Bachelor Thesis

Improving warehouse slotting at HTM Aerotec to decrease the order picking time.

Oct 2024

htm aerotec

UNIVERSITY OF TWENTE.

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“Improving warehouse slotting at HTM Aerotec to decrease the order picking time”

Date: 22-10-2024

Number of pages: 74

Number of appendices: 3

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Preface

Dear reader,

With a feel of relief and gratitude I present to you my bachelor thesis, “*improving warehouse slotting at HTM Aerotec to decrease the order picking time*”. This thesis concludes my bachelor study, Industrial Engineering & Management, at the University of Twente. The research is conducted at HTM Aerotec from February 2024 till October 2024. In this thesis the Chicago manual of style is used for number formatting and the seventh edition of APA referencing is used as the main referencing style.

I would like to express my sincere gratitude towards the people at HTM Aerotec. Especially, Arthur Kasteel and Marco van Renselaar. They both provided invaluable support during my research and enriched me with essential knowledge and information. Without their help the quality of this bachelor thesis would have been substantially less.

I also want to express my sincere gratitude towards my first supervisor, Dr. M. Koot, for his invaluable feedback and expertise. He supported me among the way and showed exceptional understanding and thoughtfulness throughout the process. I would also like to extend my gratitude towards my second supervisor, Dr. P.C. Schuur, for his invaluable feedback. I am grateful for their support, and without them I could not have reached the quality and results.

Best,

Jorn Morsink

October 2024

Management summary

This research is performed at HTM Aerotec in Hengelo. HTM Aerotec is one of the five companies from the HTM technologies group. HTM Aerotec is a supplier in high precision metal parts and mechatronical integrated modules and it is operating in the advanced aerospace and defence industries.

HTM Aerotec faced the following problem in the logistic department: *logistic processes are taking too much time* which is the action problem of this research. Right now, there is an empty hall which is destined to be the new warehouse. However, there is no clear and logical assignment of products right now, which increases the order picking time. So, the main focus of this research is to *decrease the order picking time.* This is done by improving the assignment of products inside the warehouse racks and slotting the SKUs. Therefore, the main research question to answer is:

"What is an appropriate assignment of products inside the warehouse racks to decrease the order picking time at HTM Aerotec?"

This question is answered following the seven steps of the Managerial problem solving method (MPSM). To solve the research question first the current situation is analysed. After, distinct slotting methods are researched. Then a model is conducted by Duque-Jaramillo et al. (2024) that is calculating the time it takes to fill up the warehouse for six distinct strategies. The strategy with the shortest time is exercised together with chosen slotting method, which is chosen by literature research. Finally, following the previous results a final assignment of products is made for the warehouse racks of HTM Aerotec.

The new warehouse got some variables to consider since there are various slots that are obstructed and therefore cannot be reached or filled. Also, all the warehouse dimensions are revealed, which are used later in the research. In the new warehouse there is place for a total of 245 products. Besides the new warehouse, the current supply chain of HTM Aerotec is depicted with the focus solely on the logistic department. The main actions conducted in the logistic sector are deliberated. One of the actions, picking the order, is deliberated and the current order picking time is given. Right now, the order picking time is ranging from *1 to 10 minutes* with an average of *4.5 minutes*.

The chosen slotting method, the ABC strategy, slots products according to their category A, B, or C. The Stock Keeping Units (SKUs) are prioritised based on two criteria, their revenue, and their commonality. The ABC strategy is used for its flexibility and because it can slot products following multiple criteria instead of the other researched slotting method which is the COI method. The ABC slotting method is combined with the pareto principle which states that 80% of your results come from 20% of your effort, is providing the number of slots for every category and looking into their revenue.

The ABC strategy is exercised in the model by Duque-Jaramillo et al. (2024). This model calculates, with the help of VBA, which is the programming language of Excel, what has the priority when slotting your Stock Keeping Units (SKUs). The model deliberates if you should go by the rows of the warehouse, columns per rack or levels per rack. The model deliberates in which order the SKUs should be allocated to the available slots, examining both the horizontal lanes (rows), vertical lanes (columns) and storage levels (height). The model is reviewing six distinct slot assignment strategies where in each distinct strategy the row, column or level are switched. Since there are three distinct factors, there are six different variations which are the six strategies. The VBA code calculated the times for every strategy and the strategy with the lowest slotting time is strategy three.

SAS 3, which is the third strategy, is prioritizing the columns, after the rows, and last the levels. So firstly, the levels are filled of row one and column one, then row two until all the rows and column ones are filled. Thereafter the levels of row two column one are filled.

According to the results the final assignment of product inside the racks is made. A map is provided which displays exactly where every type of SKU is slotted. The different SKUs are placed together regarding the type of SKU or the supplier. With this final assignment of products, a rough estimate of the order picking time is measured, which is *1 to 3 minutes*. So, the overall order picking time is decreased, and the new assignment of products is effective. The new average order picking time is *1.75 minutes*. HTM Aerotec should start by slotting the category A products, after the category B products, and finally the category C products. The category A products should all be placed in the best available slots and category C in the worst available slots. The final phase of the MPSM is evaluating the solution, the conclusion that is formed is based on the difference in order picking time. Since there is quite a difference in order picking time compared to the old situation the results are satisfactory.

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List of abbreviations

MPSM	Managerial Problem Solving Method
PO	Purchasing Order
WO	Work Order
SKU	Stock Keeping Unit
SAS	Slot assignment sequence
COI	Cube per order index

1. Introduction

The introduction part starts with a short description of the company (Section 1.1). Thereafter, the problem is identified (Section 1.2), it describes the problem context, depicts the problem cluster, and formulates the core problem. Then, the main literature framework is briefly introduced and explained (Section 1.3). Next, the research questions are given together with their corresponding sub questions (Section 1.4). After that, the problem solving approach is deliberated (Section 1.4) together with the deliverables and the research scope. Finally, the research design is formulated (Section 0). This part describes the research types used together with the research methods that are conducted. The next part of the research design describes the research limitations together with the research validity and reliability. The final part of chapter 1 is giving a short conclusion about everything discussed in the chapter (Section 0).

1.1. Company introduction

HTM technologies consists of five distinct companies, HTM IP, HTM PSM, HTM Aerotec, HTM precision and HTM UMI. The main aim of HTM technology is to produce high precision metal parts for other companies where HTM IP is an Industrial Partner (IP) for precision large components, HTM PSM is specialised in Precision Sheet Metal (PSM), HTM precision in precision mechanical components, and HTM UMI is specialised in the Mechanical Industry. This thesis is executed at HTM Aerotec which is a supplier in high precision parts and mechatronical integrated modules for the aerospace. HTM Aerotec is producing small high precision metal parts for larger products with the use of computer numerical control (CNC) machining (see Figure 1). The material used for these high precision parts are various types of metal. HTM Aerotec is active as a highly valued long term partner for markets in the advanced aerospace and defence industries.

Figure 1, example products produced by HTM Aerotec

1.2. Problem identification

Section 1.2 is first describing the context of the problem HTM Aerotec is facing (Section 1.2.1). The second sub section is displaying the problem cluster (Section 1.2.2), after the core problem is picked (Section 1.2.3). The fourth part is describing the company criteria (Section 1.2.4). The last part of this section is describing the difference between the norm and reality (Section 1.2.5).

1.2.1. Problem context

HTM Aerotec is looking to improve their logistic department. HTM first faced a problem in their company caused by a temperature difference between the two factory halls. Both in summer and winter time, they encountered insufficiency in their end product caused by this temperature change.

Temperature changes can exert subtle yet impactful influences on CNC precision parts, potentially affecting dimensions, material properties, and overall product quality (CNCSourced, 2023). This happened when the product was being processed by the various machinery which were spread across the two factory halls. The products failed to qualify for the regulations and were rejected by the measurement room. The products had to be remade which increased the process time and money spent.

To solve this problem, they moved all of their machinery to the large factory hall leaving a large empty space which is going to function as their new production warehouse. In the old situation there was no warehouse and the products were stored across the factory in various racks. In the new situation all the products that are being assembled are stored together in the new warehouse. However, in this new production warehouse there is no logic in placements of these products cause the products are placed at random.

This led to inefficient slotting inside the warehouse racks causing inefficiency in locating and picking products which is the main problem, *processes in the logistic department are taking too much time*. In the old situation the order picking time was high which is already decreased with the new production warehouse. However, the order picking time can be decreased even further with the support of a logical slotting method of the racks. Slotting is the assignment of items or SKUs to warehouse storage locations (Petersen et al., 2005). The distinct causes for the main problem are explained in the next chapter, the problem cluster.

1.2.2. Problem cluster

The problems explained in the problem context are now placed in a problem cluster for a clear overview. All these problems occur in the new warehouse of HTM Aerotec where the main problem is processes taking too much time in the logistic department at HTM Aerotec. This problem is the action problem HTM wants to tackle and therefore is at the top of the problem cluster. This main problem is caused by inefficiency in the logistic flows at the company. The inefficiency in these flows is therefore linked to the main problem. The inefficiency in the logistic flows is caused by three other problems.

One of the three problems is a lack of space in the logistic department. The time a product spends inside the company is causing the lack of space. The new warehouse is already helping this problem, but there are still too many products for the available slots in the new warehouse. Especially the time inside the supply chain is too long for a single product. The lack of space is a result of inefficiency in the planning department and the purchase and sales department. These departments are ordering materials too soon. This is because sometimes materials are in sale or because the planning is making the materials more urgent than they actually are. Some of these products are not being processed and are laying in pallets for a couple of months which takes valuable slots. The warehouse is more crowded and therefore it is also harder to locate products which is increasing the order picking time.

The second problem causing the lack of efficiency in the logistic flows is the time spent with picking the orders. Right now, the order picking time is too high and taking up to *10 minutes* with an average of *4,5 minutes* which has two causes. The first one being, that there is no clear assignment of products inside the warehouse racks. This means that the order picker needs to travel a larger distance to pick certain products than necessary. The second cause is that the products are not traceable since there is no programme to see where a product is stored in the warehouse.

The last problem is that it is not clear for the logistic department when an order needs to be at the machinery. Some orders are more urgent than others. So, when an order is picked, they just pick the order that came in first causing an increasing in the response time for some products. The response time is the time between releasing the order and the arrival time of the order at the machinery. The lack of communication between the logistic and planning department is the main cause of this increase in response time.

All these problems together with their causes and effects are placed inside the problem cluster in Figure 2.

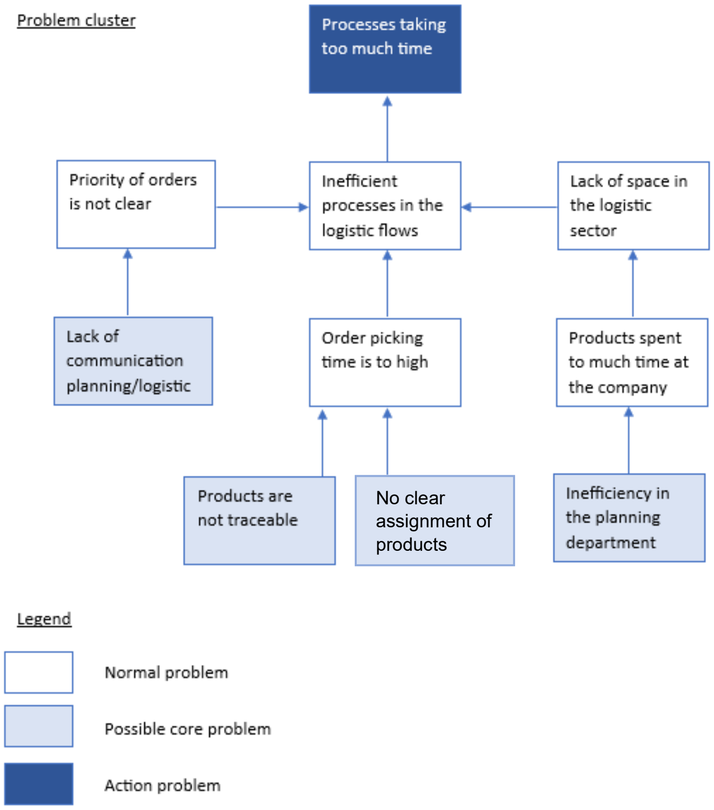

Figure 2, problem cluster.

This problem cluster displays what the possible core problems, what the action problem is, and which problems are in the end responsible for the main problem, *processes taking too much time in the logistic department.*

1.2.3. Core problem

In the problem cluster of Figure 2, it becomes clear that there are four core problems that are ultimately causing the action problem. These core problems being, lack of communication between departments, products are not traceable, no clear assignment of products in the warehouse racks and inefficient planning.

According to Heerkens and van Winden (2017) there are four different steps in identifying the core problem. Step one and two being already done in the problem cluster where step one is identifying the various problems and step two is following the chain of problems back to the problems which have no cause themselves. In the problem cluster these problems have a distinct colour and besides all the problems that are occurring are shown in the cluster. The third step according to Heerkens and van Winden (2017) is that if you cannot influence something, it cannot be a core problem.

In the problem cluster there is one problem that cannot be influenced the same way as the other three problems, being the inefficiency in the planning department. Some products are coming from other companies and arrive when they are ready or products are ordered to soon cause the purchasing price was cheaper than normal. So, some of the inefficiency that occurs in the planning department cannot be influenced directly.

Step three leaves us with three possible core problems. The last step from Heerkens and van Winden (2017) is to choose the most important problem. To decrease the total process time of the logistic department and increase the efficiency, the most influential aspect is the order picking time. Improving the communication between the planning and logistics is also improving the overall processing time, but these orders are still picked from a warehouse where the products are not efficiently assigned to the racks. So, the order picking time is still high and only a few products are faster transported thru the supply chain. The high order picking time is caused by two possible core problems, the traceability, and the assignment of products in the warehouse racks. To increase the traceability of the products a good assignment of products in the warehouse racks is required. So, the core problem is to ***improve the assignment of products inside the racks of the warehouse in the logistic department at HTM Aerotec***.

1.2.4. Company Criteria

The main focus of this research is to lower the order picking time in General, however there is some criteria to consider while conducting the research. When constructing the assignment of products for the warehouse racks, the revenue and commonality of these products are also considered. The order picking time is the main criteria, but beside that the revenue of the products and the commonality of these products also play a role in constructing the final assignment of products. The revenue of the products is however more important than its commonality and products with a higher revenue, but lower commonality are placed in better slots.

Another thing to consider while constructing the assignment of products of the slots is the varying supply of products. The demand is never fixed and is always (slightly) changing, so the supply of products is also changing. Sometimes the demand is quite steady while other times the demand is fluctuating which means the incoming products are also fluctuating. In the final design it should be clear what to do when the demand is fluctuating.

1.2.5. Norm and reality

The norm for the company is a clear assignment of products inside the warehouse where products are convenient to locate, and the logistic processes are running efficient. They want the order picking time low, especially for the high priority products. The assignment of products inside the racks should be based on distinct criteria which are explained in Section 1.2.4. In reality, products are placed at random in the new warehouse and it is hard to locate distinct products. Picking the orders is not as efficient as HTM Aerotec desires which is the core problem of this thesis. To main measurement between the difference of the norm and reality is the order picking time. This time is used to conclude the thesis and form the recommendation for a new slotting method and evaluation of that recommended method.

1.3. Theoretical framework

To realize an improvement in assigning the products in the warehouse racks two decisions must be made. The first decision is about what operation strategies are used to categorize the distinct products and their priorities. The second decision to be made is about the layout of the products inside the racks in the logistics department, which product should be assigned to which place. A place inside a warehouse rack is also referred to as a slot which term is mainly used in this thesis. The thesis is surrounding the term warehouse design which has many articles and sources regarding the topic. However, there is one article which is also deliberating on the two before mentioned decisions. The article of Gu et al. (2010) is explaining five major decisions that engage in warehouse design which are displayed in Figure 3. The five decisions of the article from Gu et al. (2010) are, determining the overall warehouse structure; sizing and dimensioning the warehouse and its departments; determining the detailed layout within each department; selecting warehouse equipment; and selecting operational strategies.

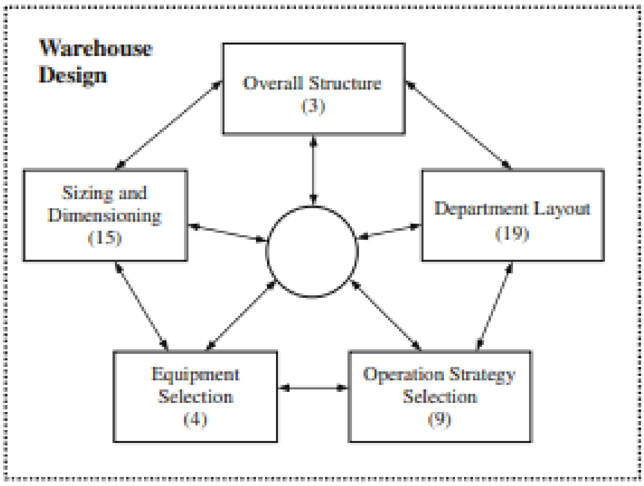

Figure 3, Warehouse design, five decisions. From "Research on warehouse design and performance evaluation: A comprehensive review," by J. Gu, 2010, *European Journal of Operational Research, 203,* p. 539–549. Copyright 2009 by Elsevier B.V.

The article from Gu et al. (2010) is used as the theoretical framework where from the five decisions of warehouse design, two are answered to solve the core problem. The main one being Department layout which is the detailed configuration within a warehouse department, for example, aisle configuration in the retrieval area, pallet block-stacking pattern in the reserve storage area, and configuration of an Automated Storage/Retrieval System (AS/RS) (Gu et al., 2010). This decision is also including the detailed configuration of the warehouse department, which implies how the distinct slots are filled. One department of the warehouse is referred to in the article as one rack for outgoing products for example. So, the detailed configuration of this department is how to assign the products to this rack. The second decision, which is used to determine the slotting strategy, is Operation strategy selection. The selection of the operation strategy determines how the warehouse will be operated, for example, with regards to storage and order picking (Gu et al., 2010).

1.4. Research questions and problem solving approach

Section 1.4 is producing the main line of this research which are the research questions. The first part is describing all the distinct research question together with their corresponding sub questions (Section 1.4.1). The second sub section is deliberating on how these questions are answered (Section 1.4.2). The next sub section is describing the intended deliverables of this research (Section 1.4.3). The last part of this section is describing the research scope and what is included in this research (Section 1.4.4).

1.4.1. Research questions

The research questions are based on the managerial problem solving method and the theoretical framework. To get a better understanding of the situation, the third phase of the MPSM is exercised and the current situation of the logistic department of HTM Aerotec is described with the first research question. This research question is answered to provide the knowledge to get a good understanding of the main bottleneck. So, the first research question is:

1. *"What does the current situation in the logistic department at HTM Aerotec look like?"*

To provide a substantiated and satisfactory answer to research question 1, four sub questions are formulated which are combined providing the answer to the main research question. The sub questions are:

> 1A *"How is the new warehouse going to look at HTM Aerotec?"*
>
> 1B "*What are the different products HTM Aerotec is storing in their warehouse?"*
>
> 1C *"What does the supply chain of HTM Aerotec look like?"*
>
> 1D *"What is the current order picking time?"*

The first sub question is describing the new warehouse of HTM Aerotec which is answered with interviews and data-driven research. The second sub question is regarding the distinct products that are stored at HTM Aerotec which is answered with the support of observing the warehouse.

The third sub question is depicting the supply chain focussed on the logistic department which is answered by observing the logistic department together with interviewing the employees. The last sub question is describing the current order picking time, which is the main problem of this thesis and is answered by conducting observations and ethnography while picking the orders.

The second research question should be about what the different strategies are for providing a solution to the main problem and just as research question one deliberating on the third phase of the MPSM. As explained before, warehouse slotting is one of the main terms used, which is described within this research question. Also, one of the two decisions described from warehouse design, operation strategy selection, is depicted here. The research question is:

2. "*What slotting methods are used to provide a good assignment of products inside the racks?"*

To give an answer to this research question, two sub questions are answered first. These questions provide the necessary knowledge to provide a conclusion to the second question. The first sub question is focussed on warehouse slotting strategies and the second sub question is more focussed on operation strategy selection. The sub questions are formulated as follows:

> 2A "*What is the best slotting strategy to use for the assignment of products at HTM Aerotec based on existing literature?*"
>
> 2B "*How are the products going to be assigned to the slots using the chosen slotting strategy?"*

Question 2 together with its sub questions is providing the knowledge to actually provide a solution. Both sub questions are answered with the support of case studies where a case outside of HTM Aerotec is studied. The data regarding the new warehouse of HTM Aerotec, the available products, and all the distinct variables are answered with observations. The first sub question is mostly focussed on what the best slotting strategy is to use in the warehouse of HTM Aerotec according to theory and literature. The second sub question is more focused on how the products should be assigned using the found slotting strategy. The second sub question is also deliberating on the fourth phase of the MPSM where different solutions are considered.

A good assignment of products inside the racks could solve the main problem HTM Aerotec is facing. The next and final research question is about how to create a good assignment of products inside the warehouse racks from the strategies chosen by answering question 2. This question is providing a solution and elaborating on the fifth phase of the MPSM and it is focussed on the other decision in warehouse design, department layout. The third research question is solely focusing on how the products are assigned inside the warehouse racks. The third research questions is:

3. *"What is an appropriate assignment of products inside the warehouse racks to decrease the order picking time at HTM Aerotec?"*

Question 2 is about colleting most of the data needed to create an assignment of the products while question 3 is creating the solution and eventually realising the assignment of products inside the warehouse racks. Then there are four sub questions left to help answer and substantiate research question 3.

3A "*How are the products assigned inside the warehouse racks to decrease of the order picking time?"*

*3*B "*What is the new order picking time at HTM Aerotec?"*

*3*C *"How should products be slotted if they exceed their assigned slots?"*

3D *"How should the assignment of products be implemented at HTM Aerotec?"*

The four sub questions are answered with the data collected while answering the previous questions. The first sub question is focussed on the fifth phase of the MPSM, which is choosing a solution, and forming the basis for the sixth phase of the MPSM, how the assignment of products should be implemented. The second sub question is forming the basis for the evaluation of the solution, which is the seventh phase of the MPSM, by estimating the new order picking time. This can in the end be compared with the current order picking time to evaluate the new assignment of products and see if there is a satisfactory result. The third sub question is explaining how products should be assigned in case they exceed their assigned slots which is extending the already found solution from the first sub question. The third sub question also addresses the situation if the demand is fluctuating and there are for example more category A products coming in. The final sub question is answered in a separate chapter and is about how the solution should be implemented at the company which is the sixth step of the MPSM. All these research questions are to help solve the main problem HTM Aerotec is facing, no clear assignment of products inside the warehouse racks. Where this research is focusing on decreasing the order picking time.

1.4.2. Problem solving method

The problem solving approach to answer the research questions is following the MPSM provided by Heerkens and van Winden (2017) as explained before. This method is used for its adaptability, and it can be used anywhere at any time. The problem solving approach is following the seven steps provided by the book which are defining the problem, formulating the problem, analysing the problem, formulating solutions, choosing a solution, implementing the solution, and evaluating the solution. The first step of the MPSM is defining the problem, which is showcased under problem identification, where the problem is identified and explained. The second step is formulating the approach, which is executed right in this part of the thesis.

The third step of the MPSM is analysing the problem. This step is taking the most time since all available data about the new warehouse and products needs to be studied. Besides that, the data about the different slotting strategies is gathered. All the data to answer the first research question together with the corresponding sub question and sub question 2A is gathered in this step. Research question 1 with its corresponding sub questions are regarding the current situation in which is the supply chain is analysed together with the new warehouse and their products. So, all data about these subjects is studied to answer the sub questions. Sub question 2A is analysing existing data and literature regarding slotting strategies. The distinct strategies are compared to find the appropriate strategy to use for HTM Aerotec.

This brings us to step four of the problem solving approach, formulating (alternative) solutions. This step is focussing on formulating different variations of strategies for the assignment of products for the warehouse racks. The main aim of this step is to produce the best possible assignment of products for the racks of the warehouse. This step also involves answering sub question 2B.

Next is step five, which is choosing a solution on how to assign the products to the racks. This step is focussed on research question 3 and especially sub question A. The main aim is providing the best assignment of products, which is decreasing the order picking time the most. Sub question 3B can be calculated using the solution found in sub question 3A. Also sub question 3C is answered which is an extension of the chosen solution from 3A. This step of the MPSM is about choosing the right assignment of products for the warehouse of HTM and extending it.

The next step is implementing the solution. This step is implementing the answer to research question 3A and answering sub question 3D. Sub question 3A is forming the basis for the implementation which is phase five of the MPSM. An overview is given which shows exactly where every product is placed according to the assignment of products chosen. One way of implementing is writing an implementation plan, which is answering sub question 3D, of the solution for HTM Aerotec.

The final step of the MPSM is evaluating the solution. This step is reviewing the order picking times. With the new assignments of products for the racks, the order picking times are hopefully decreasing. This step is based on the answer to sub question 1D and 3B about the current and new order picking time. The evaluation is based on the difference between the order picking times and if there is a satisfactory result. This step is also about forming the final conclusion of the whole thesis.

1.4.3. Intended deliverables

Looking at the research questions and the problem solving approach there are different deliverables that proceed from this research. The first obvious deliverable is a design on how all the products are assigned inside the warehouse of HTM Aerotec. This is the main deliverable concluding this thesis and forming the final solution and answer to sub question 3A. The next deliverable is a design on how to slot products that have exceeded their assigned slots which is regarding sub question 3C. Another deliverable coming together with the two designs of the assignment of the racks is how to implement these designs. An implementation plan of the design is given in the last part of this thesis explaining how HTM Aerotec should implement the found solution. Looking at research question 1C, another deliverable proceeding from MPSM step three is an overview of the supply chain of HTM Aerotec focussed on the logistic department. The purpose of the research question is to show a model depicting the supply chain and specifically highlighting all the logistic related processes.

1.4.4. Research scope

The research is solely focussing on the logistic department. However, the actions conducted in other departments that are related to the logistic department are shortly discussed which means that what is happening in the factory hall or at other machinery is briefly explained. It is only included if it influences the logistic department directly, for example the logistics department picks the orders for the machinery which includes the machinery. Inside the logistic department the sole focus is on the new warehouse where the main priority is assigning the products to the racks of the new warehouse.

1.5. Research design

Section 1.5 is producing the research design of this research explaining the research types and methods used together with the limitations, the validation, and the reliability of the research. The first part is describing the distinct research types that are used to answer the research questions (Section 1.5.1). The second sub section is explaining which research methods are used to gather the data for the research questions (Section 1.5.2). The next sub section is deliberating on the limitations of this research (Section 1.5.3). The last sub section is describing the research validity and reliability (Section 1.2.4).

1.5.1. Research types

According to Cooper and Schindler (2013) there are four different types of research studies, reporting, descriptive, explanatory, and predictive. For this thesis assignment explanatory and descriptive research are the main research types exercised in collecting and analysing the data.

Descriptive research is conducted to provide answers to the sub questions regarding the variables. Descriptive research tries to discover answers to the questions who, what, when, where, and, sometimes, how. The researcher attempts to describe or define a subject, often by creating a profile of a group of problems, people, or events (Cooper & Schindler, 2013, p. 21). Therefore, descriptive research is exercised to provide an answer to the distinct sub questions. The sub questions 1A, 1B, and 1C are answered with descriptive research. The new warehouse is described, the products are defined, and the supply chain is deliberated. Sub question 2A is also answered with descriptive research. The slotting strategies are first described and after the slotting strategy used is defined.

The other research conducted is explanatory research. Explanatory research is exercised to answer the main questions of the thesis. The research goes beyond description and attempts to explain the reasons for the phenomenon that the descriptive study only observed (Cooper & Schindler, 2013, p. 22). With this in mind, explanatory research can produce a satisfactory answer to research question 2B and 3.

Explanatory research can provide the reasons for the phenomenon and give a detailed and substantiated answer to the two mentioned research questions. Explanatory research can also help in explaining both the sub question regarding the order picking time.

1.5.2. Research methods

Research methods are exercised to gather all the data necessary to answer the research questions. During the thesis, various types of qualitative research methods are exercised to obtain the data where most data is written data and has a descriptive form. The main methods exercised to knowledge acquisition are ethnography, observations, case studies, and interviews.

Starting with the ethnographic method. Ethnography is where the interviewer and participant collaborate in a field-setting participant observation and unstructured interview (Cooper & Schindler, 2013, p. 158). Ethnography is supporting in explaining the current situation, depicting the supply chain focused on the logistics department, and it will help form possible solutions for the assignment of products. Ethnography is used to gather a combination of both qualitative and quantitative data which are gathered during step three and four of the MPSM. Besides, nominal data is gathered when depicting the supply chain of HTM Aerotec. Other types of data are discrete data which is all the data about the warehouse and the products. The last type of data gathered is continuous data, which is done by estimating the order picking time.

The next method is observing, which can be divided into behavioural and non-behavioural observations. Non-behavioural observations are observing records, this may involve historical or current records and public or private records (Cooper & Schindler, 2013, p. 173). Behavioural observations are also used in highlighting the current situation whereas non-behavioural observations are supporting in answering the two sub questions 2A and 2B about a good strategy for the assignment of products. The data gathered with observations is qualitative data where both methods are helping with formulating possible solutions.

The next form is case studies. The case study, also referred to as the case history, is a powerful research methodology that combines individual and (sometimes) group interviews and observations (Cooper & Schindler, 2013, p. 165). The case studies are helping with gathering the data, which is step three of the MPSM. It is assisting in gathering data about a good strategy for the assignment of products, which is qualitative data. Case studies are providing data to answer the second research questions together with the belonging sub questions.

The last method used for data acquisition is interviewing. This form is also assisting in describing the current situation and depicting the current order picking time. Interviews are exercised during the third phase of the MPSM, with gathering the data. The data accessed is a combination of qualitative and quantitative data. Continuous data is gathered to answer research questions about the order picking time. Besides MPSM phase three it assists in choosing the right solution, which is step five of the MPSM.

1.5.3. Research limitations

While conducting the research methods there are various limitations to this research. The most important limitations are mentioned, starting off with the data gathering. The data for research question 1 with its corresponding sub question and sub question 2A is mostly gathered by working with and questioning the employees of the logistics department which means I am dependent on their knowledge and answers. This in the end could lead to limitations regarding the availability of the data. The research design solely focusses on the logistic department which could lead to limitations since some actions are impacting other parts of the company. These impacts are not examined which limits the research solely to the logistics department and excludes any negative consequences for other departments. The last limitation that might occur during the research is regarding the time spent. This research design is used to find out if the order picking times could decrease within a ten week time span. With more time available, it is possible to find multiple solutions or causes. So, the research has to be limited to be achievable within ten weeks.

1.5.4. Validity and reliability

With this research design there could occur some issues concerning the validity and reliability. Validity can be described as the extent to which a test measures what we actually wish to measure (Cooper & Schindler, 2013, p. 257). Reliability has to do with the accuracy and precision of a measurement procedure (Cooper & Schindler, 2013, p. 257).

Starting with the validity of the research design. The validity of this research is high since all the calculations behind the final solution have a good substantiation. The models used are calculating exactly what is expected and the method used to calculate the order picking time is providing the exact answer we wish.

The measurement used in this thesis is the time spent picking orders and for the reliability this order picking time can be a minor complication. According to Cooper and Schindler (2013) reliability is concerned with estimates of the degree to which a measurement is free of random or unstable error. However, the order picking time is never free of random or unstable error since the way the employees are picking the orders is always varying. Unstable factors can be the walking speed, the findability of a product, the picking speed etc. To be as reliable as possible, the order picking times are measurement across multiple days and multiple orders to increase the reliability.

1.6. Conclusion

Chapter 1 of this thesis is reflecting on the first two steps of the MPSM from Heerkens and van Winden (2017). Step one is defining the problem and step two is formulating the approach. The basic assignment of products for this thesis is depicted in this chapter and the rest of the thesis is following the line of the research questions.

The main problem HTM Aerotec is facing is that processes are taking too much time in the logistic department. To solve this problem, the focus of the thesis is on the order picking time inside the new warehouse. HTM Aerotec is constructing a new warehouse, which has no clear assignment of products Inside the warehouse racks. Hence the core problem, no clear assignment of products inside the warehouse, is being solved. This is done by improving the slotting which is a narrow part of structuring the warehouse.

The main theoretical framework is introduced, which the research questions are partly based on. From the five decisions of warehouse design, two are required to solve the core problem. The first one being Department layout and the second decision is Operation strategy selection. The research questions are formed with various sub questions. The first research question and sub questions are describing the current situation of HTM Aerotec where the new warehouse, the products, the supply chain, and the current order picking time are discussed. The second research question with its corresponding sub questions is collecting the data and providing the strategies and methods to solve the main problem. The third and main research question is, *“What is an appropriate assignment of products inside the warehouse racks to decrease the order picking time at HTM Aerotec?”.*

The corresponding sub question are substantiating the main question and discuss the assignment of products inside the racks and the new order picking time together with what happens when assigned products exceed the assigned slots. The last sub question is an implementation plan on how HTM Aerotec should implement the solution. The problem solving approach together with the research design display the main methods used to gather all the necessary knowledge and information to answer the research questions and sub questions. The main methods exercised are observations, ethnography, case studies and interviews.

These methods help to get to the main deliverables. The first deliverable is an overview of the supply chain focused on the logistic department where the research scope is narrowed down towards the logistic sector. So, other departments are therefore excluded from this research. The main deliverable is a design of the products inside the racks in the warehouse of HTM Aerotec and besides that a design is given how assigned products should be slotted if they exceed their capacity. The third deliverable is an VBA model, which optimizes the assignment of products inside the racks. This deliverable is produced while forming an answer and making the main deliverable. The fourth and last deliverable is an implementation plan on how HTM Aerotec should implement the assignment of the products.

2. Current situation

The second chapter of the thesis is answering research question 1 “What does the current situation in the logistic department at HTM Aerotec look like?” together with the corresponding sub questions. The first section is describing the first sub question and providing a map of how the new warehouse is going to look (Section 2.1). In a distinct section of Section 2.1 the various products of HTM Aerotec are explained which is answering sub question 1B. The second section is depicting the supply chain with the focus on the logistic department (Section 2.2). The next part of this chapter is describing the current order picking time (Section 2.3). Finally, a short conclusion is given about this chapter (Section 2.4). Most of the data is gathered with the use of observations and ethnography. They both are exercised in Section 2.1, 2.2, and 2.3.

2.1. Warehouse HTM Aerotec

Section 2.1. is first displaying the new warehouse of HTM Aerotec. The first sub section is shortly explaining the old situation of HTM Aerotec (Section 2.1.1). The second sub section is deliberating on the distinct products and answering research question 1B (Section 2.1.2). The second sub section is displaying the warehouse constraints (Section 2.1.3), where after the warehouse racks are explained (Section 2.1.4). The last sub section is calculating all the warehouse dimensions (Section 2.1.5).

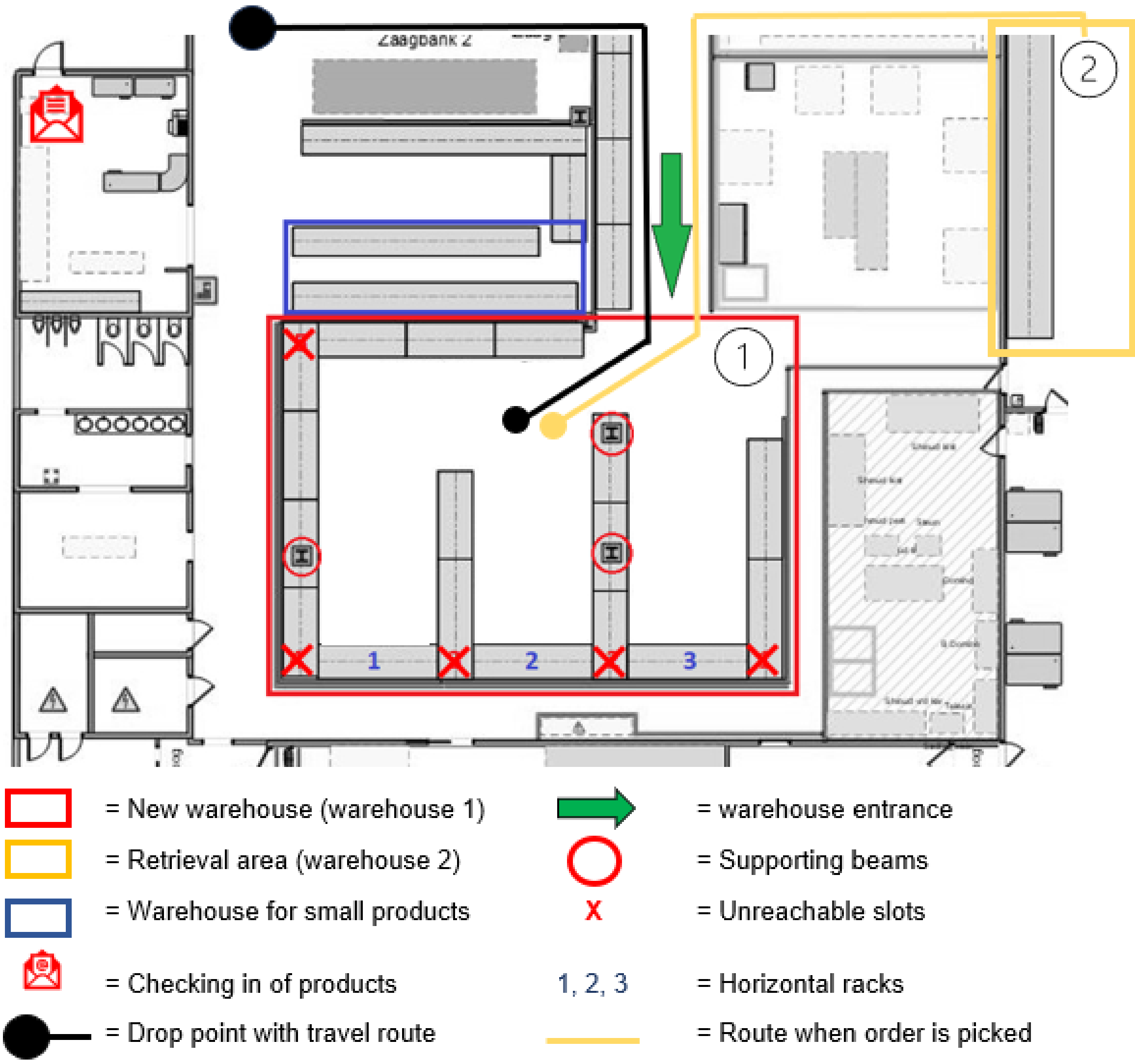

Figure 4, New warehouse design. Scale 1:180

In Chapter 1 of this thesis, it is described that there is a new warehouse coming which is shown in Figure 4. The main focus of this thesis is on warehouse one. All the shapes and icons are explained in the legend underneath the Figure. The new warehouse created during this thesis is surrounded by the red square, warehouse one. There is one small warehouse, which is surrounded by the blue square, for products stored in crates. The larger products and products with higher quantity are stored in the new warehouse since they take in more space. These products are placed on euro pallets or halve euro pallets which need larger racks (see Figure 6). The small warehouse is only existing out of smaller racks since the available space for this warehouse would not allow any other type of racks (see Figure 5). The warehouse within the red square is named warehouse one and the warehouse within the yellow square is named warehouse two for convenience. Products which are ready for the machinery are picked and stored temporarily in warehouse two, which is the retrieval area.

Figure 5, Small rack

Figure 6, Large rack

2.1.1. Old situation

In the old situation at HTM Aerotec there was no warehouse for larger products. Looking at Figure 4, the red square was filled with machinery and the racks in Figure 4 were scattered across the larger factory hall. The only warehouse that was existing was the retrieval warehouse surrounded by the yellow square and the small warehouse surrounded by the blue square depicted in Figure 4. Because of the scattered warehouse racks, the order picking time was high. There were at most two racks together and some of these racks were hard to reach with the forklift. The forklift had to travel between machines and behind machines to reach these racks. There where also less slots available in the old situation. Introducing the new warehouse and storing all the products in one place is already decreasing the order picking time, however this can be decreased further following a logical assignment of products inside the warehouse racks.

2.1.2. Warehouse products

This section is answering sub question B “*What are the different types of products HTM Aerotec is storing in the new warehouse?”.* This section explains the different sort of products, the difference in the way they arrive and the difference in how the products are stored. As shown in Figure 4 there are two distinct warehouses for storage, one for smaller products (surrounded by the blue square) and one for larger products (surrounded by the red square). There are a lot of distinct products handled by HTM Aerotec which can all be sorted in two main categories; half fabricates and raw materials. Half fabricates are products that are already processed by other companies while raw materials are unprocessed products. Both these products consist of different sorts of metals which are mostly aluminium or steel. HTM Aerotec is processing the half fabricates further and sends them back to the supplier or onto another company. The raw material is always processed and taken to a different supplier.

The number of products at HTM Aerotec is always varying which is due to the fluctuating demand of other companies. So, tomorrow there are more products or less products present in the company compared to today. Because of the fluctuating demand an exact number of products present in the company cannot be given, however an average number of pallets and halve pallets can be given which is approximately between the two and three hundred. The same applies for the number of suppliers which is also varying. Some suppliers only request a single order while other suppliers are requesting multiple orders which is influencing the fluctuating number of suppliers.

Figure 7, euro pallet (80x120x14.4cm)

Figure 8, halve pallet (80x60x14.4cm)


Figure 9, crate (40x30x14.4cm)

When a product enters HTM Aerotec, most of the times it is stored on a pallet (Figure 7) which are stored in the new warehouse. It is possible the product is smaller or in smaller quantities, then the possibility arises that it is delivered on a halve pallet (Figure 8) which is halve of a euro pallet and also stored in the new warehouse. If the product is really small, it is delivered to HTM Aerotec in a crate (Figure 9) which then is stored in the smaller warehouse surrounded by the blue square in Figure 4. A product can be referenced to as large if it only fits on a euro pallet and not on a halve pallet or in a crate. The product is referenced to as medium if it is too small for a euro pallet and to big for a crate. Finally, a product can be referenced to as small if it fits in a crate but is too small to be placed on a halve pallet. There is one possibility that a large product is delivered, which is not placed on a pallet. These products are stored in a separate place which is excluded from this research. The weight of the product is not of importance since the difference in time for the forklift to pick the order is negligible. This thesis is only considering the large and medium products which are all picked with the forklift where the whole pallet or halve pallet is picked. All the products can be categorized as follows (showing three example products).

	LARGE	**MEDIUM**	**SMALL**
HALF FABRICATES	Product 1	Product 3	
RAW MATERIAL	Product 2	Etc.	

Table 1, product classification

2.1.3. Warehouse constraints

In this new design there are some variables to consider which are important. The first variable that influences the final assignment of products are the supporting beams inside the racks which are surrounded by the red circles in Figure 4. These beams are supporting the roof of this section of the company, which means these slots are not applicable for products. However, other stuff can be placed beside the beams if HTM Aerotec wanted to.

The next variable to consider is that there are five slots which are unreachable with a forklift. The back side of the warehouse is covered with gauze which creates a safe walking space behind the warehouse where no forklift is driving. However, this means that products are only placed in the racks from within the red square. The five unreachable slots are all marked with a red cross in Figure 4. These slots are containing smaller products that are placed by hand but can not contain any pallets.

The last variables to consider are regarding the forklift, HTM Aerotec is using the Hyundai 15 BTR-9 which is also the only forklift at the logistic department. The forklift has a travel speed of 3,487 metres per second with load and a travel speed of 3,576 metres per second without load. The lowering time of the forklift without load is 0.45 metres per second and the time with load is 0.5 metres per second. The lifting time with load is 0.29 metres per second and without load 0.53 metres per second. Due to the gauze and placement of the racks the forklift can only enter the warehouse from the green arrow which is therefore the entrance of the warehouse.

Name	Abbreviations	Time
Average vehicle speed without load	$avswl$	3,576 m/s
Average vehicle speed with load	$avsl$	3,487 m/s
Lifting time with load	$tlift_l$	0,29 m/s
Lowering time without load	$tlow_l$	0,45 m/s

Table 2, forklift times (Hyundai Material Handling, 2023).

Table 2 summarises all the times of the forklift that are used in Chapter 4. The vehicle speed without load and with load is used as well as the lifting time with load and the lowering time without load. So, the times that are used are to calculate the total time it takes to fill up the warehouse from the moment every slot is empty. Table 2 also mentions the meaning of the abbreviations that are used in Chapter 4.

2.1.4. Warehouse racks

In the warehouse there are seventeen distinct racks which can be divided into two categories, type one rack and type two rack. Both these racks look like the rack displayed in Figure 6. There is a rack with three slots which is type one (see Figure 10) and a rack with four slots which is type two (see Figure 11). There are six distinct type two racks and eleven distinct type one racks inside the new warehouse.

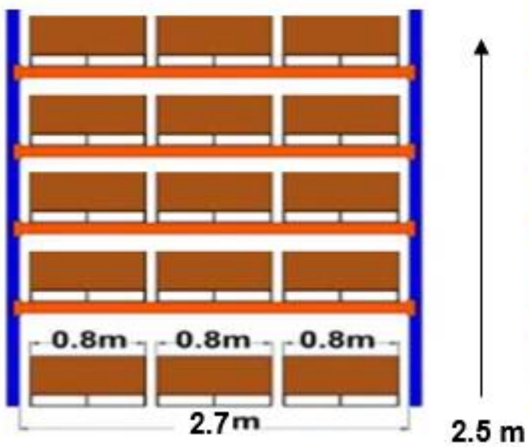

Figure 10, Type one rack

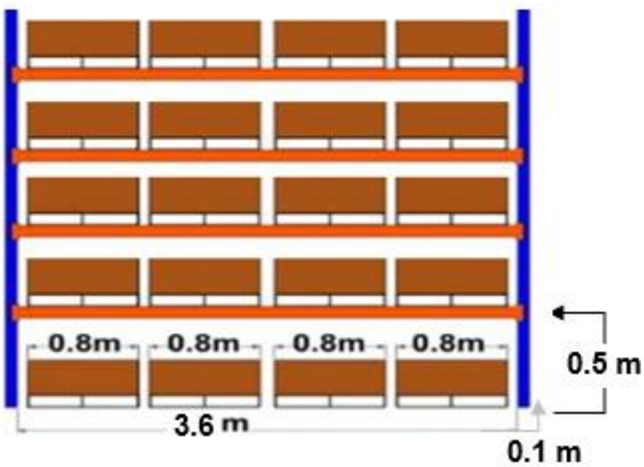

Figure 11, Type two rack

Due to the warehouse variable regarding the forklift, every rack can only have five distinct levels. There is still space between the fifth level and the roof, but because of the forklift the highest a product can be placed is the fifth level. So, a rack has five distinct levels and there are six different type two racks and eleven different type one racks which means the total number of slots in the warehouse is 285. However, there are some slots which are obstructed by a supporting beam which are in total fifteen slots. There are also some slots which are unreachable with the forklift, these are in total twenty five slots. So, in the new warehouse there are 245 available slots which value is important, because Chapter 4 calculates the time for all these 245 slots to be filled. The total number of pallet slots in the warehouse is not adjustable since there is not an option to increase the row, column, or level.

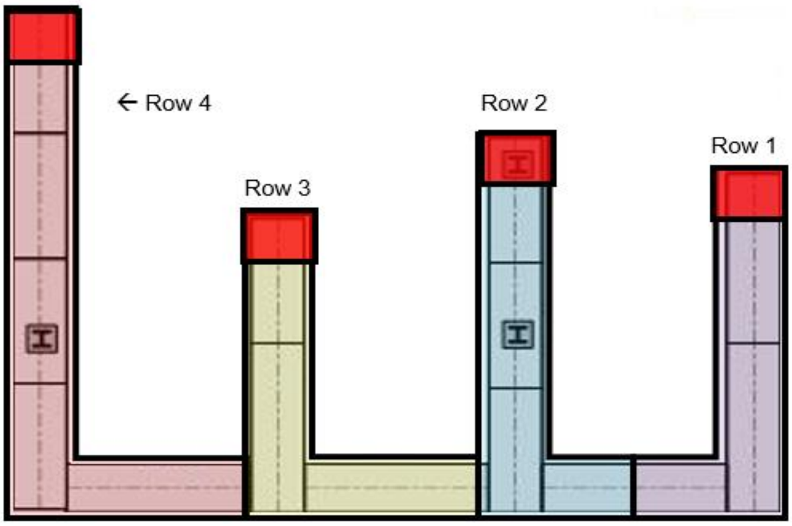

Figure 12, Row, Column, and Level visualization

The warehouse is divided into rows, columns and levels where a row is the set of rack locations arranged horizontally and vertically along the aisles. A column is a set of spaces arranged one next to the other in a row. The level number corresponds to the increasing order of the vertically available spaces in a column (Duque-Jaramillo et al., 2024). Figure 12 shows that there are in total four distinct rows which each got their own colour. Starting from the right, the purple L shape is row one, the blue L shape is row two, the yellow L shape is row three, and the final row is row four. The red square on the top of every row is showing column one which is a horizontal line of slots when standing in front of the racks. *The columns are numbered 1 till 4 from right to left, since the entrance of the warehouse is on the right side which is also how the orders are slotted and picked.* So, column one is the first slot of every row as shown in Figure 12. Row one has in total nine columns, row two has 10 columns, row three has 11 columns, and row four has 14 columns excluding the five unreachable slots as explained. There are also levels inside the rack which is the height of a slot where the slots on the floor of the whole warehouse are all included in level one. Level two is including all the slots in the warehouse on the second level etc.

2.1.5. Warehouse dimensions

There are a few dimensions which are necessary for the theoretical model in Chapter 4. Starting off with the two various racks, a rack of type two, with four slots, has a width of 360 cm and a length of 110 cm. A rack of type one, with three slots, has a width of 270 cm and also a length of 110 cm. Every rack has two stands of 10 cm when standing alone which is displayed in Figure 10 and Figure 11 by the blue beam. When there are multiple racks placed together, the number of stands become $n + 1$, were n is the number of racks. The stands do only influence the width of a rack because they are aligned with rack. With the width and length of the rack we can calculate the dimensions of the warehouse.

The first dimension is about the height of the racks. Section 2.1.4 is explaining the height of one rack which is 2.5 m (see figure 10 and Figure 11) and is the same for both of the rack types. One rack has five distinct levels, and these levels are all divided equally which makes one level 50 cm tall (see Figure 11). One pallet can be placed in one slot, therefore the height of one slot is important to calculate the time it takes to lift and lower a product. If a pallet is placed at level three, the forklift has to lift the pallet 1.5 m which can then be divided by the lifting time with load and lowering time without load.

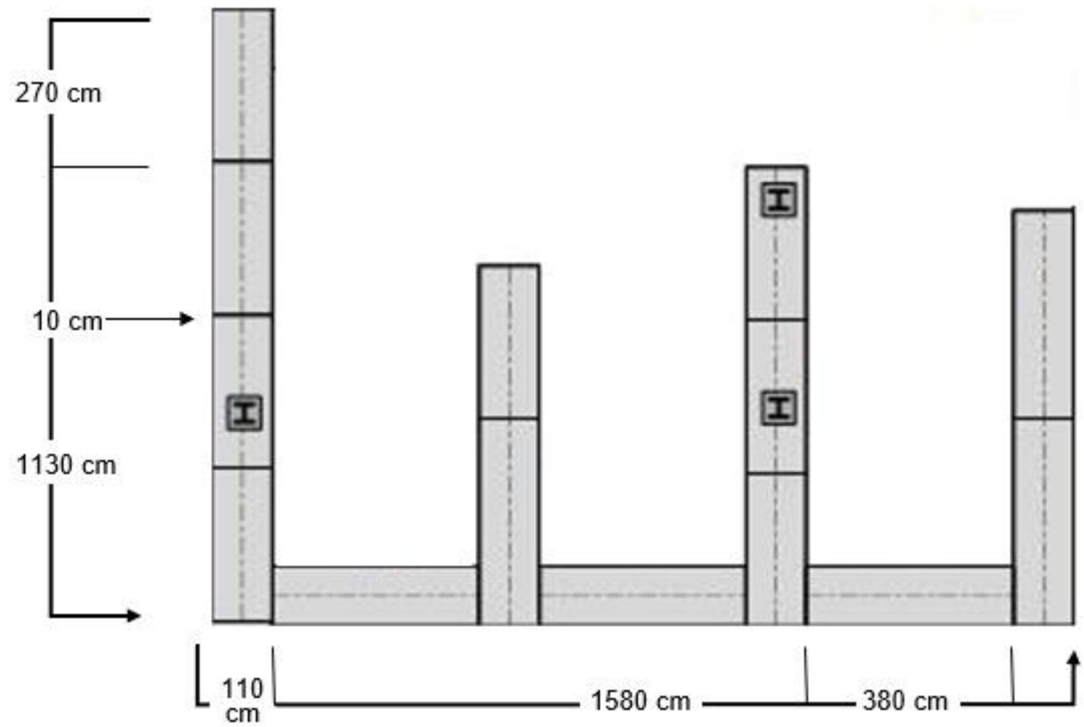

Figure 13, warehouse dimensions

The next dimensions are regarding the length and width of the warehouse which can be calculated with the help of the length and width of one rack. Starting off with the length of the warehouse which is the same as four type one racks that are each 270 cm without the stands. As explained four racks that are placed together have a total of $n + 1$ stands which is five. So, the length of the warehouse is $length = 270 * 4 + 5 * 10 = 1130\ cm$ (see Figure 13). The width of the warehouse is three type two racks together with two stands each since the racks are placed separately. These racks together with their stands have a total width of 380 cm. There are also four racks placed sideways which all got a length of 110 cm. So, the width of the warehouse is $Width = 380 * 3 + 110 * 4 = 1580\ cm.$

In Figure 4 it shows that between every row, there is a type two rack together with two stands which has a total width of 380 cm. This gives the next dimension, the hall between the different rows, a total width of 380 cm.

Every product also travels a distance towards the warehouse, which in Figure 4 is shown with the black line. When a products is delivered at HTM Aerotec it is signed in at the red mail icon, the product then arrives at the drop point of the company which is displayed in Figure 4 with a black dot. After it is delivered it follows the black line until it has reached the entrance of the warehouse which is displayed with the green arrow. The forklift has to travel the distance of this black line till the green arrow which has a total distance of 35 m.

The last dimension to consider is the width of a single slot. A type one rack has a width of 270 cm and a total of three slots, divide the width by the three slots gives one slot a width of 90 cm. To verify this, we take a look at the type two rack which has a width of 360 cm and a total of four slots. Divide the width by the four slots gives each slot also a width of 90 cm. All of the above calculated dimensions are given in Table 3 where the abbreviations are named the same as later on in the report.

Name	Abbreviations	Measurements
Racks height	rhl	2.5 m
Warehouse length	wdl	11.3 m
Warehouse width	wwl	15.8 m
Hall between rows	$hrwl$	3.8 m
Shelving depth length	$ssdl$	1.1 m
Travel distance	td	35 m
Shelving width length	swl	0.9 m

Table 3, Warehouse dimensions

2.2. Supply chain

The third section of Chapter 2 depicts the supply chain of HTM Aerotec and answers the sub question *"What does the supply chain of HTM Aerotec look like?"*. A supply chain is an interconnected and synchronised system of all related organizations, personnel, resources, processes, information, and technology involved in the production and successful delivery of a finished product to the end user, including the moving of the product throughout the whole chain from the very beginning of the supply of the raw materials (Islam, 2023). The supply chain of HTM Aerotec is shown from the moment a product enters the company until the moment the product is ready to leave the company. The supply chain is mainly focussed on the logistic department. The department that is responsible for ordering and selling products is excluded from the supply chain together with departments that do not influence the logistic department. Figure 14 shows the supply chain that is depicted with the use of Bizagi Modeller. The data from the distinct departments is gathered through observations and ethnography.

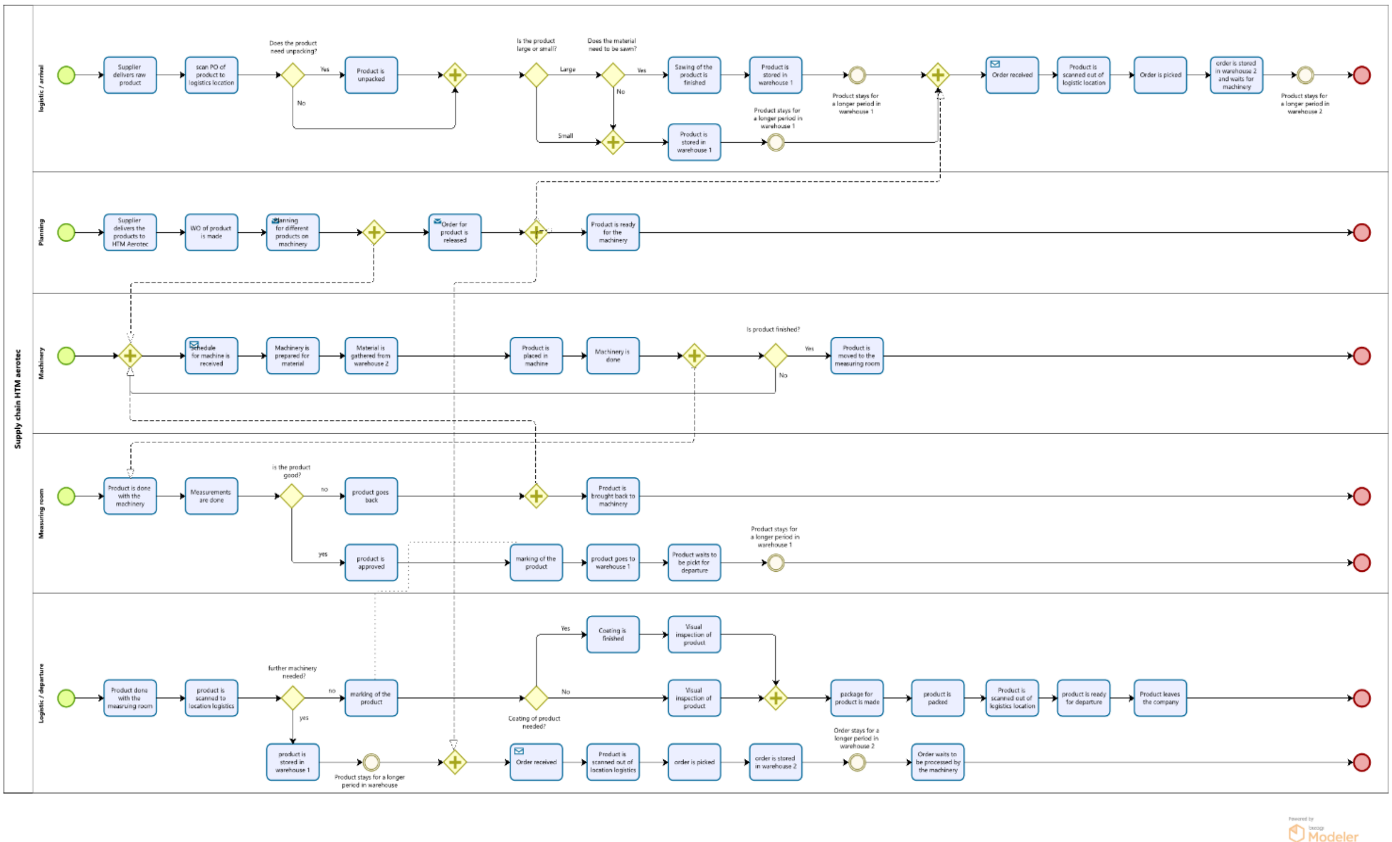

Figure 14, Supply chain HTM Aerotec (For a readable overview see Appendix B).

In Figure 14, the main supply chain is shown. There are five distinct sections, the logistic department arrival, planning, machinery, measuring room, and logistic department departure, respectively. Both of the logistic sections are the main focus of this supply chain and are depicted in full detail while the other three sections are more superficial to emphasise the logistic sector. The next sub sections are explaining the distinct departments together with their processes. For a better overview of Figure 14, all the different departments are depicted in the Appendix Figure 37 till Figure 45.

2.2.1. Logistics: Arrival

The first part of the supply chain is the logistic department which is the main focus of this thesis. Picking the orders is done in the first part of the logistics where a product always arrives at the logistic department of HTM Aerotec. Sometimes an employee from HTM Aerotec is picking up the product from the supplier, or the supplier sends it with a delivery service towards HTM Aerotec. When the product has arrived, the first thing to do is to register the purchasing order of the products. After, the first decision is made which is to unpack the product or not.

Right after comes the second decision which asks if the product is small or not. Smaller products which are in small quantities are placed in crates or halve pallets. Products with large quantities are always placed in euro pallets as explained in Section 2.1.2 as well as the larger products. If the product is small, it is stored in the small warehouse which is surrounded by the blue square in Figure 4. If the product is large, first another decision is made which is, does the material need to be sawn. If so, the product is placed by the saw and stored there until the product is sawn. When the product is sawn, it is then stored in warehouse one which in Figure 4 is surrounded by the red square. If the product does not need to be sawn, the product is immediately stored in warehouse one where the product stays for a longer period of time.

Then after some time an order from the planning arrives that a product needs to be picked for the machinery. The planner delivers the planning for the product, the Purchasing Order (PO) then becomes a Working Order (WO). The first thing to do is to register the WO out of the logistic location. After, the product is picked from warehouse one, which is done with single command order picking where the picker picks the order directly from the racks. When the order is picked it is placed inside warehouse two which is surrounded by the yellow square in Figure 4. Warehouse two is a small storage location close to the machinery and factory hall where products are also laying for some time.

2.2.2. Planning

When a product enters the company, the PO is scanned in the logistic department and the products is visible for the planning as well. The planning is then making a WO for the product. The WO of the product is the work order, which is now how the product can be identified and everyone in the company finds the product by its WO. The next step is to make the planning with all the distinct WOs available. All the tasks the product has to undertake are made inside the planning department. After the planning is made, and every process of the product is known, the product is ready for the machinery and an order is released and sent to the logistics department arrival. Now the logistic department knows that the product is ready to be picked and that is needs to be stored in warehouse two.

2.2.3. Machinery

When the planning for the machinery is made, the product is stored in warehouse two. The first thing to do is to prepare the machine for the production process of the product. When everything is ready for the product and the settings for the machine are correct, the material is gathered from warehouse two. After the product is taken from the warehouse, it is brought to the machine. The next step is to let the machine run and adjust any settings in between, if necessary, which is obviously different for every product. After the machine is done, the product is taken out of the machine and a decision is made. The decision to make is if the product is finished or if there are any further actions depicted on the planning for the product. If not, the product is done with the machinery and moves on to the measuring room.

2.2.4. Measurement room

After a product is finished at the machinery, the product needs to be checked to see if everything is according to the drawings and the corresponding measurements. It is important to see if all the measurements are correct since the customers expect a high precision product to be precise. Then the decision is made, does the product comply with the drawing and the measurements set. If so, the product is approved, otherwise the product is brought back to the machinery and there they check what went wrong.

If the product is approved there are two things possible. Sometimes the product is marked when stored near the measuring room, and sometimes the product goes to the warehouse and is marked there. However, the marking of the product is always done by the logistic department. After marking the product, the product moves back to warehouse one where it waits to be picked for departure. Here the product sometimes stays for a longer period of time.

2.2.5. Logistics: Departure

The last part of the supply chain is the logistic department again. When a product leaves the measuring room, and is already done with marking, the product is registered at the logistic department.

The first decision is then made, does the product need further machinery? If so, the product is stored in warehouse one till an order is released for that product. Then the same steps are taken, and the product is stored in warehouse two until the machinery is all set. When that is the case, the product is processed by the machinery again and later checked by the measuring room. Finally, the product is once again stored in warehouse one. The other option is that the product does not need further machinery, and a second decision arises if the decision is already marked. If so, the product moves on and if not, the product is marked.

If no further machinery is needed and the product is marked, there is another decision. The second decision is, does the product need coating? If so, the product is coated and afterwards a visual inspection is executed to see if the product complies with the conditions set. If the product does not need coating, a visual inspection is still conducted. After the visual inspection, a package is fabricated, and the order is printed. The product is packed together with its order and the package is sealed. The last part of the supply chain is to unregister the product, and the product is ready for departure.

2.3. Current order picking time

Order picking is the process of products being retrieved from the warehouse inventory to fulfil orders (Inbound logistics, 2023). In the old warehouse the products were spread, which is leading to an unsatisfactory order picking time. Constructing the new warehouse is already improving this order picking time however, there is a lack of clear assignment of products inside the new warehouse and products of the same suppliers are scattered across the racks.

The order picking time is calculated with the support of observations and interviews where the action is measured multiple times, and a range of the time is given accordingly. Since the picking time is different every time, the range is just a rough estimate which is based on observations and questioning the order pickers. The current order picking time is ranging from *1 to 10 minutes with an average of 4,5 minutes* and a standard deviation of 2,78. These numbers are based on multiple observations were sometimes a product is found within the minute and the picking time is short. The picker knows where he left the product in the warehouse, and it is easy to locate. However, when a product is hard to locate, HTM Aerotec mentioned, the order picking time can take up to 10 minutes. The main aim of this thesis is to decrease the range of the order picking time and get the 10 minutes down to a satisfactory result together with the average.

	Picking time
Minimum order picking time	1 minute
Average order picking time	4,5 minutes
Standard deviation	2,78
Maximum order picking time	10 minutes

Table 4, Current order picking time

2.4. Conclusion

Chapter 2 is reflecting on the third MPSM phase from Heerkens and van Winden (2017), analysing the problem which is done by looking at the current situation. The new warehouse is observed together with the supply chain. All the knowledge gathered in this chapter is to substantiate the next chapters and the next phases of the MPSM. Besides, chapter 2 forms an answer to research question 1 together with the corresponding sub questions.

The new warehouse of HTM Aerotec has four distinct rows of racks. All the necessary dimensions are mentioned, which are applied later on to form the solution. In the new warehouse there is place for 245 different products. The warehouse is operated by one forklift which characteristics are mentioned in Section 2.1.3. The various variables which impact the warehouse are mentioned, the dead spots in the corners of the warehouse, the supporting beams, and the variables considering the forklift.

The current supply chain is depicted, focussing on the logistic department. All the distinct actions in the logistic sector are displayed from when a product enters the company till the product is ready for departure. The main actions in the logistic department are signing in the product and picking the orders. When the product is finished, the product goes back to the logistics department. The main activities then are marking the product, a visual inspection of the product, and making the package for the product. Besides the logistic department, the measuring room, machinery, and planning department are depicted.

Section 2.3 is estimating the current order picking time, which is the main measuring norm of the thesis. The current order picking time is now ranging from *1 minute until 10 minutes*. The order picking time is varying in this range. The goal is to decrease the order picking time and decrease the 10 minute mark.

3. Formulating the strategies

The third chapter is answering sub question 2A "*What is the best slotting strategy to use for the assignment of products at HTM Aerotec based on existing literature?*". The question is answered with the support of case studies and non-behavioural observations. The main terms surrounding slotting are explained in the first section together with the chosen slotting method (Section 3.1). The second section is giving a short conclusion about the chapter (Section 4.42).

3.1. Slotting strategy

An important element of warehouse management is the slotting strategy: how to allocate Stock Keeping Units (SKU) to storage locations (Schuur, 2015). The first sub section is elaborating on the general term slotting and explaining the terms corresponding with it (Section 3.1.1). The second sub section is explaining the two main slotting methods used for single demand slotting (Section 3.1.2). The third sub section is explaining the slotting method used in this thesis with a short toy problem (Section 3.1.3) The fourth part is elaborating on the chosen slotting method (Section 3.1.4) and the final sub section is explaining how the slotting method is exercised at HTM Aerotec (Section 3.1.5).

3.1.1. Warehouse slotting

As described in Section 1.3 there are two decisions to be taken to reach a solution for HTM Aerotec which match perfectly with two decisions within warehousing explained by Gu et al (2010). One of these overlapping decisions being department layout, which is the detailed configuration within a warehouse department, which also implies slotting as explained in Chapter 2. Starting off with the main term slotting which is the assignment of items or SKUs to warehouse storage locations (Petersen et al., 2005). Slotting has various positive characteristics, where the most important characteristic is a shorter operation time. The warehouse serves as a buffer for the SKU flow in the supply chain and therefore, a correct placement of SKUs inside (slotting) helps to reduce the supply chain operation time (Rios et al., 2022). The main activity that is improved in the supply chain from warehouse slotting is the order picking time. Organizing your warehouse helps employees have clear paths for efficient order picking. A good slotting strategy and well-organised pick list allows workers to find and pick the correct SKU quickly (Rheude, 2024). Warehouse slotting is also helping in maximizing the storage capacity by using your warehouse space to its fullest (Rheude, 2024).

There are various types of slotting, which are divided into two main categories. The first category is fixed slotting or chaotic slotting where fixed slotting is a warehouse slotting method where you assign a specific space to each SKU. During inventory replenishment, you replace each SKU in its designated slot on the shelf (Rheude, 2024). Chaotic slotting is a slotting method, where items do not have set slots. When an item comes in, you assign it to the most appropriate space available (Rheude, 2024). In the warehouse of HTM there is going to be a combination of fixed and chaotic slotting since the supply of incoming products is fluctuating together with the demand as explained in Section 2.1.2. So, not all products in the warehouse can have a set slot which means the sole use of fixed slotting is not possible. For example, when a new product enters the warehouse of HTM and fixed slotting is used, the only available slots are at the back of the warehouse since all the other products in the warehouse are already assigned. The products are then only reassigned to a new slot during the next inventory replenishment. However, instead of individually assigning the slots, a group of slots can be assigned for products which means incoming products can be placed on the appropriate slots. So, not every product is assigned to a single slot, but instead to a group of slots.

Now incoming products are assigned to the appropriate slots and during an inventory replenishment less products need to be changed between slots. Here a combination of fixed and chaotic slotting is providing the solution for the fluctuating demand.

The second category of slotting is micro or macro slotting. Macro slotting involves optimizing the layout of the entire warehouse (Inbound logistics, 2023). Micro-slotting is focused on the precise positioning of individual items, from the allocated SKU area to its unique storage medium. The main objective of micro-slotting is to ensure the proper positioning of SKUs along the pick path (Inbound logistics, 2023). As explained the main goal is to provide HTM Aerotec with an assignment of products for their slots which means all the slots in the warehouse are considered for the assignment. This also infers that macro slotting is the most suitable type to use for the warehouse of HTM Aerotec. As explained before, a group of products are assigned to a group of slots, so not every product is assigned to a specific slot which is micro slotting. Table 5 provides a clear overview of the distinct types of slotting where the used types are bold.

Category 1 of slotting	**Fixed slotting**
	Chaotic slotting
Category 2 of slotting	Micro slotting
	Macro slotting

Table 5, Distinct slotting types

3.1.2. Slotting methods

Now that the term slotting is explained, the two most common strategies are explained starting off with the SKU velocity method or ABC strategy. Generally, companies should place slow-moving items at the back and fast-moving items at the front where staff can easily access them. This reduces the travel path, enhancing the efficiency and productivity of employees. The best way to determine the velocity of warehouse items is by using the ABC slotting method (Inbound logistics, 2023). The ABC strategy is providing three distinct categories, A, B, and C, to assign the products to the slots. where category A products have the highest priority and category C products the lowest. The way of classifying the categories is not fixed and can be adjusted. For example, when a certain product starts producing a higher revenue for the company, the product can go from the B category to the A category. When a product increases its commonality and exceeds its granted slot capacity the product can also switch between categories which is also handled by answering sub question 3C.

The next strategy to discuss is the Cube per Order Index (COI) slotting method. Basically, COI stores a SKU based on how frequently it is picked per unit of stock space required where fast movers are located close to the Input–Output points. For single command order picking, COI slotting is well-known to minimise order picking travel time (Schuur, 2015). However, the downside of the COI slotting method is shown by the paper of Schuur (2015) which concludes that there is always a warehouse configuration and a set of orders for that warehouse such that COI when applied to the SKUs belonging to these orders performs worse than optimal in total order picking travel time. This means that under certain warehouse designs and order conditions, COI results in considerably longer order picking times than the best possible method.

3.1.3. Toy problem

As explained in Section 1.2.4 the company criteria besides a shorter order picking time are the revenue and commonality of a product where the revenue is the first criteria, and the second criteria is the commonality. Comparing the ABC method with the COI method there are some similarities, however the COI is only looking at one criteria point at a time while the ABC method can focus on multiple criteria points. Therefore, the ABC strategy is exercised in this thesis which is explained by a toy problem that compares both of the methods.

Let us say you have a factory which is producing toys, where the three best selling toys are, Lego, Playmobil and Barbie. You want to rank these products according to two different criteria which are the revenue and the commonality of the products. You want to order the products in 9 distinct categories because of the 2 criteria points. So, we get category AA, AB, AC, BA, BB, BC, CA, CB, and CC where the first letter is the first criteria point and the second letter is the second criteria point. For this toy problem only products in category A are reviewed. After the products are sorted across the categories, they are slotted in the most appropriate slots which is explained in the next chapter.

Lego is producing the highest revenue, Playmobil the second highest revenue and Barbie is producing the third highest revenue which places them all in category A. Lego is the most common in the factory, Barbie is the second most common toy and Playmobil the third most common. The COI strategy would put Lego, which has the highest revenue, in the first slot. Then Playmobil, which has the second highest revenue, in the second slot. Finally, Barbie, which has the third highest revenue, is placed in the third slot. The ABC strategy would rank Lego, Barbie, and Playmobil based on the first criteria set by the company, which is revenue, all in category A as explained. Within category A the toys are again categorized according to the second criteria point, commonality. Barbie is then more important to the company because it is more common and therefore placed in the second slot. For example, Lego is producing the highest revenue and is the most common out of the three toys and is therefore placed in the first slot. Playmobil is producing the second highest revenue and would be placed in the second slot according to the COI, but based on the second criteria point Barbie is more common than Playmobil and for that reason Barbie is placed in the second slot. Playmobil which is producing the second highest revenue is placed on the third slot. So, after every toy is placed in a category another criteria point can be used to put the product in another category. This can be done over and over again until all your criteria points are met.

So, the ABC strategy is including the revenue of the products together with their commonality and is categorizing the products accordingly. The ABC strategy is therefore more flexible, since all the various products can be categorized based on various criteria points. The categories are not fixed on cost and revenue and other criteria points can be added to the categories if applicable. So, if HTM wants to add other criteria point to the slotting of their products the ABC strategy would allow that. This makes the ABC strategy a more popular and better suited method to use for this thesis.

3.1.4. ABC strategy

This section elaborates on the ABC slotting method since this is the main slotting method exercised in this thesis and which is the most popular class-based policy for the storage allocation assignment in warehouses (Silva et al., 2022). In a typical ABC approach, one classifies inventory items according to their transaction volume or value. A small number of items may account for a big share of volume; an intermediate category may have a moderate percentage of volume; and a large number of items may occupy a low proportion of volume. These categories are labelled A, B, and C (Millstein et al., 2014).

The ABC strategy is used for different types of slotting, as discussed in Section 3.1.1 slotting has various categories where the ABC strategy can be used for both fixed and chaotic slotting. For fixed slotting every SKU is classified in the three categories and each SKU has a set slot, according to this the slots are filled. Chaotic slotting assigns a space to A products, B products, and C products and when a new SKU comes in, you decide the category and place it in the corresponding place. Each SKU does not have a set slot which is more flexible for incoming products. The other slotting category is micro vs macro slotting where the ABC strategy can be used again in both cases. The ABC strategy can be used for the precise location of a SKU (micro slotting) and the overall design of the warehouse (macro slotting).

The ABC strategy is in this thesis also combined with a theory, namely the pareto principle. The pareto principle states that 80 % of your results come from 20 % of your efforts (Harvey et al., 2023). In inventory management the pareto principle implies that 20 % of your SKUs account for 80 % of your revenue where these 20 % of the SKUs automatically become the A category. Following the pareto principle, the B class is approximately 30 % of your total SKUs and accommodates for 15 to 20 % of your revenue (Harvey et al., 2023). Finally, class C is 50 % of your SKUs and is making up 5 % of your total revenue.

Not every company gets 80 % of their revenue from only 20 % of their SKUs, so category A becomes 20 % of your total SKUs with the highest possible revenue. Category B is 30 % with the second highest revenue and category C has the SKUs with the lowest revenue and is 50 % of your total SKUs. These percentages are also used to slot the distinct categories where category A is 20 %, category B is 30 % and category C is 50 % of the available warehouse slots, respectively.

3.1.5. Chosen Strategy

The Slotting method used in this research is the ABC strategy. The toy problem explained why the ABC strategy is the most suitable method to use right now and looking at the future. As explained in Section 3.1.1 the ABC strategy can be exercised for all types of slotting cause of the flexibility of the strategy. It is very flexible for newly incoming products and combining the ABC strategy with the pareto principle gives a suitable slotting strategy for HTM Aerotec. The pareto principle is partly exercised in this thesis which means that 20 % of the racks are for category A products, around 30 % are for category B products, and 50 % are for category C products. The 20 % of products in category A are accounting for the highest revenue, whereas the 50 % of category C products accounts for the lowest revenue.

There are two main criteria on which the SKUs are classified as explained. Flores and Whybark (1987) proposed a multiple criteria framework to manage ABC analysis and applied it to a service organization and a manufacturing firm. This approach begins with selecting another critical criterion which depends on the nature of the industry, may be obsolescence, lead time, substitutability, reparability, criticality, or commonality (Flores & Whybark, 1987)(Chen et al., 2008). For this research, the SKUs are classified based on their revenue, but also their commonality as explained before. The commonality of a product is measured with the shipping quantities which implies that a highly shipped product is really common. With multiple criteria, Chen et al. (2008) is introducing a second classification for the ABC strategy which implies that after the SKUs are classified in categories A, B, and C there is another classification. Now SKUs inside the distinct categories are classified. So, in category A you have AA, AB, and AC.

3.2. Conclusion

Chapter 3 is reflecting on the third phase of the MPSM which is analysing the problem Heerkens and van Winden (2017). This is done by analysing the distinct slotting methods which can be used to form (alternative) solutions which is the fourth step. This chapter is also answering sub research question 2A with the support of case studies and non-behavioural observations.

Slotting can be divided into two categories with each two types, where the first category is fixed slotting or chaotic slotting, and the second category is micro slotting or macro slotting. The two main slotting methods used for single demand picking are explained which are the COI strategy and the ABC strategy. The COI strategy stores an item based on one criteria and slots them according to that criteria. The ABC strategy puts all the products into three categories and slots them according to these categories.

The ABC strategy is used in this thesis cause of multiple criteria points set for slotting the products by HTM Aerotec which are the revenue and the commonality of products. The ABC strategy is therefore using a multiple criteria framework suggested by Flores and Whybark (1987). The ABC strategy is combined with the pareto principle which basically suggests that 80% of your results should come from 20% of your effort.

4. Priority of the racks

This section is focussed on research question 2B, "*How are the products going to be assigned to the slots using the chosen slotting strategy?".* The question is answered with the help of case studies and non-behavioural observations. The first section is describing the model and adjusting the model according to the warehouse of HTM Aerotec (Section 4.1). The second section is explaining some parts of the code that is used to calculate the model (Section 4.2). The third section is elaborating on the outcomes of the code and drawing conclusions (Section 4.3). The last section of this chapter is shortly concluding this chapter (Section 4.4).

4.1. Theoretical model

Section 4.1 is explaining the theoretical model used to answer sub question 2B. The first sub section is deliberating on the choice for this specific model together with a toy problem (Section 4.1.1). The second sub section is explaining the theoretical perspective from the model (Section 4.1.2), where after the model assumptions are given (Section 4.1.3). The fourth and last sub section is explaining the model and explaining how the model is adjusted to fit the warehouse of HTM Aerotec (Section 4.1.4).

4.1.1. Chosen model

To make a final assignment of the products inside the warehouse racks, it is important to know which slots have the best location for the shortest order picking time, where products from category A can be placed for example. Should the slots be filled starting by the row, or is it better to slot by the columns or level? A row is the set of rack locations arranged horizontally along the aisles. A column is a set of spaces arranged one above the other in a row. The level number corresponds to the increasing order of the vertically available spaces in a column (Duque-Jaramillo et al., 2024). To answer this question a theoretical model should be used to find the optimal slot assignment sequence to assign your SKUs to your warehouse slots. A slot assignment sequence is a strategy on how to place your SKUs in the slots, first the row, column, or level. This model should cover the distances of the warehouse and times to fill in every distinct slot and give the optimal strategy. An article by Duque-Jaramillo et al. (2024) is providing a similar model to calculate the optimal strategy. The model used in the article can be adjusted to the warehouse constraints and measurements of the warehouse of HTM Aerotec. How the model exactly works is explained with a short toy problem.

Let's say there is a factory which is producing a large variety of toys. Each of the toys should get a place inside the warehouse on the available slots. However, you want your best-selling products assigned to the best slots available in the warehouse, so that these products have the lowest order picking time. The model by Duque-Jaramillo et al. (2024) is calculating exactly what the most popular slots are with the lowest order picking time. Let's say toy type one is the best-selling toy in the warehouse, were do you slot all of the toys of type one? Are you placing them all in the same row, or are you placing them all in the first column of each row? The model used is calculating where you should place your best-selling toys and worst selling toys according to six different strategies that are deliberated later in this chapter.

To provide an answer to sub question 2B the following steps are taken. The first step in finding the solution to the research question is to add the input parameters of the warehouse and all the measurements to get the exact virtual warehouse that is eventually used at HTM Aerotec. The second step is to classify all the SKUs that are stored in the warehouse according to the chosen slotting method and apply the total number of category A, category B, and category C products to the code which is done with the ABC method explained in the previous chapter. The third step is to run the code and let the code fill in every slot until the warehouse is filled and all the SKUs have received a slot. The fourth step is to calculate the times of filling up all the slots for every strategy and the final step is to compare these distinct times of all the strategies and choose the strategy with the lowest time to operate in the warehouse of HTM Aerotec.

4.1.2. Theoretical perspective

As described above, the theoretical model used to find the priority of the row, column or level is the model from Duque-Jaramillo et al. (2024). This model is used to find the optimal strategy to use in the warehouse of HTM Aerotec and to provide an answer to sub question 2B "*How are the products going to be assigned to the slots using the chosen slotting strategy?".* Exercising this model is directly answering the sub question with a good and solid substantiation using the dimensions of the warehouse of HTM Aerotec, which are given in Chapter 2.

In the article from Duque-Jaramillo et al. (2024) six distinct slot assignment sequences (SAS) are described to assign the products to their warehouse racks. The slot assignment sequences describe what the first step is in slotting, what the second step is, and what the final step is. In the article they also provide a fourth step which are the sections of a warehouse, however this is excluded since the warehouse of HTM Aerotec only has one section.

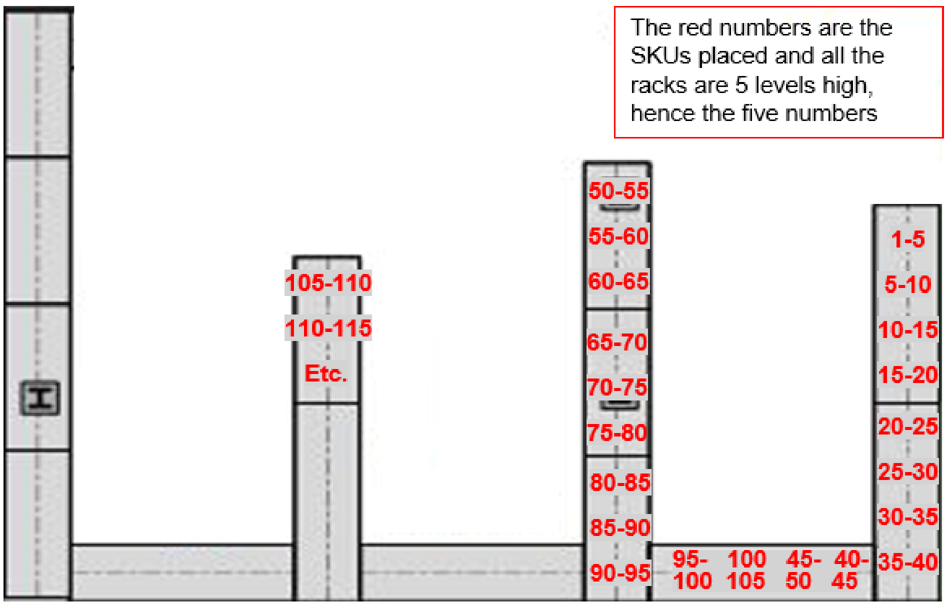

Figure 15, SAS 1 visual example

An example of SAS 1 is given in Figure 15 where the first step is row, the second step is column, and the third step is level. This means that the level has the least priority and is filled first, so SKU one till five is placed in column one and row one on the five distinct levels. The second lowest priority are the columns, so the next step is column two and fill all the levels there. The highest priority is the row, so if row one is completely filled then row two gets filled completely. Figure 30 in the Appendix shows what the six distinct SAS strategies are.

4.1.3. Model assumptions

The model of Duque-Jaramillo et al. (2024) has in total eight different assumptions. These assumptions were made to provide a working and functioning model. However, only seven assumptions apply to the model used in this thesis, since the demand of each SKU is not known but fluctuating as explained in Section 2.1.2. The assumptions are as follows:

1) The SKUs do not need special warehousing conditions.
2) The slot sizes are homogeneous.
3) Any pallet can be stored in any slot.
4) The dimensions and weights of the pallets are similar.
5) The warehouse layout is known
6) The picking orders are made in pallets.
7) The vehicle loading and unloading times are not considered.

Assumptions (1), (2), and (3) are saying that every SKU can be stored in any slot which looking back at Chapter 2, show the different SKUs can indeed be slotted in all the slots since the new warehouse is only containing products on pallets. Assumption (4) is saying all the SKUs are equal since the difference in weight is for the time negligible as explained in Section 2.1.2. Assumption (5) is saying the layout of the warehouse is known which is shown in Figure 4. Assumption (6) is saying all SKUs are placed in pallets, which means every slot is containing one SKU. Assumption (7) is excluding the vehicle loading and unloading times, because these times are influenced by factors which cannot be calculated, since these times are varying for every employee and SKU. An average could be taken but this would not influence the final answer since every time is summed up with this average. So, the difference between the strategy times stays the same.

4.1.4. Model

The theoretical model used by Duque-Jaramillo et al. (2024) is a mathematical model which calculates six distinct strategies. The model calculates how the SKUs should be slotted according to these six strategies. The model contains two decision variables, B_{ircl} and Q_{ircl}, The two decision variables are respectively for slot assignment and for quantity assignment times. The decision variables look like the following.

$$B_{ircl} = \begin{cases} 1 \ if \ item \ i \ is \ assigned \ to \ the \ slot \ srcl \\ o \ in \ other \ case \end{cases} \tag{1}$$

$$Q_{ircl} = \begin{cases} \geq 1 \ if \ B_{ircl} = 1 \\ o \ in \ other \ case \end{cases} \tag{2}$$

The first decision variable is assigning the SKUs in the slots. If an item is assigned to a slot, B_{ircl} gets the value one which means the slot is full and the main equation is providing a time for that SKU. If a slot is empty, B_{ircl} gets the value zero cause no SKU is placed, and this value is multiplied with the equation resulting in a time of zero. This is done because if no SKU is placed, no time can be given for that SKU. The second decision variable is producing the quantity of a single slot. So, if Q_{ircl} has the value two is means that there are two products placed in slot i. Since in the warehouse of HTM Aerotec there is only place for one pallet in every slot, Q_{ircl} is excluded from the model.

To get a better understanding of the model the terms that are used are explained in Figure 16. Not all the terms and abbreviations are used in my model only the abbreviations given in Table 3 in Section 2.1.5 are used. However, first the model of Duque-Jaramillo et al. (2024) is given with the accommodating abbreviations.

Symbol	Meaning
wwl	Warehouse width length
wdl	Warehouse depth length
mhwl	Main hall width length
hswl	Hall between sections width length
hrwl	Hall between rows width length
ssdl	Single shelving depth length
dsdl	Double shelving depth length
swl	Shelving width length
avswl	Average vehicle speed without load
avsl	Average vehicle speed with load
pq, sq, rq, cq, lq	Periods, sections, rows, columns, and levels quantities, respectively
$tsku_p$	Total SKU in the period *p*
d_r	Distance to row *r*
d_s	Distance to section *s*
d_c	Distance to column *c*
$tlift_l$	Lifting time from the floor to level *l*
$tlow_l$	Lowering time from the level *l* to the floor

Figure 16, Model abbreviations. from "Warehouse Management Optimization Using A Sorting-Based Slotting Approach," by J.C. Duque-Jaramillo, 2024, *Journal of Industrial Engineering and Management*, 17(1), p. 133-150. Copyright by Juan C. Duque-Jaramillo.

With the decision variables and terms explained the main model is given. The main model from Duque-Jaramillo et al. (2024), looks like the following. The model minimizes the strategy times of filling up a warehouse from he beginning using the six distinct strategies ST_p for each period p.

$$Min \sum_{p=1}^{pq} ST_p \tag{3}$$

$$ST_p = \sum_{i=1}^{tsku_p} \sum_{s=1}^{sq} \sum_{r=1}^{rq} \sum_{c=1}^{cq} \sum_{l=1}^{lq} [avswl * (d_r + d_c + d_s + wwl) + tlift_l + tlow_l + avsl * (wwl - d_r + d_c + d_s)] * B_{isrcl} * Q_{isrcl} \tag{4}$$

$$d_r = ssdl + \left[round.up\left(\frac{r}{2}\right) * hrwl\right] + \left[\left(round.up\left(\frac{r}{2}\right) - 1\right) * dsdl\right] \tag{5}$$

$$d_c = c * swl \tag{6}$$

$$d_s = mhwl + (s - 1) * (hswl + c * swl) \tag{7}$$

However, the model used for the warehouse of HTM Aerotec is different from the model described above. First the sections are removed since the warehouse of HTM Aerotec only has one section which means sq and d_s are removed from the equation. In the warehouse there are only single racks while in the model above the warehouse is including double and single racks. This means d_r is changing in the new model and $dsdl$ is removed from the equation. The demand is also different between the models, in the model by Duque-Jaramillo et al. (2024) there are distinct periods while for the model used in this thesis there are no distinct periods. This means that ST_p is changing to ST and $tsku_p$ is changing to $tsku$.

In the model from Duque-Jaramillo et al. (2024) the forklift has to travel the warehouse width before being able to place a SKU, which is wwl. In the warehouse of HTM Aerotec the forklift has to travel a different distance, from the place the product is dropped to the start of the warehouse. This distance is called td in the adjusted model. The last major change is with the distance where d_r , d_c, and td are used to calculating the distance to a slot. In the model above they multiple the distance with the travel time per metre of the forklift. However, in my model the distance is divided by the speed of the forklift to provide the number of seconds. With all the changes to the model provided by Duque-Jaramillo et al. (2024) the equation is partly changing. The new model is shown:

$$\min ST = \sum_{i=1}^{tsku} \sum_{r=1}^{rq} \sum_{c=1}^{cq} \sum_{l=1}^{lq} \left[\frac{(d_r + d_c + td)}{avswl} + tlift_l + tlow_l + \frac{(d_r + d_c + td)}{avsl} \right] * B_{ircl} \quad (8)$$

$$if\ r = 1\ ;\ d_r = [r * ssdl] + \left[\frac{1}{2} * r * hrwl \right] \quad (9)$$

$$if\ r > 1\ ;\ d_r = [(r-1) * ssdl] + \left[\frac{1}{2} * (r-1) * hrwl \right] \quad (10)$$

$$d_c = c * swl \quad (11)$$

This is the main module used to calculate the priorities. The objective function minimises the strategies times ST for the six distinct slot assignment sequences using the ABC slotting method. The four main summation signs are, starting from left to right, the total number of SKUs, the total rows of the warehouse, the total columns of one row, and the total levels of one column. The model puts one SKU on one level, inside one column, and inside one row until all the various SKUs are placed in the racks. This model uses the time from a forklift and the time it takes to lift and lower a material with the forklift to calculate ST. They divide the distances travelled within the warehouse by the speed of the forklift used.

The three equations beneath the main equation are calculating the distances to travel. Where d_r is calculating the distance to the row that the SKU is placed in. Looking at the equation of d_r, the number of rows is called r and the single shelve depth length is called, $ssdl$. So, if row is one, the forklift has to travel past one rack. The next part of d_r is the distance between the racks, hwl. Since only single racks are used, row two is filled from between row one and row two. This explains the two different equations for d_r. Since row one and row two have the same travel distance. When entering the hallway between both rows, halve of the hallway is travelled which explains the half at the beginning. So, from the start to row one, we have to travel one rack and halve a hallway. The distance to row two is exactly the same, which is why the second equation has the minus one. The last equation is d_c, which is calculating the distance to a column. Here c is the number of column and swl is the Width of one single rack this also has some variations, but these are described in the VBA code.

The last thing to make clear are the model constraints which are regarding the adjusted model. So, all the terms not used are excluded in these constraints. The following constraint sets were defined: Eq. (12) defines the type of the decision variable which is of type Boolean. So, B_{ircl} is true and receives value one if the slot is filled and false receiving the value zero if the slot is empty. Equation (13) defines the upper limits for total SKUs, rows, columns, and levels indexes. So, the total rows filled cannot be more than the total rows available etc. The quantities for these are given in chapter two which quantities are set and can not change. Equation (14) defines the maximum number of products that can be assigned to the racks which has to be smaller than the total available slots since B_{ircl} can never be larger than the maximum number of slots. Equation (15) indicates the total assigned SKUs which has to be equal to the slots that are filled. This is calculated by going over all the slots of all the rows, columns and, levels. Equation (16) defines that the total SKUs are less or equal to the maximum warehousing capacity. Since the total SKUs assigned cannot be more than the available slots. Finally, Equations (18) and (19) are limiting the distance to the rows and columns, respectively. The distance to the final row can never be larger than the warehouse width. The same goes for the distance to a column, this cannot be larger than the length of the warehouse (Duque-Jaramillo et al., 2024).

$$B_{ircl} = binary\ variable \tag{12}$$

$$i \leq tsku; r \leq rq; c \leq cq; l \leq lq \tag{13}$$

$$\sum_{ircl} B_{ircl} \leq rq * cq * lq \tag{14}$$

$$\sum_{ircl} B_{ircl} = tsku \tag{15}$$

$$if\ tsku \leq rq * cq * lq; \leq 1 \tag{16}$$

$$d_r \leq wwl \tag{17}$$

$$d_c \leq wdl \tag{18}$$

With all the equations, decision variables and constraints the model is complete which can calculate what the best strategy times are to use in the warehouse of HTM Aerotec. Running the final model gives the times for the six distinct strategies. The lowest time is from the best strategy and that strategy is exercised in the warehouse of HTM Aerotec to provide the final assignment of products. The next section deliberates on the VBA code. The VBA code is written to calculate these distinct strategy times and find the best strategy. For a detailed explanation of the strategies see Appendix A.

4.2. VBA code

The Mathematical model is calculated with the use of VBA where the model is implemented together with the constraints and decision variables. However, there are some variations in the VBA model compared to the code. These variations are explained in this section of the thesis together with the most important code. For an overview of the whole code, see Figure 46 till Figure 49.

```
' Initialize all slots to False (empty)
For r = 1 To rq
    For c = 1 To cq
        For l = 1 To lq
            B_ircl(r, c, l) = False
        Next l
    Next c
Next r
```

Figure 17, VBA code setting all the slots to empty.

This first part of the code is setting all the slots to empty, so they are getting filled later on in the code. Figure 17 depicts three distinct for loops which go from row one, column one, and level one to their maximum until all the slots are set to empty. *B_ircl* is the array in which all the SKUs are placed. This is put to false, which gives it the value zero since it currently contains zero products.

```
' Place products in the warehouse
For r = 1 To rq
    For c = 1 To cq
        For l = 1 To lq
            If productCounter <= tsku Then
                ' Place the product in the slot
                B_ircl(r, c, l) = True
                Debug.Print "Product " & productCounter & " placed at Row " & r & ", Column " & c & ", Level " & l
                productCounter = productCounter + 1
            Else
                Exit For
            End If
        Next l
        If productCounter > tsku Then Exit For
    Next c
    If productCounter > tsku Then Exit For
Next r
```

Figure 18, VBA code filling the slots.

After all the slots are set to empty, the SKUs are getting placed in the warehouse. The *product counter* is counting all the slots that are already filled in which the code goes thru all the different slots, and if there are still empty slots the slot gets filled. The *debug print* line is printing the place of the code if there is an error occurring. The code shows exactly at which row, column, and level the error is occurring. Every time a SKU is placed in a slot, *product counter* is increased by one. The for loop continues until *product counter* is larger than *tsku,* which is the total number of SKUs. If all the slots are filled, then the code exits the for loops and the code moves on.

```
' Calculate d_c for the different rows
If r = 1 Then
d_c = c * swl + 0.9
End If
If r = 2 Then
d_c = c * swl
End If
If r = 3 Then
d_c = c * swl + 1.8
End If
If r = 4 And c > 2 Then
d_c = c * swl - 1.8
End If
```

Figure 19, VBA code calculating the distance to a column.

Since not all the rows start at the same length, the distance to the first column of every row is different. Row two is taken as the beginning, so therefore 0.9 m is added to row one since row one is one column shorter than row two. With these if statements all the various distances for the rows are the same. Row four has two slots directly in the hallway, so the first two columns have a distance of zero. The third column is starting two columns behind, hence the minus 1.8.

```
' Set different columns for the rows
If r = 1 And c > 9 Then
stopping = 0
End If
If r = 2 And c > 10 Then
stopping = 0
End If
If r = 3 And c > 10 Then
stopping = 0
End If
If r = 4 And c > 14 Then
stopping = 0
End If
```

Figure 20, VBA code setting different columns for the four distinct rows.

Figure 20 is depicting the number of columns for every row. Row one consists out of seven columns and row two has eight columns and both rows get two slots from the horizontal row, since these slots can get filled between row one and two. Row three consists of six columns with four columns of the horizontal row. Row four consists of ten columns and also four columns of the horizontal row. If the number of columns is larger than the number of columns of a row, *stopping* becomes zero. The final equation is multiplied by *stopping*. So, if for example row one is at column ten, which is non existing, the equation gets the value zero.

```
' Set d_c the same for the last few columns
If r = 1 And c > 7 Then
d_c = 7.2
End If
If r = 2 And c > 8 Then
d_c = 7.2
End If
If r = 3 And c > 6 Then
d_c = 7.2
End If
If r = 4 And c > 10 Then
d_c = 7.2
End If
```

Figure 21, VBA code setting the distance for the horizontally placed racks.

The distance to the horizontal rows is the same as for the last slots. To get this in the final equation the code of Figure 21 gives each column of the horizontal row the same distance. Since the beginning of each row is set to be the same as row two, the distance to the horizontal rows is the same as the distance to the last column of that row. Row two is eight columns with a length of 0.9 m, so the total distance is 7.2 m.

```
' Calculate the expression inside the brackets
Dim expr As Double
expr = ((d_r + d_c + td) / avswl + tliftl(l) + tlowl(l) + (d_r + d_c + td) / avsl) * B_ircl(r, c, l) * stopping
p = p + 1
Cells(p, 1) = expr
' Accumulate the sum for ST
If B_ircl(r, c, l) = True Then
    totalST = totalST + expr * Q_ircl(r, c, l)
End If
```

Figure 22, VBA code main equation

Figure 22 depicts the main equation, which calculates the best strategy for structuring the racks. The equation is the same as the adjusted mathematical model where the results of the equation are put into column one. The distance to a row and to a column is summed up with the distance the forklift travels. When a SKU is placed in the slot, the equation is multiplied by one, otherwise if the slot is empty the distance is also zero.

4.3. Results

To get to the results the ABC slotting method is used as explained in chapter 3 which classifies all the SKUs in three distinct categories. Where A has the highest priority, B the second highest, and C the lowest priority. This method is combined with the pareto principle which said that category A is 20 % of the total SKUs, category B is 30 % of the total SKUs, and finally category C is 50 % of the total SKUs. The distinct categories all have different priorities. To get these priorities in the model the pareto principle is used once again. The pareto principle is describing, as explained in Section 3.1.4, that category A is accounting for 80 % of the revenue, category B is accounting for 15 % of the revenue, and category C is accounting for 5 % of the total revenue. These percentages are changed from revenue to their priority. So, category A has the highest priority and is multiplied with 0.8, category B is multiplied with 0.15, and category C is multiplied with 0.05. With these priorities the code is run.

To provide the results for the distinct strategies, which are explained in Section 4.1.2, the letters r, c, and l are switched around in the code. This is done according to those six distinct strategies provided by Duque-Jaramillo et al. (2024). For example, strategy one has the rows first, then the columns and finally the levels. In the VBA code, the first for loops are the rows now, the next for loops are the columns, and the final for loops are the levels. Also, for the decision variables the letters r, c, and l are switched according to the corresponding strategy.

Applying the priorities of the distinct categories gives a different value for the distinct Strategies. To give the priorities and percentages of the SKUs to the classes A, B, and C, The results of every single category are printed onto the excel worksheet and all the zeros are deleted with some extra code shown in Appendix C. After, the first 20 % of the total SKUs is summed up and multiplied with 0.8 according to the pareto principle. The same is done with category B and category C which results are displayed in Figure 23.

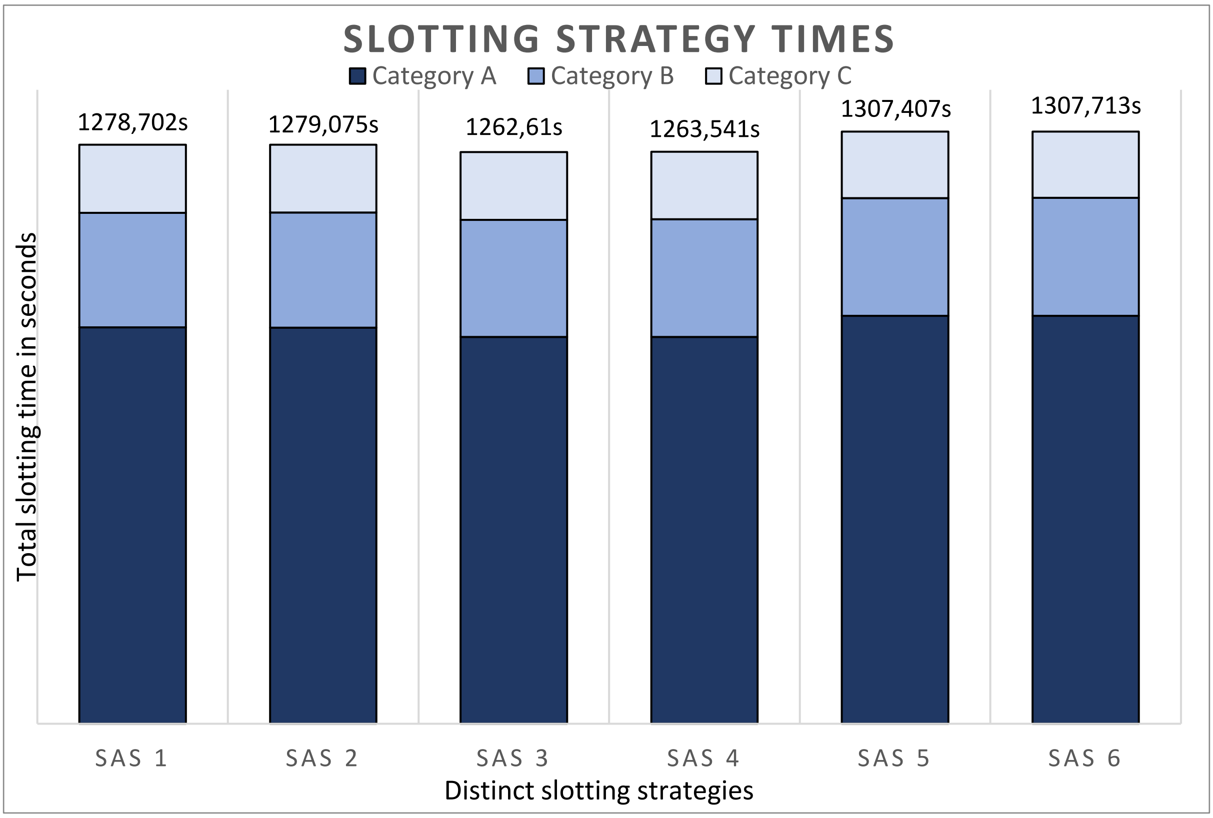

Figure 23, Best slot assignment sequence.

As shown in Figure 23, the best strategy to order the racks is SAS 3. First, the levels are filled from row one and column one. Then the levels of the second row, column one are filled until every level is filled in column one. The strategy then moves on to the second column. SAS 3 has the lowest overall time, but also the lowest time for category A. The difference between the times in the solution is quite small, the reason for this is that the warehouse of HTM Aerotec is also quite small. So, the time difference between the strategies is only seconds. This is also the case because certain factors have been let out of the equation. However, the result is satisfactory and a final assignment of products inside the racks can be designed from the solution found.

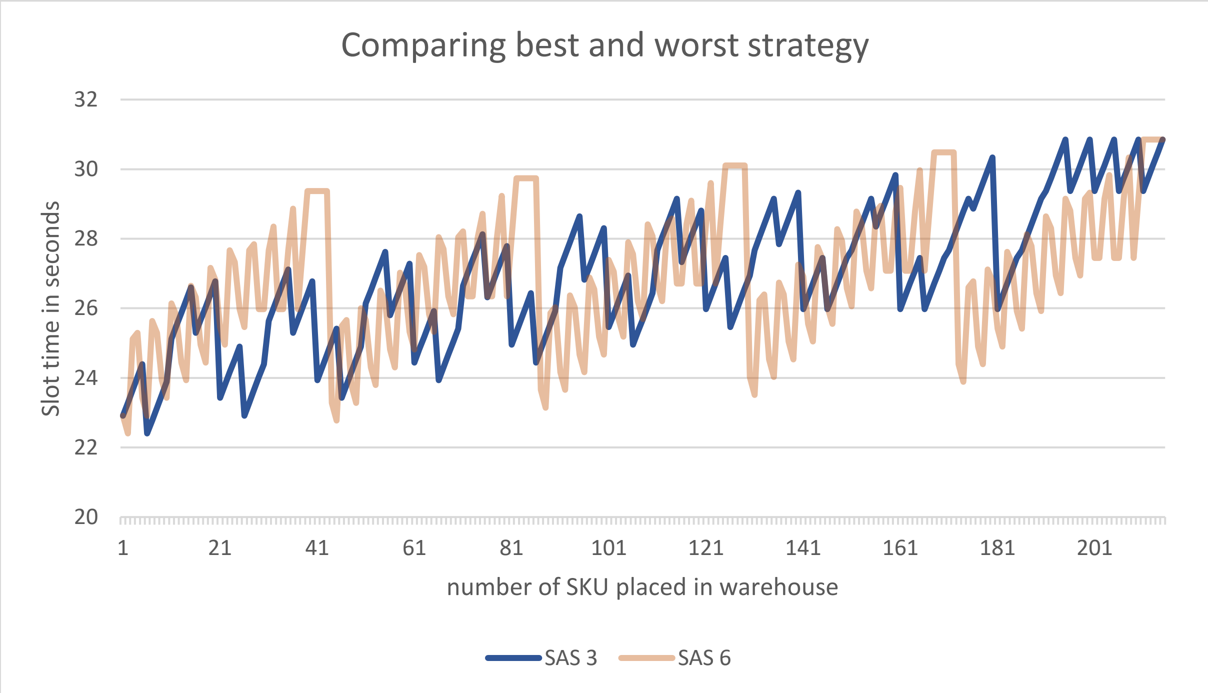

Figure 24, Comparison of best and worst slotting strategy

Figure 24 displays the best strategy in comparison with the worst strategy. The times for filling in one singular slot are given in the chart for filling in every single slot for both strategies. Figure 24 shows the times for filling in the warehouse exercising SAS 3 and exercising SAS 6. The graph shows that the pattern of SAS 3 is more compact compared to the line of SAS 6 which has higher highs and lower lows. Figure 24 especially shows that for category A products SAS 3 is much better than SAS 6. Category A products only occupy the first forty available slots and looking at both lines the blue line is almost always beneath or equal to the orange line. This shows that the time it takes to fill up the category A products, which have the highest priority, to their assigned slots is faster using SAS 3. Looking at the line after the first forty products it start to get similar where the blue line is both above and beneath the orange line. This shows that looking at the whole of both lines SAS 3 is indeed faster for order picking, since especially the first slots are picked faster. Since the priority is on the category A products, which have the biggest impact within the company and the overall picking time is shorter using SAS 3, the final result is satisfactory. So, the result from the model can be used for the assignment of products inside the warehouse racks.

4.4. Conclusion

Chapter 4 is deliberating phase four of the MPSM from Heerkens and van Winden (2017). formulating (alternative) solutions. The solutions are formulated by the strategies chosen in Chapter 3. Chapter 4 is answering sub question 2B.

With the adjusted model from Duque-Jaramillo et al. (2024) the best strategy is chosen. Coding the model in VBA and running the model provided six distinct times from the six distinct strategies. The pareto principle is also used to provide satisfactory answers where the category A products were multiplied with factor 0.8. These factors were taken from the pareto principle and the same was done for the two other categories. After these steps, the best strategy to assign the SKUs to the slots is conducting slot assignment sequence 3. This means that first level one to five is filled in row one and column one. Then the levels of row two column one are filled. This method is used till every slot is filled. The final assignment of products of the warehouse is exercising SAS 3.

5. Forming the solution

The fourth chapter is forming an answer to research question 3, *“What is an appropriate assigment of products inside the warehouse racks to decrease the order picking time at HTM Aerotec?”* The corresponding sub questions are answered as well. The first section is putting the distinct products in the different categories of the ABC strategy (Section 5.1). The second section is answering the first sub question and is providing a map of how the products should be assigned to the racks (Section 5.12). The next section is deliberating how the SKUs should be distributed if there are more SKUs in one category than available slots provided and answering the second sub question (Section 5.3).The fourth section is answering the third sub question by giving the new estimate of the order picking time (Section 5.4). Finally, the last section is giving a short conclusion of the chapter (Section 5.5).

5.1. Product classification

Before making a final solution, first the products need to be assigned into the three distinct categories, starting with category A SKUs. Two suppliers of HTM Aerotec are classified in category A which are named company Y and company X for privacy issues. These two suppliers accommodate together for the highest generated revenue, which number is withheld from this thesis according to privacy reasons. With the shipping quantities the revenues can be traced back to the supplier, hence the reason to leave the number of revenue from the suppliers out of this thesis. The two suppliers accommodate for a large number of units that are processed by HTM Aerotec which are shown in Figure 25.

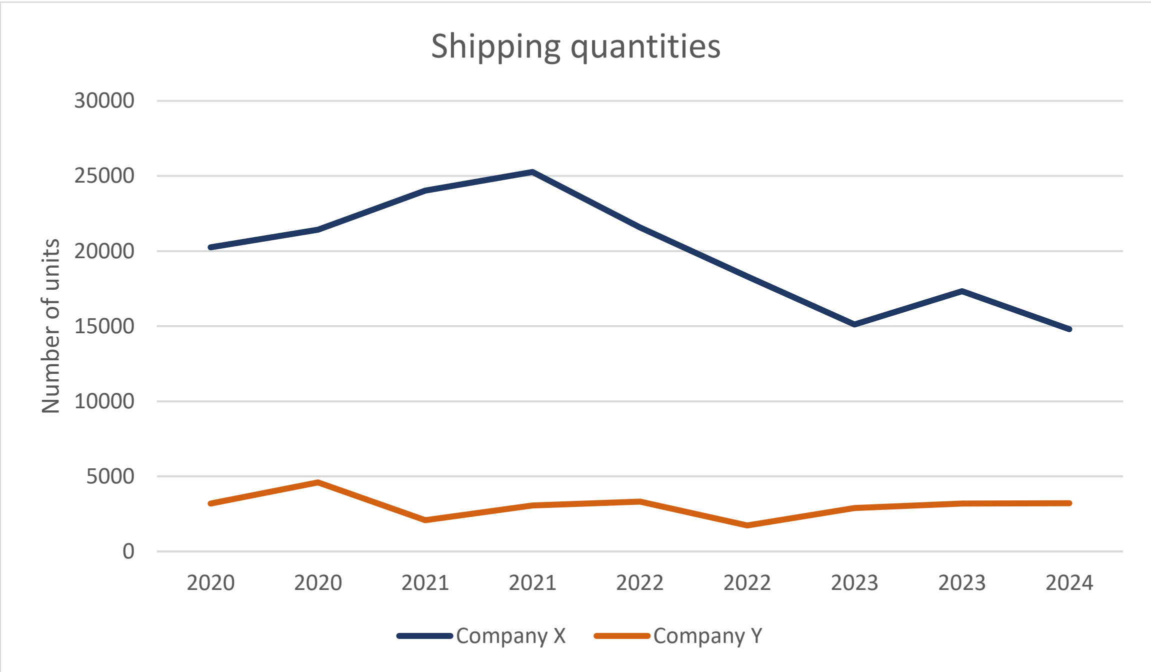

Figure 25, Shipping quantities category A

Figure 25 describes the shipping quantity of the products from the year 2020 till July of 2024 for every six months. Company X is by far the biggest supplier of HTM Aerotec, and company Y is the second largest supplier. Both companies also provide the highest revenue which puts them both in category A. According to Figure 25 company X is the most common across HTM Aerotec which puts company X above company Y in the A category. So, company X is classified as AA and company Y as AB.

The next category that is discussed is category C. HTM Aerotec is containing various slow movers which are SKUs that sit in the warehouse for a long time without being processed by the machinery. These slow movers occupy large amounts of the warehouse and are bad for the total revenue of the company. Since these slow movers spend a long time in the warehouse, the total ship quantity is low as well. These slow movers are from different suppliers but are slotted together since they are of the same SKU type.

The next type of SKUs in the C category is raw material. Raw material is from different suppliers but slotted together to improve the overall assigment and findability of the SKUs. Raw material has generally less priority than other SKUs. Depending on the raw material the revenue they produce is not high in comparison with the A category and even the B category. So, both the slow movers and the raw material is placed in the C category. Within category C the second classification is made for both SKU types. Slow movers are producing the least revenue and have a low ship quantity. For that reason, slow movers are CB and raw material becomes CA.

The last SKUs that are classified are all in category B. Different suppliers are all in category B since these suppliers are producing a lower revenue compared to company X and company Y but a higher revenue than the SKUs in category C. the number of suppliers in this category is not set as explained in Section 2.1.2. These suppliers are also shipping fewer units to HTM Aerotec, in comparison to company X and Y which makes them less common. There is one big supplier among all suppliers in category B, which is named company Z. This supplier is partly higher in revenue compared to the other suppliers and has a higher shipping quantity. The last SKUs in category B are machining SKUs, which are most common compared to the other SKUs in category B and have an equal revenue compared to company Z. These SKUs are processed by the same machinery and of the same type and therefore placed together. So, category B contains three different types of SKUs. The most important type is machining, which is classified as BA. Company Z has a higher shipping quantity than the other suppliers, which classifies company Z as BB. All the remaining suppliers are placed in one class, which is BC.

	A	***B***	***C***
First priority - ***A***	Company X	Company Y	-
First priority - ***B***	Machining	Company Z	Other products
First priority - ***C***	Raw material	Slow movers	-

Table 6, Classification products HTM Aerotec

Table 6 is providing an overview of how all the different SKUs that are classified. Since there are only two suppliers in category A, class AC is not used which also accounts for category C, class CC. These classifications are used in the next section to provide an assignment of products inside the warehouse racks.

5.2. Structuring the racks

This section is focussed on research question 3A, "*How are the products assigned inside the warehouse racks to decrease of the order picking time?".* The assignment of products inside the warehouse racks is following the results produced by the VBA code together with the outcomes of the ABC analysis. All the different SKUs are placed in the warehouse following the double classification method explained in the previous section. So, for the assignment of products all the various SKUs are assigned, starting with category A. The number of slots is following the pareto principle where category A has 20 % etc. There is one slight adjustment, because during the observations HTM Aerotec mentioned that they did not have a section in the warehouse for finished products. So, one section is added where SKUs are placed that are (almost) ready for departure. This section is placed at the top of the warehouse since the finished products produce the revenue, which is the main criteria, of the company and need to have the shortest order picking time.

Figure 26 displays the final assignment of products of the racks, which is the main solution of this thesis. As explained, the top rack is for finished products or semi-finished products. This place is chosen because finished products are providing the revenue stream for the company. These products are slotted in column one which was according to the results of the mathematical model the best place. To improve the overall assignment of products the decision is made to slot all the products of the same type together.

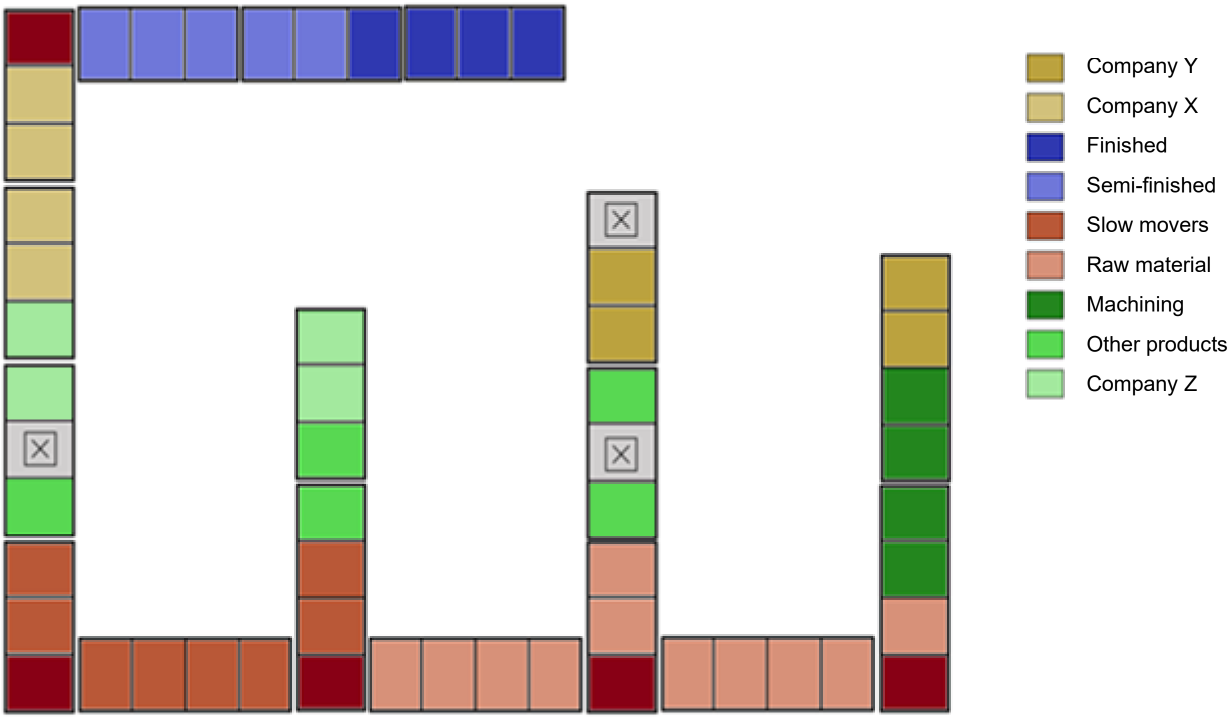

Figure 26, Final solution.

In category A there were two main suppliers which were important for HTM Aerotec. Company X which is placed in AA is producing the biggest revenue and has the highest commonality. Therefore, company X is slotted in the first available columns following the results of the VBA code. Company Y is the second largest supplier and is therefore placed at the beginning of the warehouse in the first columns of row one and two.

Category B is containing three mayor types of SKUs as explained in Section 5.1. The most important type is machining and for that reason it is placed closest to the entrance of the warehouse. It is not slotted in the first available column because then it would be spread across multiple rows. Since machining is the most important among category B SKUs they are slotted together in the second best columns and also closest to the entrance of the warehouse. Company Z is the second rated in category B. Therefore, it is placed at the best available columns and slotted together. The last type of SKUs left in category B are a combination of suppliers which are slotted in the empty places mentioned for category B. These are spread across three distinct rows, but since these are all different suppliers, the products of every supplier can still be slotted together.

The last types of SKUs are from category C, which are slotted at the bottom of the warehouse. Category C existed out of two types of SKUs which were raw material and slow movers. Slow movers are slotted farthest away from the entrance. The raw material is slotted closer to the entrance of the warehouse but still in the last columns available, which is following the results in Section 4.3.

5.3. ABC distribution

Slotting as explained in Section 3.1.1 is the distribution of SKUs in the warehouse and can reduce the operating picking time (Rios et al., 2022). This sub section is answering sub question 3C, *"How should products be slotted if they exceed their assigned slots?"*. When the situation occurs that there are more SKUs from category A than 20 % of the available assigned slots, some of the SKUs need to be placed in the category B slots. Also, with the fluctuating demand it can occur that at one point more category A products arrive at the company instead of category B products. These problems are solved, and the products are assigned according to the answers from Section 5.1. For all the categories a distribution is made on how extra SKUs are slotted.

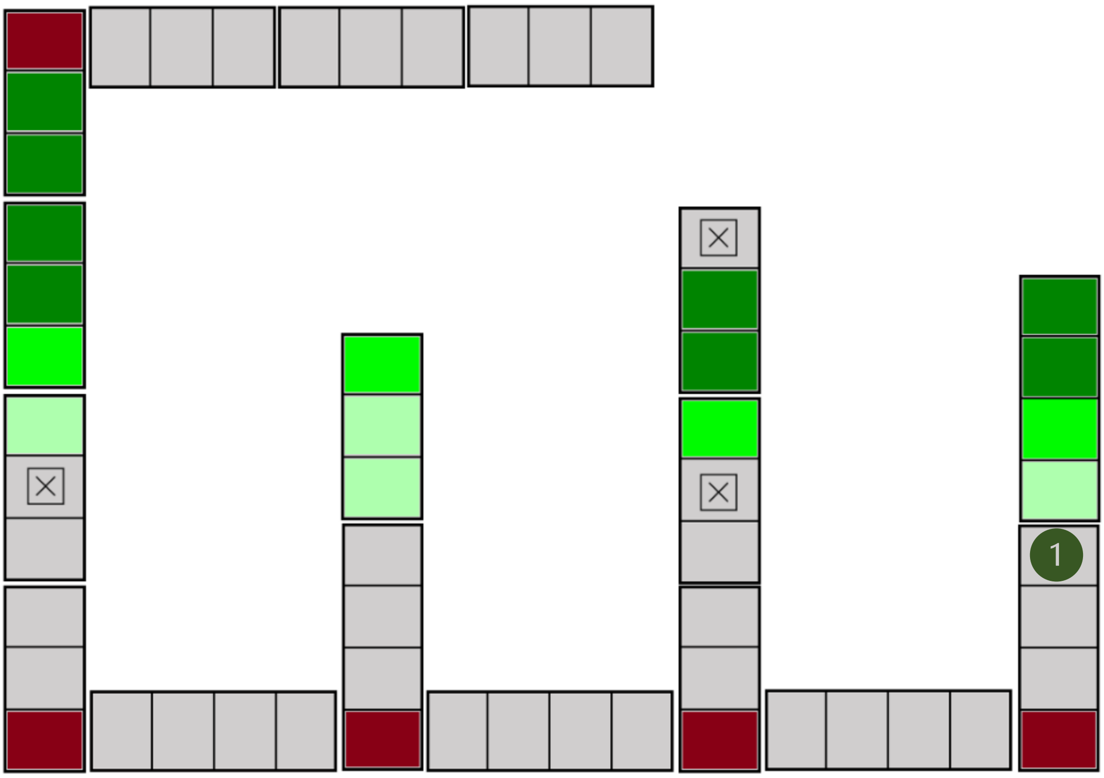

Figure 27, Category A distribution.

Figure27 displays how SKUs in category A are slotted and following the explanation in Section 5.1 the rack on the top stays empty. So, if there are more than forty SKUs in category A, which is 20 %, the SKUs are slotted in the B section. The dark green slots depict the original slots assigned for the category A products and the lighter green depicts the spots if there is a larger amount than 20 % of category A products. Finally, slots which are coloured with the lightest green depict spots if all the other slots are taken. Figure27 showed a total of 50 % extra slots for category A products. If there are even more SKUs in category A, which is exceptional, the SKUs are slotted from right to left, starting at the slot with number one.

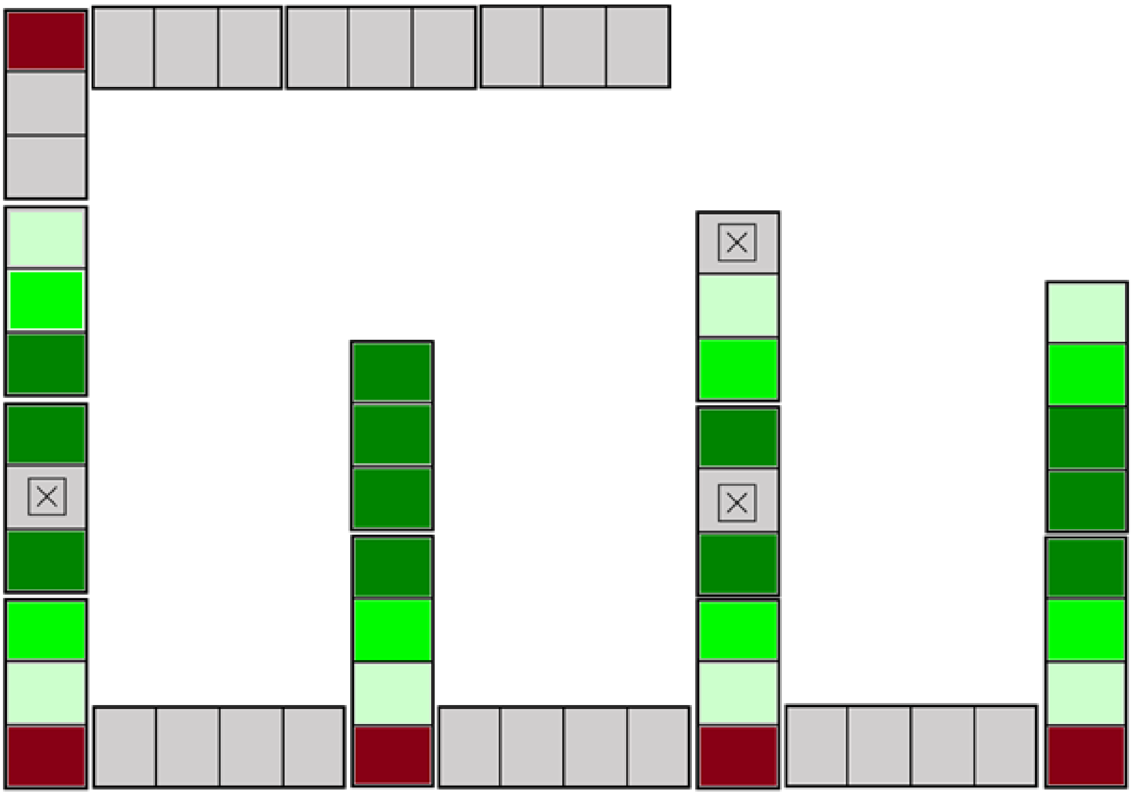

Figure 28, category B distribution.

Figure displays how the SKUs in category B are slotted. Here the same colours with the same meaning are used as in Figure 27. So, the dark green slots depict the original slots for category B, if it follows the pareto principle which is 30 % of the available slots. However, for the B category, SKUs are slotted in the A category and the C category if necessary. If there is place in the A section, these slots are filled up first. First the middle green coloured slots are filled and after the light green slots are filled. If in section A all the slots are occupied, the SKUs are slotted in the C section where the same rules are used as in section A. So first the middle green coloured slots are filled and after that the light green slots are filled up. If the total number of SKUs in category B is still exceeding the number of assigned slots some products are moved from category B to category A, since otherwise all the slots for category A are filled with category B products. This means there are no products in category A and the SKUs in category B needs to be reassigned. In this situation the products in category BA are placed in category A and the other products move up a category.

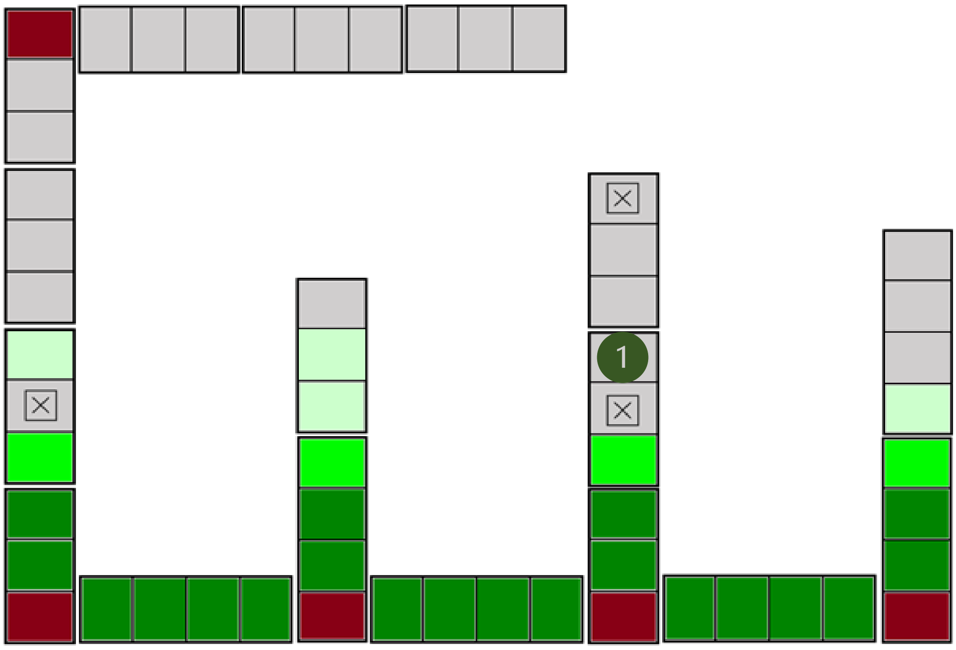

Figure 29, category C distribution.

The last section to be filled is section C which is displayed in Figure 29. The dark green slots depict the original slots, which is accounting for 50 % of the available slots according to the pareto principle. If there are more SKUs, first the middle green coloured slots are filled and after the light green slots are filled. If there are more SKUs in category C, slots are filled from left to right starting in the slot with number one. Since SKUs in category C have the lowest priority, they are slotted from left to right, giving the SKUs in category B the more valuable slots following the results from the mathematical model.

5.4. New order picking time

The new order picking time is a rough estimate, since the warehouse is not yet finished, and the SKUs are not yet placed. However, with the new assignment of products inside the warehouse racks, the change to lose track of, or overlook a certain SKU is smaller. When you are looking for a SKU of company X you now in what area to look. If the SKU is in the state of raw material, you now in which region to look. So, you do not have to look across the whole warehouse anymore. To provide a rough estimate multiple “orders are picked”. To evaluate this, various times the route to the warehouse is taken and it is pretended that the SKU is not findable. Every slot of a certain category is checked, which would locate the right SKU in the end and the time is measured. This method is explicitly done with the SKUs in category C. Since these SKUs have the highest quantities and are furthest away from the entrance of the warehouse which implies that these products have the longest order picking time.

The slot furthest away from the entrance of the warehouse has a slot time of 30.85 seconds according to the VBA model. However, the model does not include the turning of the forklift and actual slotting of a SKU. For this we can add another 30 seconds which is a rough estimate. The last option is that the product is not findable right away. So, in the worst case we have to look at every slot and check every WO of the SKU. This process is executed multiple times, and the longest time is taken. The time it took to review all the WOs was between the 1 and 2 minutes. Therefore another 2 minutes is added to the order picking time. So, the time it takes to pick an order at the back of the warehouse, which is not findable right away is 3 minutes and 1 second. Therefore, we take the maximum order picking time as 3 minutes.

The range is still starting at *1 minute* where sometimes the time is less than the minute, but to provide a clear range the starting time is taken as 1 minute. After multiple measurements, the longest possible time to locate a SKU is *3 minutes.* Using these measurements to calculate random slots we can also provide a new average order picking time. The average order picking time is now 1,75 minutes. Besides the average order picking time we can calculate the standard deviation. So, the new order picking time, with the new assignment of products, is ranging from *1 minute to 3 minutes*, which is stated in Table 7.

	Time in seconds
Minimum order picking time	1 minute
Average order picking time	1,75 minutes
Standard deviation	0,89
Maximum order picking time	3 minutes

Table 7, New order picking time

5.5. Conclusion

Chapter 5 of this thesis is reflecting on the fifth phase of the MPSM provided by Heerkens and van Winden (2017), choosing a solution. The solution is based on the findings in the previous chapters and is exercising the ABC method. Three sub questions, 3A, 3B, and 3C are answered in the distinct sections.

Following the ABC strategy together with the pareto principle and the results from the model of Section 03 the main solution is chosen. One section of the warehouse is reserved for semi-finished and finished products. Every type of SKU can be identified by the various colours. The SKUs of company X and company Y are placed at the front of the warehouse. The machining SKUs are placed in the B category and closest to the entrance. The SKUs of company Z are placed in the next available columns and the final places in section B are for all the smaller suppliers. At the back of the warehouse the raw material and the slow movers are placed where the slow movers are placed in the columns furthest away from the warehouse entrance.

With the new assignment of products inside the warehouse racks the order picking time is decreased. The order picking time was ranging from 1 to 10 minutes. Implementing the solution would decrease the range of the order picking time varying from *1 minute to 3 minutes*. With the measurements and test order picks a rough estimate of the new range is calculated.

6. Implementation plan

This Chapter is reflecting on the last sub question 3D *“How should the assignment of products be implemented at HTM Aerotec?” and* the sixth phase of the MPSM, implementing the solution. Since the warehouse is not totally finished a full implementation cannot be executed. However, an implementation plan is written for HTM Aerotec to implement the final solution executing the following steps.

1. The first step is to finish the warehouse completely according to the drawings and designs.
2. The second step is to count all the distinct products to see how many SKUs there are.
3. The third step is to follow the ABC method and Table 6 to rank all the SKUs and sort them among the categories.
4. The fourth step is to start filling the warehouse starting with category A.
5. If category A exceeds the assigned slots place them in the B category following Figure 27.
6. The sixth step is to place the category B SKUs inside the warehouse following the final assignment of products.
7. If category B exceeds the assigned slots place them in category A slots if possible, otherwise place them in category C slots following Figure 28.
8. The eighth step is to fill the rest of the warehouse with category C SKUs starting from the back of the warehouse.
9. If category C exceeds the assigned slots place them in category B slots following Figure 29.

The final solution should be implemented in the warehouse to improve the order picking time. Figure 26 displays how all the different SKUs should be slotted. If there are more SKUs than the percentages provided by the pareto principle, Figure27, Figure 28, and Figure 29 should be followed where the distribution of more SKUs per category is shown and explained. Following these Figures should provide the right assignment of the products inside the warehouse racks. No processes are delayed while implementing the solution, so no special actions need to be taken. When the warehouse is finished and the SKUs are placed, the recommended assignment of the products can be followed.

When the occasion arises where a new supplier cooperates with HTM Aerotec, first consider in what category the supplier should be. Most of the new suppliers are placed in category B by the category “other products” since newly arrived suppliers mostly start with supplying a little amount. When a supplier exceeds one of the companies in category A with both revenue and commonality, then the two companies should be swapped and the company previous in category A should be placed in class BA. The rest of the B category should be placed one class lower. The new supplier in the A category is then placed in category AB. Category C should never change, slow movers are always providing the smallest revenue stream. Similar for the raw material, this SKU is always slotted at the back of the warehouse.

The last recommendation to give, is to provide each slot with a number according to their row, column, and level. This can help with future research and for a better understanding and overview of the warehouse. Giving a slot for example the number 2.3.8, tells that it is the second row, third level and eight column. To further improve this, you can also give each rack a number which would result in a four number code for every slot. With future research, this can make a big difference on decreasing the order picking time more and improving the findability of SKUs.

7. Conclusion

The last chapter of this thesis concludes the research. It is reflecting on MPSM phase seven, evaluating the solution. The main research question is answered, *"What is an appropriate assignment of products inside the warehouse racks to decrease the order picking time at HTM Aerotec?".* The first section is answering the research questions, concluding the different chapters, and evaluating the solution (Section 7.1). The second section is deliberating what could be done with future research to decrease the order picking time even further (Section 7.2).

7.1. Conclusions

This research is guided by the research questions together with their corresponding sub questions. This section of the research answers the sub questions and main research questions, starting with the first research question.

Question 1: "What does the current situation in the logistic department at HTM Aerotec look like?"

Currently HTM Aerotec is realising a new warehouse. Sub question 1A is therefore, *"How is the new warehouse going to look at HTM Aerotec?".* The new situation is containing one new warehouse which is the main area of this research. This warehouse is consisting out of seventeen distinct racks and a total place for 285 SKUs. However, forty slots are obstructed by supporting beams and unreachable slots for the forklift. The warehouse width is 1580 cm and the length is 1130 cm. The racks are five high, which means five products can be placed above each other and the height of this is equal to 250 cm. For a detailed overview see Figure 4 and Table 2 and 3.

The second sub question, 1B is deliberating about the distinct products. The question is "*What are the different products HTM Aerotec is storing in their warehouse?".* There are three different ways a product arrives. On a euro pallet, on halve a euro pallet, and in a crate. The crates are stored in a distinct warehouse. The pallets and halve pallets are stored inside the new warehouse. The products can be classified in two distinct categories, namely half fabricates or raw material. A product is labelled large if it only fits on a euro pallet, medium if it only fits on halve a euro pallet and small if it fits inside a crate. When an order is picked the whole euro pallet or halve euro pallet is picked. The only products considered in this thesis are medium and large products.

The third sub question, 1C is displaying the current supply chain. The question is, *"What does the supply chain of HTM Aerotec look like?".* The current supply chain is existing out of five distinct departments, logistics arrival, planning, machinery, measuring room, and logistics departure, respectively. The main operation conducted in the logistics departments are picking the orders and moving the orders between warehouses which is the main focus of this thesis. The planning department is making the planning for the products and notifies when the order can be picked. The machinery operates the products according to the measurements and drawings. The measuring room is checking if the product meets these measurements and finally the logistics department picks the final products and makes it ready for departure. Every department is communicating with each other and the product is scanned in and out to see in what phase the product is. For a detailed overview of the supply chain look at Figure 37.

The last sub question of research question 1 is about the current order picking time. The question answered is, *"What is the current order picking time?".* The order picking time is the main measurement to see if the research is satisfied. The current order picking time is ranging from *1 to 10 minutes.* Multiple orders are picked, and the average order picking time is around the *4,5 minutes.*

Question 2: "What slotting methods are used to provide a good assignment of products inside the warehouse racks?"

The first sub question answered is "*What is the best slotting strategy to use for the assignment of products at HTM Aerotec based on existing literature?*". To provide a satisfactory assignment of products inside the warehouse racks, a good slotting strategy is conducted. The slotting method exercised is the ABC slotting method which is combined with the pareto principle that is stating that 80 % of your results come from 20 % of your efforts. So, 20 % of the warehouse is for category A SKUs, 30 % for category B SKUs, and 50 % for category C SKUs. For the ABC strategy a second classification criterion is selected. The two criteria are total revenue provided by the SKU and the commonality of a SKU.

The second sub question is regarding the priorities while structuring the racks. The second sub question reads, "*How are the products going to be assigned to the slots using the chosen slotting strategy?".* This question is answered with the help of a model from Duque-Jaramillo et al. (2024). The main mathematical model is adjusted to resemble the warehouse of HTM. Using the measurements found with the first sub question the model was run in VBA for the six distinct strategies. The results showed that the shortest time filling up the warehouse was using SAS 3 where first the levels are filled of the first column and first row. After the levels of the first column second row are filled until all the slots are filled up.

Question 3: "What is an appropriate assignment of products inside the warehouse racks to decrease the order picking time at HTM Aerotec?"

The last research question is about forming the solution. The first sub question is about structuring the racks, "*How are the products assigned inside the warehouse racks to decrease of the order picking time?".* With the use of the ABC method and the answers of the mathematical model the final assignment of products is constructed. The racks on top of the warehouse are assigned for products that are (almost) finished since these products are the revenue flow of the company. Company X and Y are both in the A category and therefore slotted in the best available slots which are among the first columns of each row in the warehouse. Slow movers together with raw materials are slotted at the back of the warehouse spread across the last columns of every row. The products left are slotted in the middle where SKUs of type machining are slotted at the best places and company Z received the second best place in the B category. The suppliers left are all slotted in the middle close to the slow movers and raw materials.

The second sub question is checking if the new assignment of products is decreasing the order picking time. The second sub question is, "*What is the new order picking time at HTM Aerotec?".* With the new assignment of products some sample orders were picked to give a rough estimate of the new order picking time. These times were measured for the slow movers since they are furthest away from the warehouse entrance. The new maximum order picking time was measured at three minutes. This gives the new range a smaller maximum, therefore the new order picking time is estimated to be *1 minute to 3 minutes*. Also, an average is calculated after calculating the times for multiple slots. The new average order picking time is estimated to be *1,75 minutes*.

The third sub question is addressing the situation that some products exceed there assigned slots and need to be slotted in other areas of the warehoused. The third sub question is, "*How should products be slotted if they exceed their assigned slots?".* Starting with products in category A, these are slotted further down the warehouse in category B slots where the columns are filled from right to left, since these are the valuable slots. Category B slots are slotted in category A slots if there is place and otherwise in category C slots. The products are slotted left to right if slotted in category A, since category A products need the more valuable slots. If there is no place, they are slotted from right to left in the C category to give them the more valuable slots. Finally, category C products are slotted in category B from left to right, giving the more valuable slots to the products inside category B.

The fourth and last sub question is addressing the implementation plan for HTM Aerotec on how to implement the final assignment of products. The fourth sub question is, *"How should the assignment of products be implemented at HTM Aerotec?".* To implement the final assignment of products a nine step plan is provided with further explanation beneath. The step explains that after finishing the warehouse and ordering the SKUs in the distinct categories following the ABC method, the warehouse should be filled up. First the A category products are slotted, after the category B products, and finally the category C products are slotted. The answer to the third sub question is also considered in the implementation plan to provide the company with knowledge on what to do if certain products exceed their assigned slots.

7.2. Future research

During the research, a time span of ten weeks is given which led to some limitations in the research. With more time available the order picking time could be decreased even further by improving one main action. Right now, there is a programme named Glovia, which HTM Aerotec is using to sign in their SKUs. Within this programme it is also possible to assign a SKU to a specific location. There is also an overlap with excel and the two programs can be used together and with the help of excel the distinct slots can be programmed into Glovia. This is providing the option to assign a SKU to a specific slot. Finding a SKU is much simpler, and the order picking time would decrease even further.

However, the coding between excel and Glovia is difficult. It would take time to understand and learn how the coding and programming works. The other downside is that it is already possible to assign the SKUs to a location, but the people working in the logistics choose not to do so since this takes to much time. Right now they assign all the SKUs to “reloc”, which means the SKUs needs to relocate. If with a future research all the slots become available to assign SKUs, it is still possible the people working in the logistic department choose to not use it.

Another way to improve the allocation of SKUs is with the use of barcodes. HTM Aerotec was some time ago introducing the use of barcodes with their slots and products. When a SKU is placed in a slot, the barcode of the SKU and of the slot is scanned. This would then be visible in a programme where every SKU is findable with their corresponding slot. However, they stopped with this before properly introducing the system for unclear reasons. With more time this could be an option to look into. Looking at what went wrong while introducing the system and what stopped HTM Aerotec from using it.

The last thing that is possible for future research is the changing demand. How to adjust the warehouse to fit this changing demand. Right now, the products are placed in a certain area, but maybe this is not the most efficient since the demand is changing. Right now if the demand for a product is changing they are moved to slots of another category. With more time it could be possible to see what is possible with a changing demand and what to do with the uncertainty.

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9. Appendix

Appendix A - Model abbreviations

SAS	First step	Second step	Third step	Fourth step
SAS 1	Row	Column	Level	Section
SAS 2	Row	Level	Column	Section
SAS 3	Column	Row	Level	Section
SAS 4	Column	Level	Row	Section
SAS 5	Level	Row	Column	Section
SAS 6	Level	Column	Row	Section

Figure 30, Table slots assignment sequence (SAS). from "Warehouse Management Optimization Using A Sorting-Based Slotting Approach," by J.C. Duque-Jaramillo, 2024, *Journal of Industrial Engineering and Management*, 17(1), p. 133-150. Copyright by Juan C. Duque-Jaramillo.

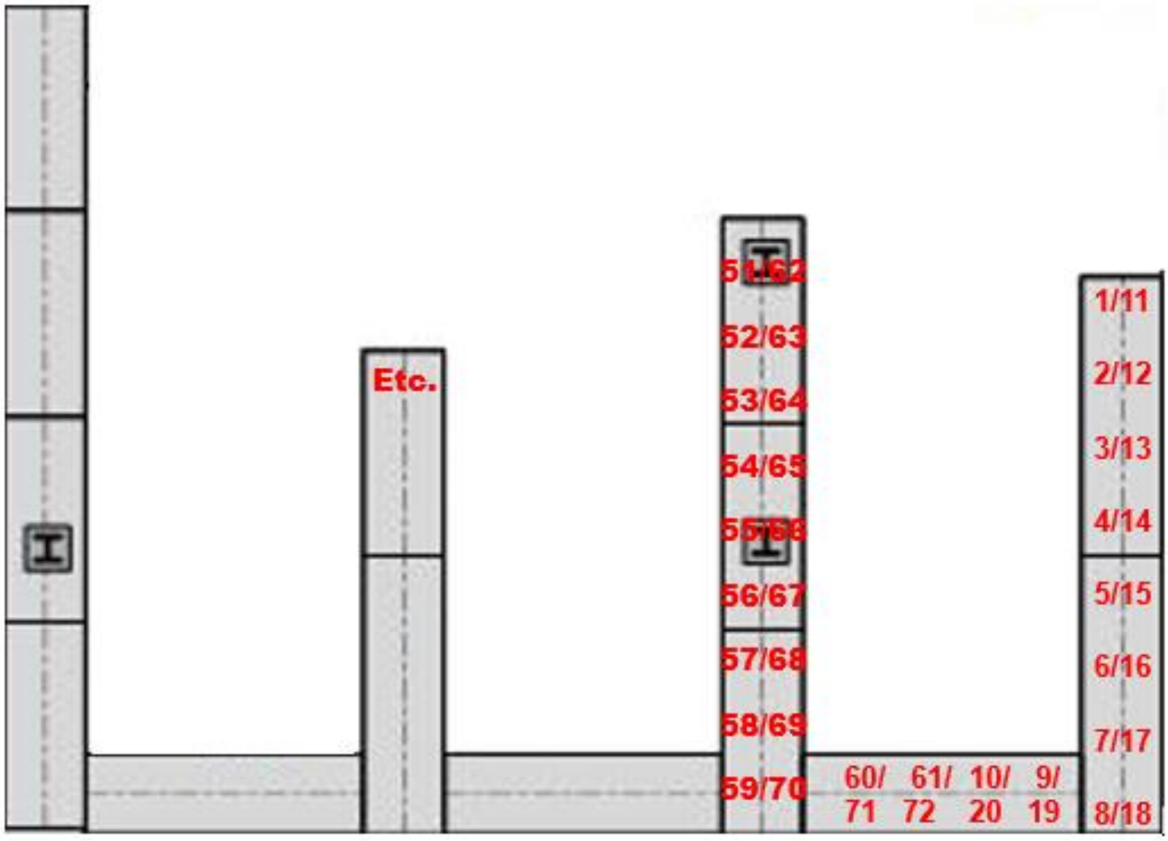

Figure 31, SAS 2

Figure 31 displays SAS 2 where only the first two levels are filled to make it more convenient. So, 1 is on the first level and 11 is on the second level and normally 21 would be on the third level, 31 on the fourth, and 41 on the fifth level.

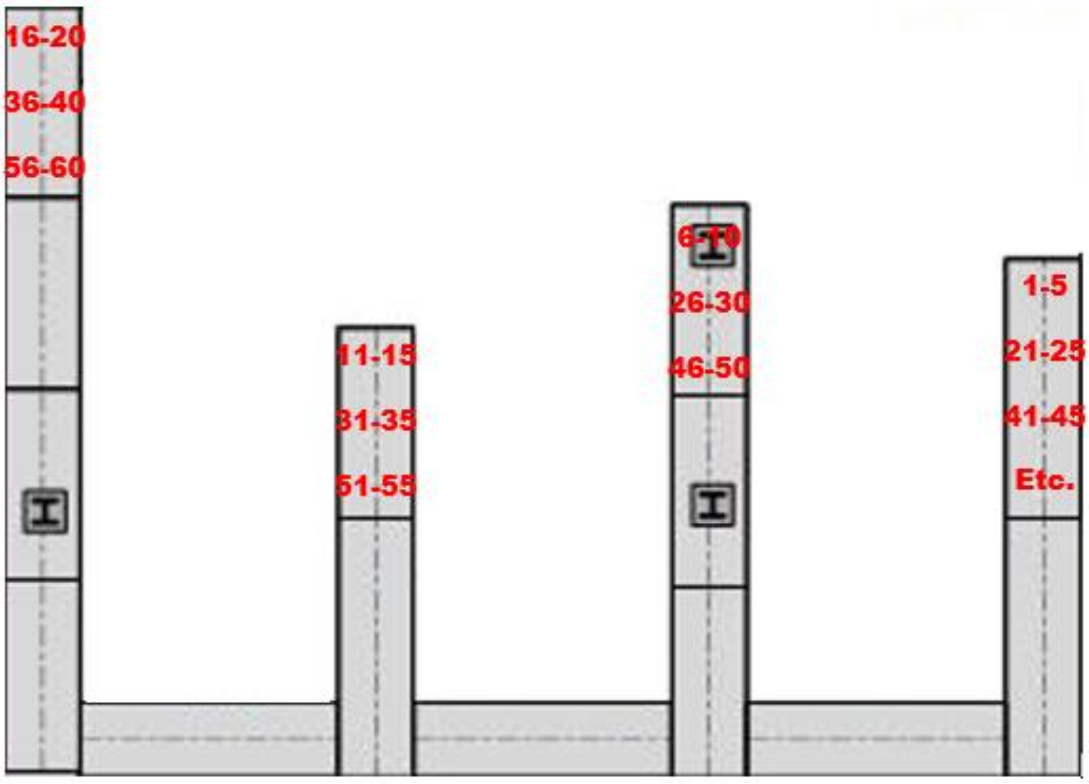

Figure 32, SAS 3

Figure 32 displays SAS 3 where 1-5 are the first five products and placed on level 1 till 5.

Figure 33, SAS 4

Figure 33 displays SAS 4 where again only the first two levels are filled to give a better overview. So, products 1, 5, 9, 13, and 17 are all placed on the first column of the first row.

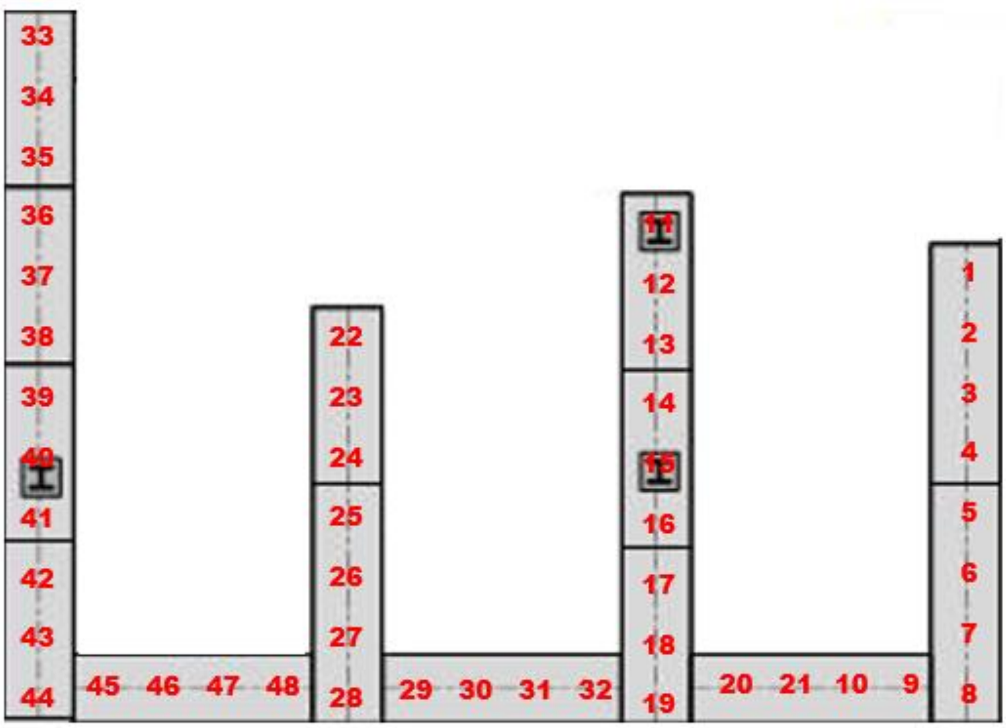

Figure 34, SAS 5

Figure 34 displays SAS 5 where only the first level is filled for convenience. So, the next product is placed behind the number 1, on the second level.

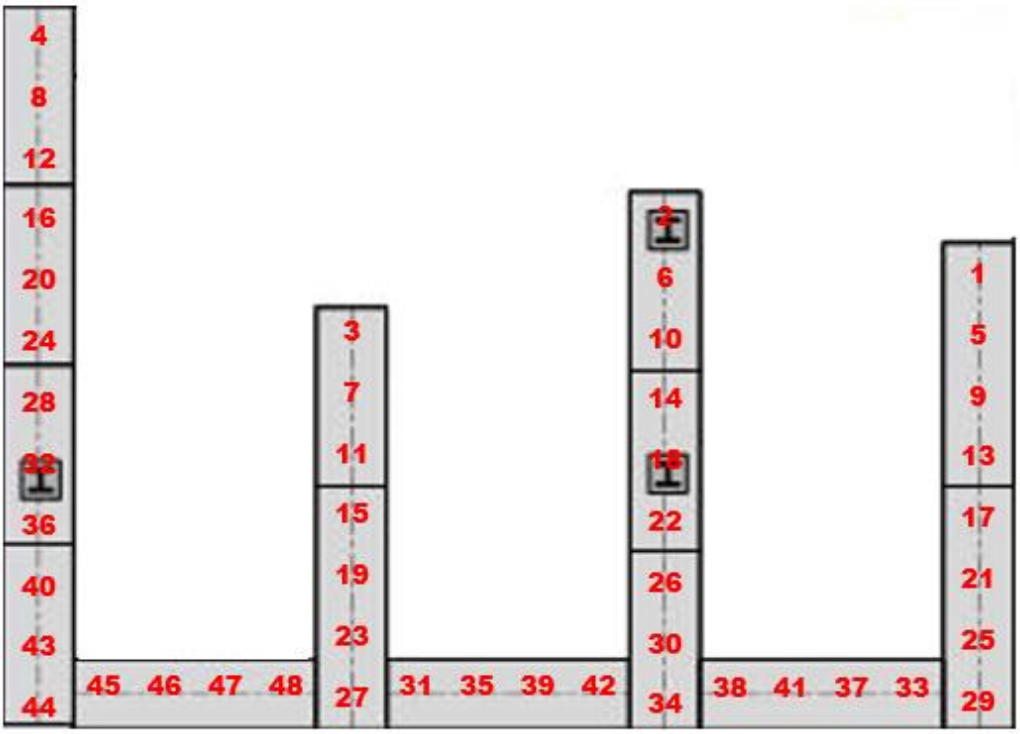

Figure 35, SAS 6

Figure 35 displays SAS 6 where also only the first level is filled. The rows and columns are filled till there are no more columns left inside a row which explains that the last products are all inside row 4. The next product is placed on the second level behind the number 1.

Symbol	Meaning
wwl	Warehouse width length
wdl	Warehouse depth length
mhwl	Main hall width length
hswl	Hall between sections width length
hrwl	Hall between rows width length
ssdl	Single shelving depth length
dsdl	Double shelving depth length
swl	Shelving width length
avswl	Average vehicle speed without load
avsl	Average vehicle speed with load
pq, sq, rq, cq, lq	Periods, sections, rows, columns, and levels quantities, respectively
$tsku_p$	Total SKU in the period *p*
d_r	Distance to row *r*
d_s	Distance to section *s*
d_c	Distance to column *c*
$dctlif_l$	Lifting time from the floor to level *l*
$tlow_l$	Lowering time from the level *l* to the floor

Figure 36, Model abbreviations. from "Warehouse Management Optimization Using A Sorting-Based Slotting Approach," by J.C. Duque-Jaramillo, 2024, *Journal of Industrial Engineering and Management*, 17(1), p. 133-150. Copyright by Juan C. Duque-Jaramillo.

Appendix B - Supply chain

The model beneath shows five different elements, a green circle, a red circle, a yellow circle a square and a rectangle. The green circle means the process in a single department has started. A red circle means the process is finished in the department and the process is moving on. The yellow circle is to show that a product stays there for a longer time. The square is a decision, and the rectangle is a single process in the supply chain at a department.

In the model there are three distinct lines. A solid black line, which means a process exceeds into the next process. The second line is a dashed line with an arrow, which means the communication between the departments. The last line is a dashed line without an arrow, which means the process is the same.

First the whole model is shown to give a better overview of the complete model and after the individual departments are shown to make it readable. However, the individual departments are shrunk to improve the readability.

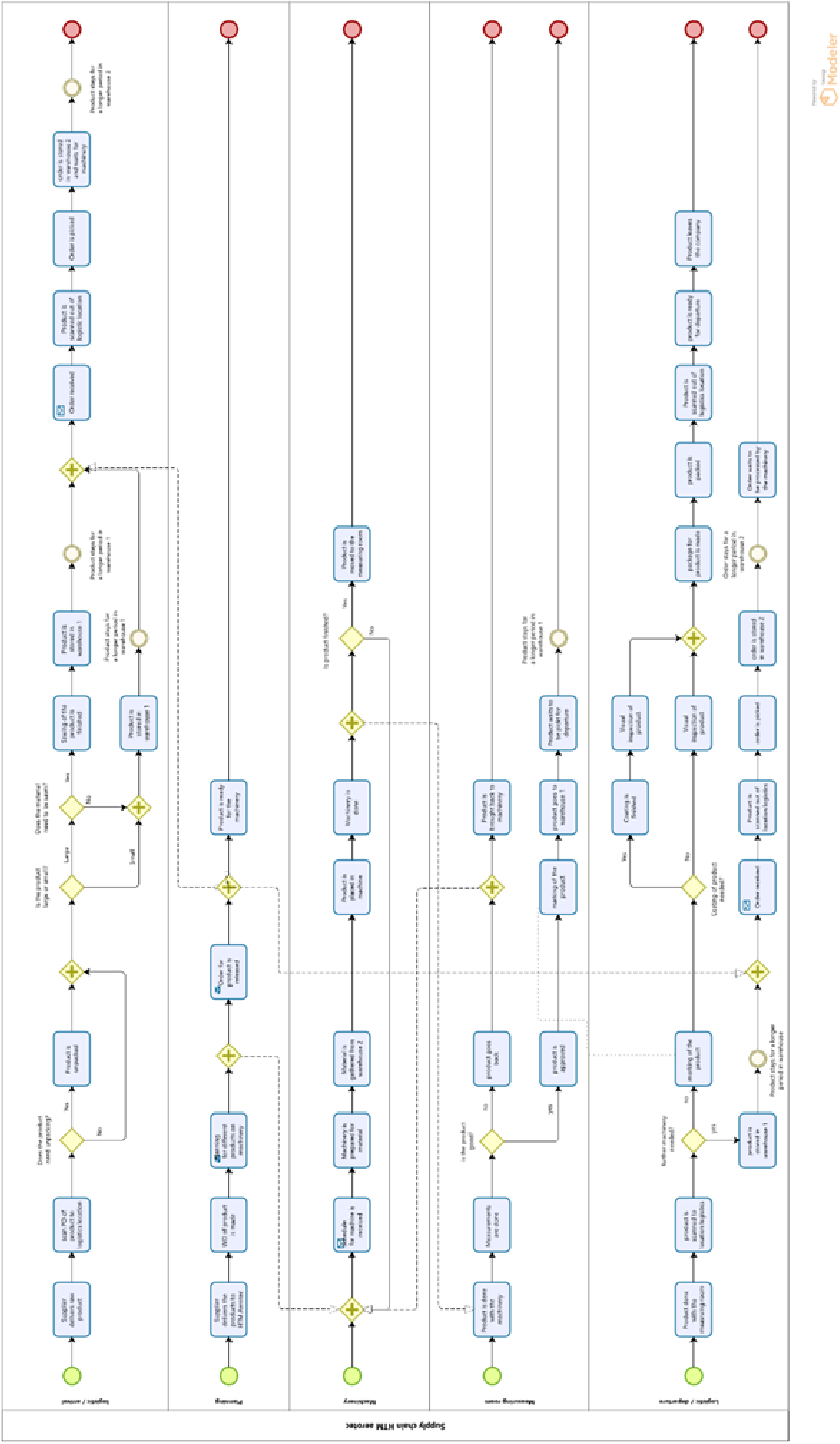

Figure 37, Supply chain HTM Aerotec

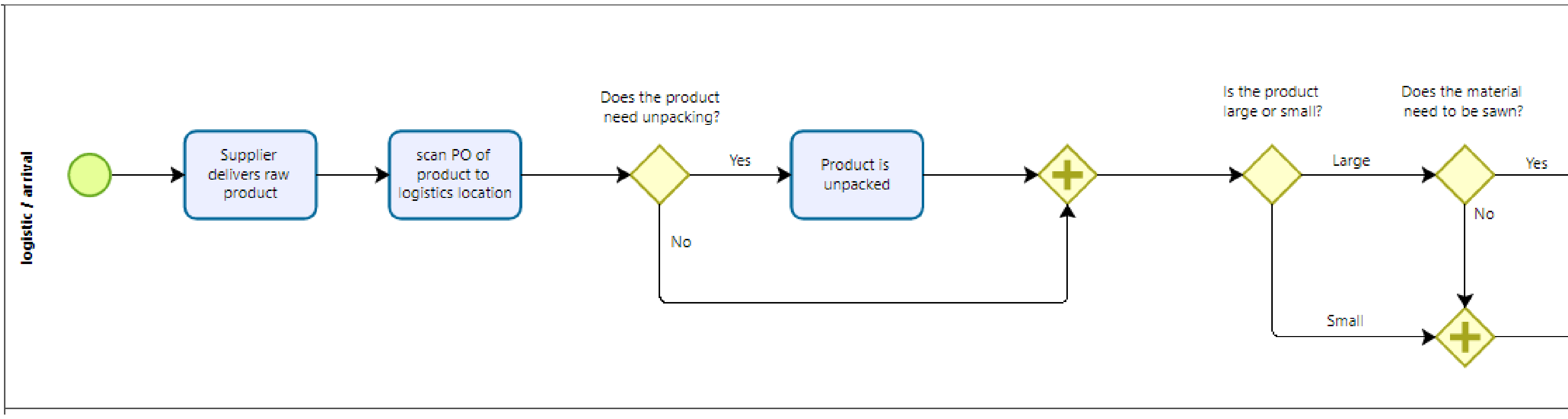

Figure 38, Supply chain Logistics arrival part 1

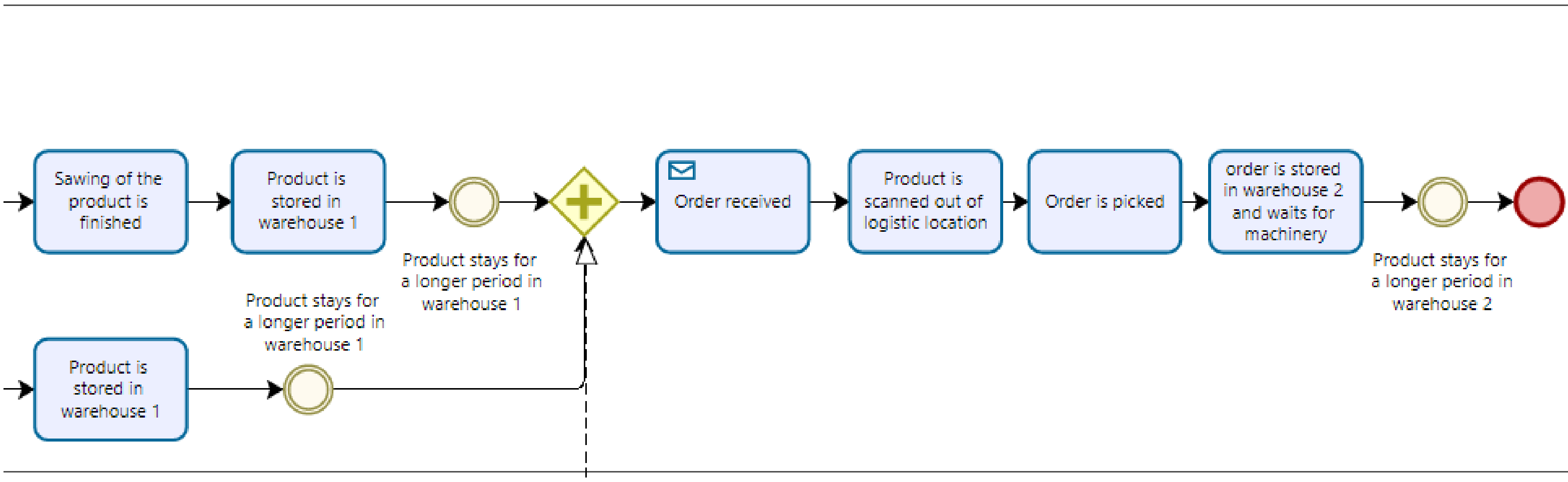

Figure 39, Supply chain Logistics arrival part 2

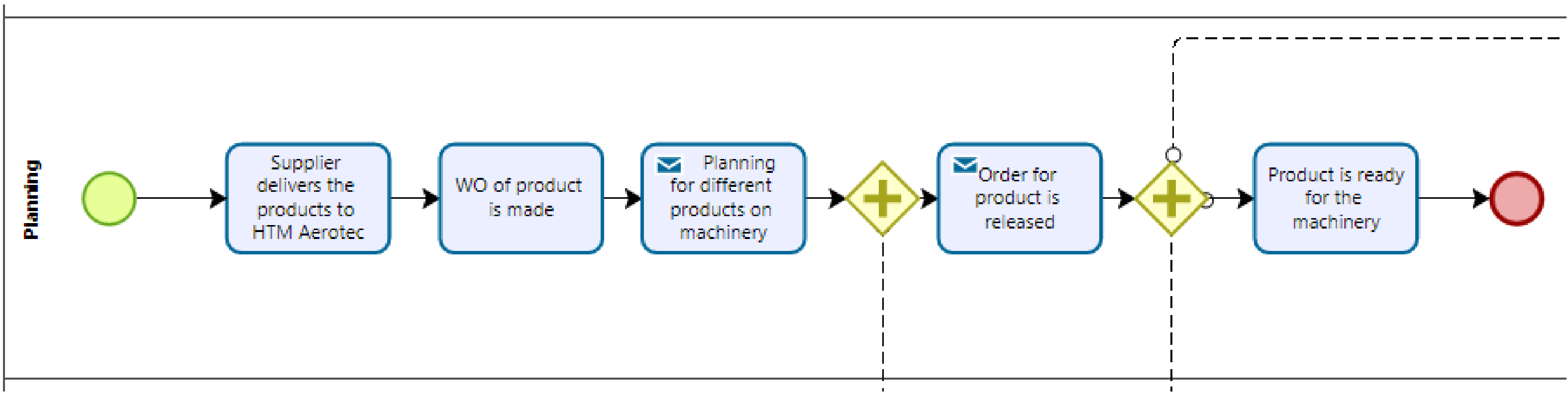

Figure 40, Supply chain Planning

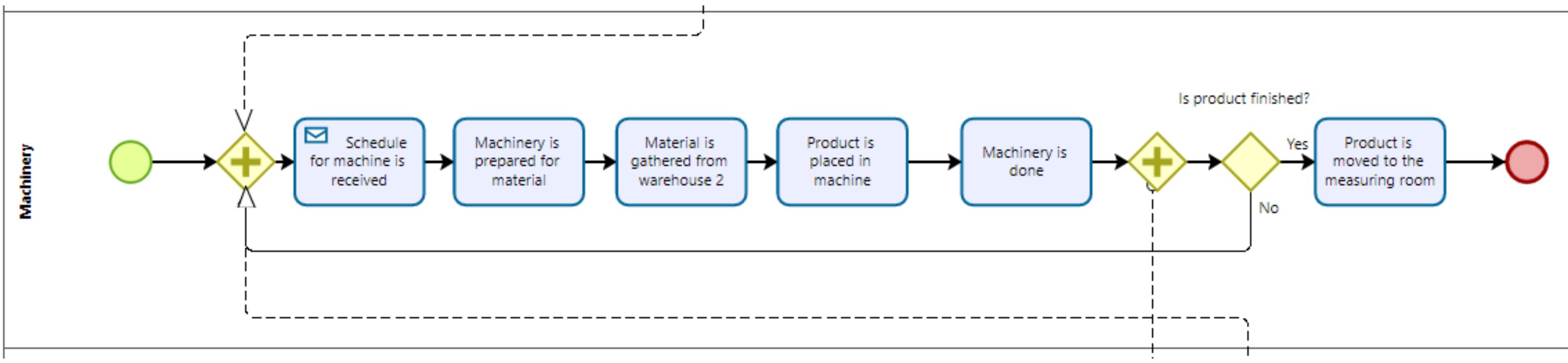

Figure 41, Supply chain Machinery

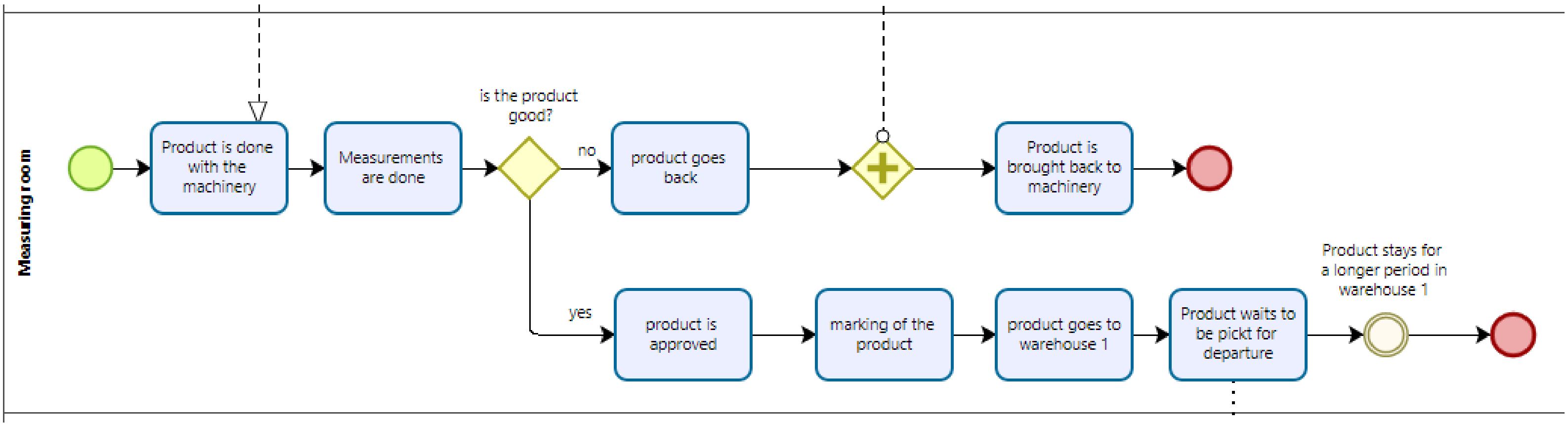

Figure 42, Supply chain Measuring room

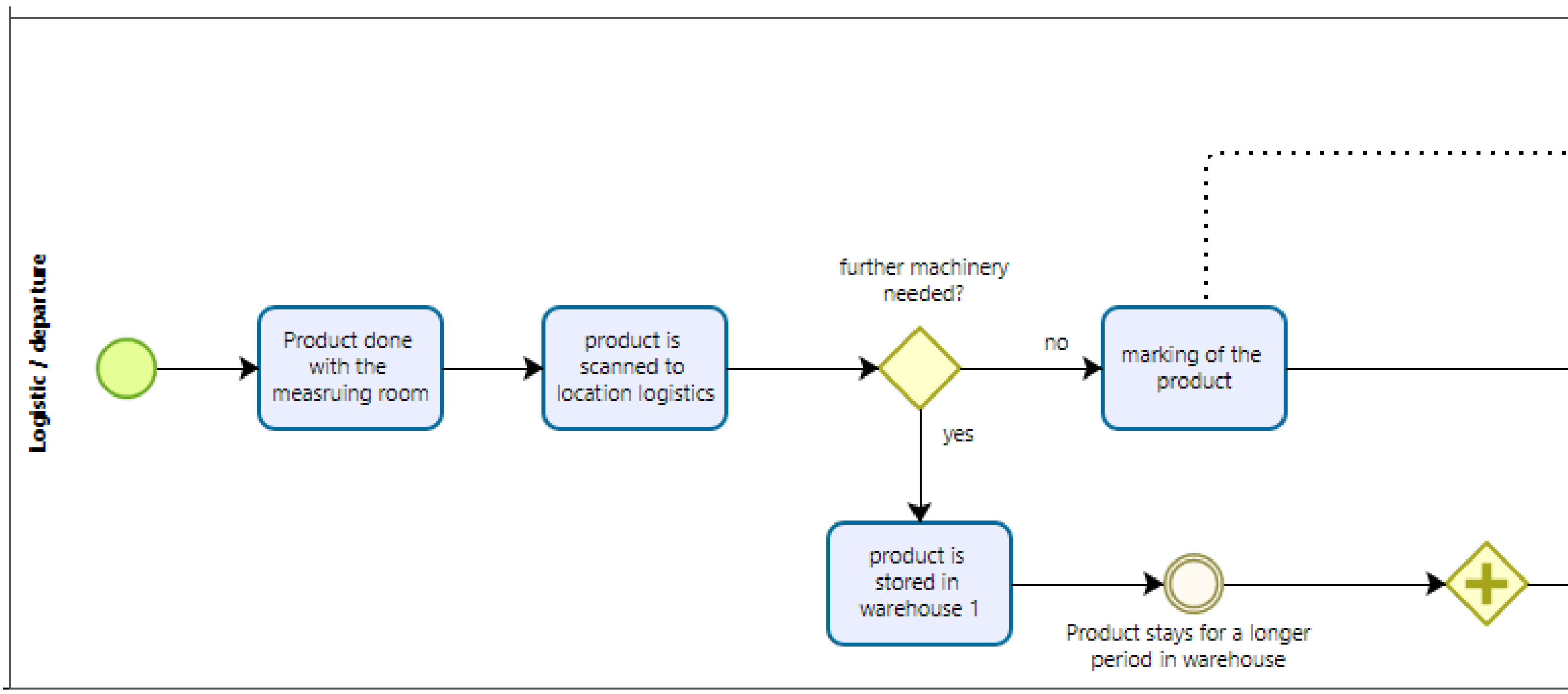

Figure 43, Supply chain Logistics departure part 1

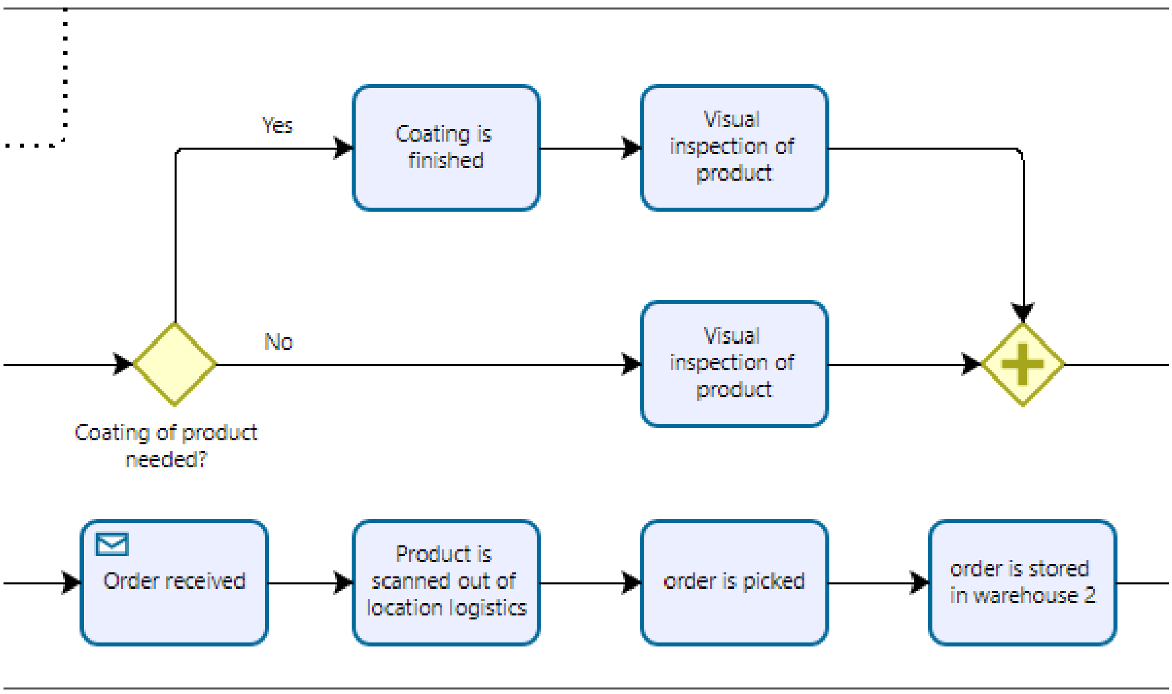

Figure 44, Supply chain Logistics departure part 2

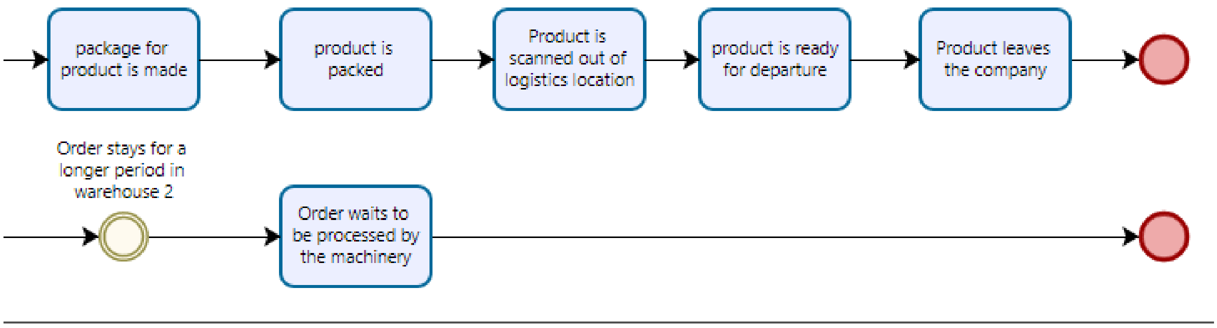

Figure 45, Supply chain logistics departure part 3

Appendix C - VBA code

```
Sub MinimizeTotalST()

    ' Parameters and constants
    Dim tsku As Long: tsku = 280 ' Number of products
    Dim rq As Long: rq = 4 ' Rows
    Dim cq As Long: cq = 14 ' Columns per row
    Dim lq As Long: lq = 5 ' Levels per column
    Dim td As Double: td = 35 ' travel distance
    Dim hrwl As Double: hrwl = 3.8 ' Hall between rows length
    Dim ssdl As Double: ssdl = 1.1  ' Single shelving depth length
    Dim swl As Double: swl = 0.9 ' Shelving width
    Dim avswl As Double: avswl = 3.576 ' Average vehicle speed without load
    Dim avsl As Double: avsl = 3.487 ' Average vehicle speed with load
    Dim p As Long, r As Long, c As Long, l As Long

    ' make the different Arrays
    Dim B_ircl() As Boolean
    Dim Q_ircl() As Long
    Dim tliftl() As Double ' time to lift a product
    Dim tlowl() As Double ' time to lower the forklift

    ' give values to the arrays
    ReDim B_ircl(1 To rq, 1 To cq, 1 To lq) As Boolean
    ReDim Q_ircl(1 To rq, 1 To cq, 1 To lq)
    ReDim tliftl(1 To 5)
    ReDim tlowl(1 To 5)

    ' Set the total ST to 0
    Dim totalST As Double
    totalST = 0

    ' fill the array for the lifting time
    For l = 1 To 5
        tliftl(l) = l * 0.5 * 0.29
        tlowl(l) = l * 0.5 * 0.45
        Cells(l + 25, 5) = tliftl(l)
        Cells(l + 25, 6) = tlowl(l)
    Next l
```

Figure 46, VBA code defining parameters and constants.

```
' Set product counter to 1, p to 0
Dim productCounter As Integer
productCounter = 1
p = 0

' Initialize all slots to False (empty)
For r = 1 To rq
    For c = 1 To cq
        For l = 1 To lq
            B_ircl(r, c, l) = False
        Next l
    Next c
Next r

' Place products in the warehouse
For r = 1 To rq
    For c = 1 To cq
        For l = 1 To lq
            If productCounter <= tsku Then
                ' Place the product in the slot
                B_ircl(r, c, l) = True
                Debug.Print "Product " & productCounter & " placed at Row " & r & ", Column " & c & ", Level " & l
                productCounter = productCounter + 1
            Else
                Exit For
            End If
        Next l
        If productCounter > tsku Then Exit For
    Next c
    If productCounter > tsku Then Exit For
Next r

' Print a message when all products are placed
If productCounter > tsku Then
    MsgBox "All products have been successfully placed in the warehouse."
End If
```

Figure 47, VBA code filling the empty slots.

```
    ' Calculating the minimal totalST
    For r = 1 To rq
        For c = 1 To cq
            For l = 1 To lq
                ' give Q_ircl a value according to the constraints
                Q_ircl(r, c, l) = 1
                ' Calculate d_r for first row
                Dim d_r As Double
                If r = 1 Then
                    d_r = r * ssdl + 0.5 * r * hrwl
                End If
                ' calculate d_r for other rows
                If r > 1 Then
                    d_r = (r - 1) * ssdl + 0.5 * (r - 1) * hrwl
                End If
                ' set d_c to 0
                Dim d_c As Double
                d_c = 0
                ' set stopping to -1
                Dim stopping As Long
                stopping = -1
                ' Calculate d_c for the different rows
                If r = 1 Then
                d_c = c * swl + 0.9
                End If
                If r = 2 Then
                d_c = c * swl
                End If
                If r = 3 Then
                d_c = c * swl + 1.8
                End If
                If r = 4 And c > 2 Then
                d_c = c * swl - 1.8
                End If
                ' Set different columns for the rows
                If r = 1 And c > 9 Then
                stopping = 0
                End If
                If r = 2 And c > 10 Then
                stopping = 0
                End If
                If r = 3 And c > 10 Then
                stopping = 0
                End If
                If r = 4 And c > 14 Then
                stopping = 0
                End If
                ' Set d_c the same for the last few columns
                If r = 1 And c > 7 Then
                d_c = 7.2
                End If
                If r = 2 And c > 8 Then
                d_c = 7.2
                End If
                If r = 3 And c > 6 Then
                d_c = 7.2
                End If
                If r = 4 And c > 10 Then
                d_c = 7.2
                End If
                ' Calculate the expression inside the brackets
                Dim expr As Double
                expr = ((d_r + d_c + td) / avswl + tliftl(l) + tlowl(l) + (d_r + d_c + td) / avsl) * B_ircl(r, c, l) * stopping
                p = p + 1
                Cells(p, 1) = expr
                ' Accumulate the sum for ST
                If B_ircl(r, c, l) = True Then
                    totalST = totalST + expr * Q_ircl(r, c, l)
                End If
            Next l
        Next c
    Next r

    ' Output the minimized total ST
    MsgBox "Minimized total ST: " & totalST, vbInformation
End Sub
```

Figure 48, VBA code main equation.

```
Sub deletezeros()
' Parameters
Dim i As Long

' Deleting the zeros from the cells
For i = 1 To 280
    If Cells(i, 1).Value = 0 Then
        Cells(i, 1).Delete
    End If
Next i

End Sub
```

Figure 49, VBA code deleting zeros from the results.