 – 44 division)	€ 158,000	€ 44,000	€ 3,070,000	€ 3,272,000
Combined (205 – 45 division)	€ 157,000	€ 45,000	€ 3,068,000	€ 3,270,000
Combined (204 – 46 division)	€ 154,000	€ 46,000	€ 3,063,000	€ 3,263,000
Order policy	**Start value inventory**	**Average inventory value**	**Inventory throughput time (months)**	**Percentage orders late**
Current		€ 457,000	0.30	89.1%
Inventory	€ 1,846,000	€ 1,312,000	3.79	2.1%
Safety lead time		€ 473,000	1.25	0.1%
Combined (208 – 42 division)	€ 420,000	€ 663,000	1.83	2.0%
Combined (207 – 43 division)	€ 413,000	€ 661,000	1.83	1.7%
Combined (206 – 42 division)	€ 403,000	€ 656,000	1.81	1.8%
Combined (205 – 45 division)	€ 398,000	€ 655,000	1.81	1.1%
Combined (204 – 46 division)	€ 381,000	€ 641,000	1.76	2.0%

Sensitivity analysis current order policy

Table 36: Sensitivity analysis current order policy Article group 2

Lead time uncertainty	Holding costs	Order costs	Purchase costs	Total yearly costs	Average inventory value	Percentage orders late	Inventory throughput time (months)
100%	€ 110,000	€ 86,000	€ 3,156,000	€ 3,352,000	€ 457,000	89%	0.30
80%	€ 94,000	€ 86,000	€ 3,156,000	€ 3,336,000	€ 391,000	75%	0.38
60%	€ 84,000	€ 86,000	€ 3,156,000	€ 3,326,000	€ 349,000	55%	0.49
40%	€ 74,000	€ 86,000	€ 3,156,000	€ 3,316,000	€ 309,000	23%	0.64
20%	€ 70,000	€ 86,000	€ 3,156,000	€ 3,312,000	€ 293,000	1%	0.74
0%	€ 70,000	€ 86,000	€ 3,156,000	€ 3,312,000	€ 292,000	0	0.75

Sensitivity analysis inventory order policy

Table 37: Sensitivity analysis inventory order policy Article group 2

Lead time uncertainty	Holding costs	Order costs	Purchase costs	Total yearly costs
100%	€ 315,000	€ 31,000	€ 3,070,000	€ 3,416,000
80%	€ 251,000	€ 31,000	€ 3,070,000	€ 3,352,000
60%	€ 234,000	€ 31,000	€ 3,070,000	€ 3,335,000
40%	€ 225,000	€ 31,000	€ 3,070,000	€ 3,326,000
20%	€ 223,000	€ 31,000	€ 3,070,000	€ 3,324,000
0%	€ 199,000	€ 31,000	€ 3,070,000	€ 3,300,000
Lead time uncertainty	**Value start inventory**	**Average inventory value**	**Percentage orders late**	**Inventory throughput time (months)**
100%	€ 1,846,000	€ 1,312,000	2.1%	3.79
80%	€ 1,576,000	€ 1,044,000	2.3%	3.03
60%	€ 1,507,000	€ 967,000	1.9%	2.84
40%	€ 1,467,000	€ 938,000	1.1%	2.74
20%	€ 1,459,000	€ 929,000	1.0%	2.72
0%	€ 1,337,000	€ 828,000	1.3%	2.42

Sensitivity analysis safety lead time order policy

Table 38: Sensitivity analysis safety lead time order policy Article group 2

Lead time uncertainty	Holding costs	Order costs	Purchase costs	Total yearly costs
100%	€ 114,000	€ 86,000	€ 3,156,000	€ 3,356,000
80%	€ 95,000	€ 86,000	€ 3,156,000	€ 3,337,000
60%	€ 87,000	€ 86,000	€ 3,156,000	€ 3,329,000
40%	€ 74,000	€ 86,000	€ 3,156,000	€ 3,316,000
20%	€ 59,000	€ 86,000	€ 3,156,000	€ 3,301,000
0%	€ 56,000	€ 86,000	€ 3,156,000	€ 3,298,000
Lead time uncertainty	**Average inventory value**	**Percentage orders late**	**Inventory throughput time (months)**	**Safety factor**
100%	€ 473,000	0.13%	1.25	2.58
80%	€ 395,000	0.99%	1.08	2.14
60%	€ 364,000	2.49%	0.98	2.05
40%	€ 309,000	0.65%	0.86	1.96
20%	€ 247,000	0.19%	0.71	1.06
0%	€ 233,000	0.00%	0.66	0.00

Sensitivity analysis combined order policy

The sensitivity analysis for the combined order policy is done for the 206-44 combination.

Table 39: Sensitivity analysis combined order policy Article group 2

Lead time uncertainty	Holding costs	Order costs	Purchase costs	Total yearly costs
100%	€ 158,000	€ 44,000	€ 3,070,000	€ 3,272,000
80%	€ 136,000	€ 44,000	€ 3,070,000	€ 3,250,000
60%	€ 120,000	€ 44,000	€ 3,070,000	€ 3,234,000
40%	€ 113,000	€ 44,000	€ 3,070,000	€ 3,227,000
20%	€ 103,000	€ 44,000	€ 3,070,000	€ 3,217,000
0%	€ 95,000	€ 44,000	€ 3,070,000	€ 3,209,000
Lead time uncertainty	**Value start inventory**	**Average inventory value**	**Percentage orders late**	**Inventory throughput time (months)**
100%	€ 403,000	€ 656,000	1.8%	1.81
80%	€ 378,000	€ 568,000	1.8%	1.58
60%	€ 357,000	€ 501,000	2.1%	1.37
40%	€ 350,000	€ 470,000	2.1%	1.29
20%	€ 340,000	€ 430,000	2.0%	1.20
0%	€ 328,000	€ 396,000	1.6%	1.12