Improving warehouse efficiency: A study of the KPIs and picking process at Benchmark

- Master Thesis -

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Gaining insight and improving the warehouse process at Benchmark

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Preface

In front of you lies a report that is the result of my research conducted at Benchmark in Almelo, Netherlands to acquire my master's degree in industrial engineering and management. This research aimed to help Benchmark gain insight into the future occupancy rate of their warehouse and improve the warehouse picking process. This preface is written to express a word of thanks to everyone that made it possible to realize this thesis report.

I want to thank Benchmark for providing me with the opportunity to conduct this research, and all the lessons I learnt during my time there. I especially would like to thank my supervisor from Benchmark, Paul Hagen, who gave me this opportunity and from whom I learned a lot. Furthermore, I would like to thank John Nijland and Ronald Rikmanspoel, with whom I had a biweekly meeting, for their valuable input and feedback.

Next, I would like to express my gratitude to my supervisors from the University of Twente, Derya Demirtas and Peter Schuur, for their guidance and support throughout the research process. I really appreciate the honest and constructive feedback I received from both of them during my thesis research.

I hope that this research provides useful insights to Benchmark and that you enjoy reading this report.

Management summary

This thesis report is written for a graduation project for the Master of Industrial Engineering Management at the University of Twente. The graduation project takes place at Benchmark Netherlands in Almelo, a manufacturer of electronic modules and printed circuit boards. In this thesis report the problem of Benchmark is presented together with the approach used to solve this problem. This research is conducted with the aim of answering the following research question:

> How can Benchmark **improve their insight** in the occupancy rate of their warehouse, both in the present and future, and use this insight **to improve their warehouse process?**

The problem of Benchmark is that they currently lack insight into their warehouse process. Because of this lack of insight, Benchmark is unable to make decisions on the improvement of their warehouse. To improve this insight and the warehouse process this thesis research consists of the following five phases:
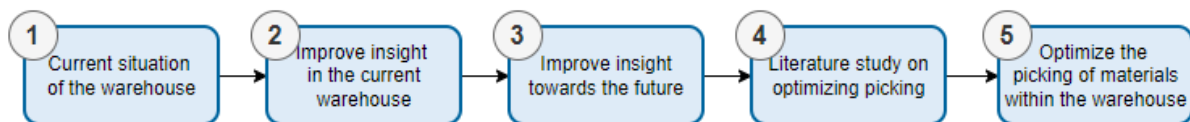
The warehouse of Benchmark consists of three different storage zones. The focus of this research is on the ZKDX1001 zone. The ZKDX1001 zone contains a total of eight Vertical Lift Modules (VLMs) in which items are stored in six different types of storage bins. Within the ZKDX1001 zone, each new delivery is batched into a randomly selected bin, so one item can have multiple storage locations. Furthermore, the picking process of Benchmark follows the FIFO-policy such that bins with an earlier put date are picked first.

Currently, Benchmark only has insight into the current occupancy rate of the ZKDX1001 zone through a not user-friendly dashboard. Because of this, the data about the occupancy rate of the ZKDX1001 zone is not easily available for the employees of Benchmark. Therefore, a dashboard is created that gives a clear insight into three KPIs that are relevant for Benchmark. These are the occupancy rate, the bins on which there is no demand within a certain period and the bins in use per end-customer. Having a dashboard on which these three KPIs are easily accessible improves the insight into the warehouse for Benchmark.

The insight into the current occupancy rate of the warehouse is used as a starting point to create a forecast model of the future occupancy rate. Using the MRP-information of the future demand and supply of each item makes it possible to forecast the future occupancy rate. This future demand and supply are used by the model to forecast the number of empty and occupied bins. With these expected number of empty and occupied bins the model is able to create a forecast of the expected occupancy rate. These outcomes are presented on a dashboard to create a transparent insight for Benchmark. Initial outcomes of the forecast model expect the occupancy rate to be over 100% in around six months. So, based on the forecast model, additional VLMs are needed for Benchmark to create additional storage space.

Despite the lack of literature discussing models of a VLM, this thesis research discusses two mathematical models. These mathematical models are able to compute the completion time of picking a batch of items on a single or multiple VLM system. The conclusion is that the mathematical model of Nicolas et al. is the most applicable to the situation of Benchmark.

Next, the literature study presents earlier performed research by Jansman on the storage process of Benchmark. Based on the outcomes of this research Benchmark incorporated the random storage

policy within the ZKDX1001 zone. Since Benchmark is currently not willing to change their storage policy, the conclusion is that the main focus of the thesis research is on improving the picking policy. Improving the picking policy of Benchmark however is a NP-hard problem that cannot be solved within polynomial time. Therefore, additional literature research is performed concerning optimization techniques that could be used to solve NP-hard problems. The conclusion of this research is that a local search method such as simulated annealing can be used to deal with the improvement of the picking policy.

Based on the aforementioned model of Nicolas et al., a mathematical model that represents the situation of the ZKDX1001 zone is created. With the help of the input values of the *PickTime* and *StoreTime* this model is able to compute the completion time of picking a set of items from the ZDKX1001 zone. This mathematical model serves as the basis of the improvement model that aims to reduce the completion time of picking by selecting alternative picking locations. As a starting point the improvement model uses an initial solution based on the FIFO-policy of Benchmark. The improvement model then tends to improve this initial solution by using the simulated annealing method in which the neighbor space is explored. Based on initial findings the improvement model is capable of reducing the completion time by selecting alternative picking locations.

To validate the improvement model a total of 18 experiments are performed. Based on the outcomes of these experiments the model is able to reduce the completion time by 5-20%, depending on the quantity of items. This is a significant reduction of completion time which increases the efficiency of the order pickers at Benchmark. A downside of the improvement model on the other hand is the substantial computational time, which is around 5 to 10 minutes for a single work order. A possibility to reduce the computational time is to simplify the objective of the improvement model. Changing the objective to the number of tray retrievals manages to decrease the run time by more than 50%, while still reducing the completion time by 5 to 10%.

In conclusion, this research provides Benchmark with two dashboards that improve their insight into their warehouse process. One for determining the current occupancy rate and another for forecasting future occupancy rates based on supply and demand. Additionally, an improvement model is presented to reduce the overall picking time by selecting alternative locations, which has shown a 5-20% reduction in completion time. Therefore, the main recommendation of this research for Benchmark is to incorporate the improvement model into their picking process. However, before implementation, further research is needed to reduce the computational time. Additional research could explore the use of incremental completion time calculations or simplifying the objective of the model. Furthermore, additional research should be performed into the effect of the assumptions of the outcomes of the model.

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1. Introduction

In the framework of completing the Master Industrial Engineering Management research is performed at the company Benchmark into improving the insights into their warehouse process. In this first chapter the reader gets an introduction towards the company Benchmark and the research that is performed. This first chapter therefore consists of the following sections:

1.1 – Background
1.2 – Problem context
1.3 – Research objectives & scope

1.4 – Research questions and research design
1.5 – Deliverables
1.6 – Research approach

1.1 – Background

This section introduces Benchmark Almelo. Furthermore, an explanation is given on the company structure of Benchmark Electronics Inc.

1.1.1 – Introduction to Benchmark Almelo

Benchmark Almelo is part of the multinational Benchmark Electronics. Benchmark is a listed company in the field of manufacturing electronics and providing services to Original Equipment Manufacturers (OEMs). The location of Benchmark in Almelo manufactures electronic modules and printed circuit boards (PCBs) for their customers. These electronic modules or PCBs manufactured in Almelo are used by customers worldwide as control units for all kinds of machines. Besides a manufacturing department Benchmark Netherlands also has an engineering department. These engineers are responsible for the design of the electronic modules and the PCBs in cooperation with the customers of Benchmark.

In recent years, the number of employees at Benchmark in the Netherlands has increased significantly. Currently, the number of people employed in Almelo is around 550. Around 420 of these employees are responsible for manufacturing and general operations. The other 130 employees are part of the engineering department of Benchmark Almelo. Collectively, these employees account for an annual turnover of around 100 million euros.

1.1.2 – Company structure

As mentioned, Benchmark Almelo is a part of the multinational Benchmark Electronics, which is active worldwide. In total Benchmark Electronics has twenty-two locations all around the globe, although most of these locations are in the United States. The headquarters of Benchmark Electronics is located in the United States, in Tempe, Arizona specifically. Next to the locations in the Netherlands and the United States there are also locations in Asia, Eastern Europe and Mexico. Collectively, a total number of around 11.000 people are employed at these twenty-two locations worldwide. Together they managed to achieve a revenue of around 2 billion US dollars last year.

The location of Benchmark in Almelo is completely independent but does make use of the general systems and economies of scale of its parent company. So, the entire production process, from design to manufacturing, takes place in the Netherlands. In general, no other locations of Benchmark are involved in this production process. This also means that Benchmark Almelo is responsible for managing its own business.

1.2 – Problem context

This section introduces the multiple processes within Benchmark Almelo, with a focus on the warehouse process. Following the current situation, a problem description together with the research problem is presented.

1.2.1 – Current situation at Benchmark Almelo

The order decoupling point for Benchmark is somewhere in between engineer-to-order and make-to-order. Meaning that Benchmark is a customer-order-driven organization, so the entire production process only starts once an order is placed by a customer. In this research the focus is only on the warehouse process at Benchmark. This warehouse process consists of the storage of materials and later on also the order picking of these materials.

Layout of the storage zones at Benchmark
Before further introducing the warehouse process, a brief overview is given of the current layout of the warehouse of Benchmark in Almelo. In general, there are three different storage zones currently in the warehouse. These are the general Kardex zone, the general warehouse and the SMD Kardex-system. Internally the general Kardex location is also referred to as the ZKDX1001 zone, this name is also used in this report. The ZKDX1001 zone and the general warehouse are located next to each other in the large warehouse area, which is internally referred to as *warehouse 1000*. The *warehouse 1000* area also contains a small office space for the personnel of the warehouse department and a consigned Thales warehouse. In *Appendix A.1,* a map of the *warehouse 1000* area gives an overview of the location of the ZKDX1001 location as the general warehouse. The SMD Kardex-system is located in the room where the PCBs are produced.

The first storage zone is the ZKDX1001 zone, here the majority of the materials are being stored. The ZKDX1001 location consists of eight vertical lean lift modules (VLMs) which are produced by the company Kardex Remstar, hence the name Kardex location. One of the advantages of such a VLM is that it is possible to store a lot of items in a small space. Besides that, a VLM also ensures an automated picking process, which increases the picking frequency. In *figure 1* an illustration of a VLM of Kardex Remstar can be viewed. Next, there is a storage zone for the rolls with SMDs, these are also stored in VLMs from Kardex Remstar. Here five different VLMs are used to store the SMD-rolls, this is named the SMD Kardex-system. Such an SMD-roll contains a lot of *Surface Mounted Device* (SMD) capacitors that are used in the production process of the PCBs. See *figure 2* for an example of such an SMD-roll. Finally, there is another storage location which is referred to as the general warehouse. The general warehouse is used to store materials that are too big to fit into a VLM at the ZKDX1001 zone. Occasionally, materials are also stored in the general warehouse if there is no place anymore at the ZKDX1001 zone.

Figure 2 - SMD-roll   *Figure 1 - A look inside a vertical lean lift module from Kardex*

Storage of received goods

Once Benchmark receives a new order from a customer the materials required for this order are ordered from the various suppliers and arrive in Almelo after a while. Next to that Benchmark also stores various materials that are not attached to a specific order. These specific materials tend to have a high demand, a safety stock level and are often relatively cheap. As soon as new materials arrive at the location of Benchmark in Almelo the inbound process starts, this is the first part of the warehouse process. A simplified flowchart of the inbound process of newly received materials is displayed in *figure 3* below*.* This first phase of this inbound process takes place at the inbound department where the materials are received and checked.
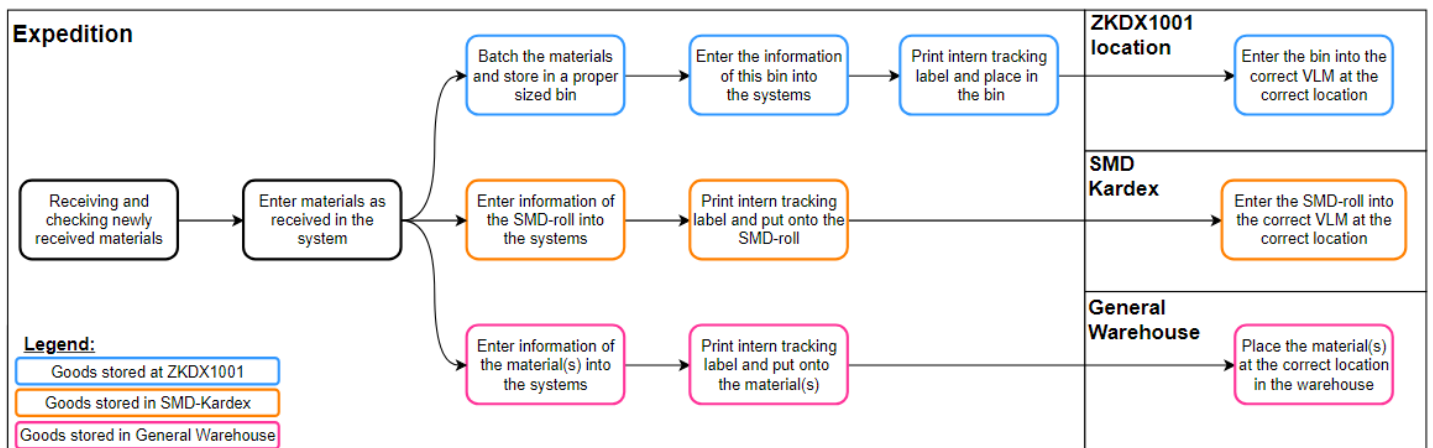
Figure 3 - Flowchart of the inbound process at Benchmark

The following part of the inbound process that takes place depends on the final storage location of the newly arrived materials. Materials that are stored at the ZKDX1001 zone are stored in a proper sized bin; this bin only contains materials of a single batch. Each new batch of materials that arrives at the inbound department is stored into new separate bin(s). This is done so that Benchmark can ensure that they are able to retrieve each batch in case of a component failure. The information of this bin is entered into the system after which the Kardex-software automatically assigns a location within the Kardex system to this bin. After the internal tracking label is placed inside the bin, the bin is moved to the ZKDX1001 zone. Here the bin is placed inside one of the VLMs at the location that it got assigned to earlier. The SMD-rolls that are stored at the SMD Kardex are also entered into the system, after which a location within the SMD Kardex-system is automatically assigned. Following the attachment of an internal tracking label the SMD-roll can be moved to the SMD Kardex zone. Arrived at the SMD Kardex zone the SMD-roll is stored at the location it got assigned to earlier. Finally, the materials that are to be stored inside the general warehouse get an internal tracking label as well. Following this these materials are transported to the general warehouse and stored at an available location.

Order picking

When the production of an order is about to begin the various materials needed for this specific order are picked by the personnel inside the warehouse. These materials are picked from the various storage locations and stored on a shelving unit with wheels. These drivable shelving units are then moved to the location where the final product is manufactured. This order picking process is explained more in depth in *section 2.4*.

1.2.2 – Problem description

Benchmark Almelo has recently obtained a few large sale orders and, as a result, has grown at a rapid pace. However, this has now led to capacity problems in the warehouse, which is getting full. This capacity issue in the warehouse has become a substantial problem in the last period. There are days on which the occupancy rate of the Kardex-systems is close to 99%. To deal with this Benchmark's various Kardex cabinets are currently being rearranged about once a week to free up some space for newly received products. Besides that, the various hallways inside of Benchmark are also filled with pallets containing materials for which no storage space is available yet. So, these capacity issues are definitely an urgent problem for Benchmark.

Next to that Benchmark currently does not really have a clear insight in the actual occupancy rate in their warehouse. There is data available about this, especially for the Kardex-systems, however this is only sporadically used. This lack of insight makes it difficult for Benchmark to optimize their current warehouse process. In addition to this, Benchmark also has no clear insight how the capacity issues will develop in the short, medium and long term. Eventually it is certainly possible for Benchmark to invest in an extra VLM or pallet racks, but this investment must be substantiated to the global headquarters. Having a better insight into the capacity that is needed on the long term is therefore helpful.

To overcome these capacity issues the first focus is to gain more insight in the occupancy rate of the warehouse in Almelo, both in the present and in the future. Based on these insights research is performed to optimize the warehouse and reduce the occupancy rate. The research problem that is addressed in this thesis is therefore:

> *Currently Benchmark has no clear insight in the occupancy rate of their warehouse, both in the present as in the future. Due to this lack of insight the use of the warehouse is currently not optimal.*

1.3 – Research objectives & scope

In this section, the multiple research objectives are defined. Furthermore, the scope of this research is explained in more detail.

1.3.1 – Research objectives

The overall objective of this thesis research is to solve the research problem presented in the previous section. However, to solve this research problem there are a total of three general research objectives that should be fulfilled. These research objectives are stated in this section, together with an explanation of the necessity of each research objectives.

> *Create an interface that gives (real-time) insight in the current occupancy rate in the warehouse of Benchmark.*

As mentioned earlier there is currently no clear overview of the occupancy rate of the warehouse of Benchmark. To be able to optimize the warehouse in Almelo it is necessary to have such an overview. So therefore, an interface/tool is created that gives insight in the occupancy rate of the warehouse, preferably in real-time. This tool is able to give an insight into the occupancy rate if other inventory policies are being used.

Develop a model that can forecast the expected occupancy rate of the warehouse for at least the upcoming 6 to 12 months.

One of the reasons for this thesis research is that Benchmark would like to gain more insight in the expected occupancy of their warehouse in the upcoming future. So, for this purpose a prediction model is created that is able to forecast the future occupancy rate based on the planned orders and goods expected to arrive. This model is able to deal with different inventory policies so that these policies can be compared with each other.

Give advice to Benchmark how they could improve their warehouse picking process such that the warehouse capacity is used more efficient.

Based on initial research there are reasons to believe that the usage of the warehouse in Almelo is not effective and efficient. A significant reason for this is the picking process that Benchmark uses currently. Therefore, given the insights into the warehouse storage process, some advice is given to Benchmark how they could improve their picking process. The scope of this objective is on deciding which in from locations and in which sequence to pick a pre-determined set of items. The outcomes of this research are supported by results that are generated with the help of the earlier created models/tools.

1.3.2 – Scope of the research

The entire warehouse process at Benchmark in Almelo is complex and there are multiple factors that influence the current problems in the warehouse. To keep the research feasible a decision is made on which part of the warehouse process the focus is on during the research. The decision for the scope is also based on the urgency of the problems in cooperation with Benchmark.

For this research, the decision is made to focus on the ZKDX1001 zone. Together with the general warehouse this is internally referred to as *warehouse 1000*. The ZKDX1001 zone is where most of the materials that arrive at Benchmark are stored. Therefore, most materials that are needed for production are picked from this ZKDX1001 zone. For the problem-solving phase of this research the focus is on the picking process of materials from the ZKDX1001 zone.

The purchasing policy currently used also has a significant effect on the capacity problems inside the Kardex-system and *warehouse 1000* in general. However, for this research the decision is made to not focus on the purchasing policy since changes here are difficult to make. However, recommendations regarding their purchasing policy are always appreciated by Benchmark.

1.4 – Research questions and research design

This section of the thesis report gives an explanation about the approach that is used to successfully fulfil this research. An introduction is given to the main research question together with the five phases used to find an answer to this main research question. To solve the research problem and to fulfil the research objectives mentioned earlier, the following main research question is formulated:

> How can Benchmark **improve their insight** in the occupancy rate of their warehouse, both in the present and future, and use this insight **to improve their warehouse process?**

To solve this main research question multiple sub-research questions are stated. The research question is answered in a total of five phases, each of the sub-research questions is linked to a specific phase. (*See figure 4*) Besides that each of the five sub-research questions is contributing towards reaching the research objectives presented in the previous section. The sub-research questions themselves also have a few sub-questions. Below the sub-research questions presented together with an explanation.
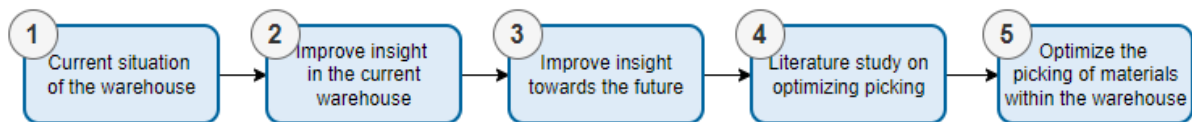
Figure 4 - The five phases of the problem approach

Phase 1 – Get insight into the current situation at the warehouse in Almelo
The goal of the first phase is to get a general idea of the current situation of the warehouse in Almelo. Here the main focus is on the insight of the ZKDX1001 zone. Specifically, information is gathered about the policy that is currently being used to store received materials in the warehouse. Next to that, this phase also gives a general understanding about the current degree of insight Benchmark has into the occupancy rate of their warehouse.

1. What is the current situation of the warehouse in Almelo?
   a. What is the current policy being used by Benchmark for the storage of materials?
   b. How is decided which items to store at the ZKDX1001 zone and which items at the general warehouse?
   c. To what degree does Benchmark currently have insight into their ZKDX1001 zone?
   d. What is the current occupancy rate at the ZKDX1001 zone?

Phase 2 – Improve the insight into the current situation of the warehouse
Based on the information about the current situation of the warehouse, and specifically on the degree of insight Benchmark currently has, the second phase can begin. The goal of the second phase is to improve the insight that Benchmark can have into their ZKDX1001 zone. This insight is needed to be able to execute the following phases of this research.

2. How can Benchmark improve their insight into the current situation inside their warehouse?
   a. What data is available about the ZKDX1001 zone in the various systems used by Benchmark?
   b. Which KPIs are important and need to have more insight?
   c. In what way should the improved insight be presented to Benchmark?

Phase 3 – Improve the insight into the future of the warehouse
As mentioned before, Benchmark expects their current growth in orders to continue in the near future. Because of this growth the expectation is that more raw materials need to be stored into the warehouse. However, currently Benchmark has no idea what the effect of this growth will be on their warehouse. Therefore, the goal in phase 3 is to gain more insight into the expected occupancy rate in the upcoming 6 to 12 months. Next to that an overview of the future occupancy rate is given to Benchmark based on multiple scenarios.

3. <u>How can Benchmark improve their insight into the occupancy rate of the warehouse in the upcoming 6 to 12 months?</u>
    a. What is the current degree of insight Benchmark has into the future occupancy rate of their warehouse?
    b. How to forecast the expected orders and materials needed for these orders for the upcoming 6-12 months?
    c. How to determine the storage space needed inside a VLM for certain materials?
    d. What are the expectations for the occupancy rate in the upcoming 6-12 months?
        i. What are the actual and expected orders for the upcoming 6-12 months of Benchmark?
        ii. What are possible scenarios that could happen in the upcoming 6-12 months?

Phase 4 – Performing a literature study on improving the picking in a warehouse
The previous three phases were about gathering information about the situation in the warehouse of Benchmark, both currently as in the near future. In the last two phases however, the goal is to improve the warehouse picking policy such that picking items from the ZKDX1001 zone becomes more efficient. In the fourth phase a literature study is performed to gain information about improving the picking of a set of materials in a warehouse. The goal is to find picking improvement methods based on existing theories.

4. <u>What is stated in the literature about efficient picking policies and how can this be applied to Benchmark?</u>
    a. Can a similar problem as the one Benchmark is facing currently be found in the literature?
    b. What existing theories are there in the literature about efficiently picking items from a vertical lean lift module?
    c. What alternative picking policies are there in literature that could be used by Benchmark?
    d. What are relevant KPIs to measure the efficiency and effectiveness of a picking policy for Benchmark?

Phase 5 – Improving the picking policy within the ZKDX1001 zone
In the final phase of the research the aim is to improve the picking policy used to pick items from the ZKDX1001 zone. This is done in the form of a tool/dashboard that can support Benchmark with the improvement of their picking sequence. For this the theories found during the literature research are used. The ultimate goal of this phase is to give a clear overview that the improved picking policy is indeed able to reduce the total completion time of picking a certain set of materials.

5. <u>What are policies that Benchmark can use to improve the picking policy within their warehouse?</u>
    a. Based on the literature research, which alternative picking policies can be applied and used to improve the picking process at Benchmark?

b. Besides the literature research, are there other alternative picking policies that are interesting for Benchmark?
c. What should be present on a dashboard that gives insight to the current and future situation in the warehouse of Benchmark?
d. How can a model be created that is able to improve the picking sequence of a set of materials?
e. Which output(s) should this improvement model give to Benchmark?
f. How can the model that is created for Benchmark be validated?
g. Which different scenarios and/or policies should be compared with the help of the model that is created?

1.5 – Deliverables

Based on the research design and research questions described in the previous section, the intention is to provide the following deliverables to Benchmark Almelo at the end of this research:

1. An analysis of the current situation in *warehouse 1000* and the policy currently used for the storage of materials in this warehouse.
2. A dashboard that gives a clear overview of multiple KPIs, such as occupancy rate, of the ZKDX1001 zone. Next to that, this dashboard also gives an insight into potential bottlenecks of the warehouse.
3. A dashboard is created that gives an overview of the expected occupancy rate in the upcoming months based on the forecasted orders. This dashboard is able to deal with different future scenarios based on multiple forecast methods that are used.
4. In the end, one overview is created that contains both the dashboards and the model created earlier. So, with this overview Benchmark immediately has insight into the current and future occupancy rate of their warehouse.
5. Based on the storage- and picking policy currently being used, an insight is given into alternative storage and- picking policies found in the literature.
6. A model is created that is able to improve the picking policy of Benchmark. Based on a given set of data and parameters this model improves the sequence in which the picking process is taking place such that the total completion time is minimized.
7. Finally, a report is delivered that states how the research is conducted.

So, in the end the aim is to deliver one complete overview that gives an improved insight into the current situation and improved insight into the future situation based on multiple scenarios. Next to that a model is delivered that is able to improve the picking process such that the total completion time is minimized. Finally, a report is also delivered to Benchmark which they can use as reference material.

1.6 – Research approach

In section 1.4 the five main phases of this thesis research are introduced. The goal of each of these phases is to answer a research question and a few sub-questions. The answers found in those five phases are contributing towards solving the main research question. In this section the research approach that is used during each of the five phases of the research is briefly explained.

First, in **phase 1**, the goal is getting an overview of the insight that Benchmark currently has into the current situation of *warehouse 1000* and the ZKDX1001 zone specifically. The research approach that is used for this phase is to first gather a lot of information about the current storage- and picking process used by Benchmark. Already during writing the project plan a lot of information has been gathered about this storage- and picking process. However, in phase 1 the missing information is gathered through observations and various interviews. Next, information is gathered about the insight Benchmark currently has into their ZKDX1001 zone. This is done through talking with various employees of the ZKDX1001 zone.

In **phase 2** more insight into the current situation at the ZKDX1001 zone is given to Benchmark. The approach used for this phase is to first get insight into the relevant KPIs and the data that is available about these KPIs. This is done by conducting various interviews, such as with the supervisor logistics and the supply chain analyst. Finally, a dashboard is created in Excel that is easy to use and shows the most relevant KPIs.

Next, in **phase 3** the main goal is to create a model that is able to forecast the occupancy rate in the warehouse for the upcoming 6 to 12 months. Before creating a model, first research is done to the degree of insight Benchmark currently has into their future occupancy rate. This is done through interviews and searching through data in the different software packages Benchmark uses. Following this information research is performed how to forecast the in- and outflow of materials and how this effects the occupancy rate. This can be done through internal research at Benchmark but also through literature research. Based on the findings a model is created that is able to forecast the occupancy rate.

The goal of **phase 4** is to collect information from the literature about picking a set of materials efficiently, with the main focus on picking from a VLM. The research approach for this phase is to perform an extensive literature study into existing theories that could help improve the current picking process at Benchmark. During this literature study only theories that could potentially be applicable to the warehouse situation of Benchmark are considered. Finally, the literature study also leads to information about relevant KPIs for a warehouse. The information of these KPIs is helpful during the fifth and final phase of the thesis.

Finally, in **phase 5** the picking process at Benchmark is improved in such a way that materials are picked more efficient within the ZKDX1001 zone. The first step during this phase is to determine which theories from the previous literature phase could be helpful. Next, a list is created of all the KPIs that are relevant during the picking process. This list is created based on the literature study from the previous phase and internal research. Finally, in this phase a model is created that is able to improve the picking sequence in such a way that the total completion time is minimized.

2. Current situation

In this chapter the first research question together with its sub-research questions is answered. Therefore, this chapter outlines the current situation within *warehouse 1000* of Benchmark Almelo. The focus of this chapter is on making the reader familiar with the storage- and picking process within this warehouse. This chapter contains the following sections:

2.1 – Layout of *warehouse 1000*   2.5 – Current degree of insight ZKDX1001
2.2 – Current storage process   2.6 – Current occupancy rate ZKDX1001
2.3 – Storage location decision   2.7 – Conclusion
2.4 – The picking process

2.1 – Layout of *warehouse 1000*

Within *warehouse 1000* there are two locations where materials can be stored. The first one is the Kardex-system, which consists of a total of eight VLMs. All VLM systems in *warehouse 1000* together are internally also known as ZKDX1001. This name is used in the internal communications and also in the software tools that are used by Benchmark. The other is the general warehouse, which is located next to the Kardex-system. This general warehouse consists of multiple lanes of pallet racks on which the materials can be stored. Before going into more detail about the characteristics of both locations, a map of *warehouse 1000* can be found in *Appendix A.1*.

2.1.1 – ZKDX1001

The Kardex location in *warehouse 1000* consists of eight VLMs produced by the company *Kardex Remstar.* From now on this storage zone is referred to as ZKDX1001, just as in the internal communication of Benchmark. A VLM consists of multiple trays on which items can be stored. In the case of Benchmark each tray contains several bins in which the various materials are stored. The VLMs of Kardex come together with software, *PowerPick*, which makes both storing and picking materials rather simple. The *PowerPick* software makes sure that, upon request, the tray with the requested material or location automatically comes forward. See *Appendix A.3* for multiple pictures of this process. Because of this automatic process the ZKDX1001 is the preferred location to store materials for Benchmark.

As mentioned, each of the trays inside the VLM contains a certain number of the same bin depending on the size of the specific bin. In total there are six different bin sizes in which the materials can be stored. The different bin types can be seen in *table 1* below together with the number of available bins of each type available inside all the eight VLMs together. In theory this number of locations can change if Benchmark decides to alter their allocation of bins within the VLMs. However, for this research the number of locations presented below is used.

Bin type:	Number of locations:	Dimensions in mm (LxWxH):
B001	4399	200 x 148 x 117
B002	2684	300 x 200 x 170
B003	2240	400 x 300 x 220
B004	920	600 x 400 x 320
B005	650	600 x 400 x 120
B006	374	555 x 90 x 80

Table 1 - Different bin types at Benchmark

2.1.2 – General warehouse

The other important storage location inside *warehouse 1000* is the general warehouse, which can also be seen in the map in *Appendix A.1*. Although the general warehouse is not the main focus of this thesis research a brief explanation about the layout is given.

The general warehouse is located right next to the ZKDX1001 zone, both storage zones therefore share their entrances. The general warehouse location consists of multiple pallet racks next to each other. Between the pallet racks there are multiple driving aisles that are used by forklift trucks to store and pick the materials. See the pictures in *Appendix A.4* to get an impression of these pallet racks. As mentioned before, materials stored in these pallet racks are typically larger products or products with a low picking frequency.

2.2 – Current storage process

For the second sub-question the process currently being used by Benchmark to store their materials inside *warehouse 1000* is identified. In this section a more in-depth look is given into the process used by Benchmark to store their raw materials in either the ZKDX1001 or the general warehouse. Although the focus of the thesis research is on the ZKDX1001 the process used for the general warehouse is briefly explained. Reason for this is that initially the process is the same for products being stored somewhere in *warehouse 1000*. For the sake of clarity, a flow diagram of this process is created, this flow diagram can be found in *Appendix A.5*.

2.2.1 – Incoming materials

The first step in the storage process is to receive the new materials and store them inside the inbound department. When materials arrive at the inbound department the employees first look whether the incoming material is an already familiar material for Benchmark. Meaning that Benchmark currently already stores this material within a certain storage zone or has stored this material before in the past. In case the incoming material is already familiar to Benchmark the incoming material is stored within the previously used storage zone. In this case that could be either the ZKDX1001 zone or the general warehouse. When the newly arrived material is not yet familiar to Benchmark the new material initially gets location *ooNew*. This indicates that a decision on the optimal storage zone for this material should still be made. Based on this decision the materials then follow the storage process of either the ZKDX1001 or the general warehouse. A more detailed explanation of this *ooNew* process is given later on in *section 2.3*.

As one can see in this flow diagram the storage process for the materials can slightly differ, depending on whether the materials are stored within the ZKDX1001 or the general warehouse. The process of the materials that are stored in the ZKDX1001 is illustrated by the blue rectangles. Whereas the process of the materials that are stored into the general warehouse is depicted by the orange rectangles. In the sections below a more in-depth insight is given into both different storage processes.

2.2.2 – Storage process ZKDX1001

Materials that are stored into the ZKDX1001 follow the storage process for the ZKDX1001. Generally speaking, this are often smaller materials that have a high pick frequency. In this section a more in-depth insight is given into the storage process of materials that are stored in the ZKDX1001. This storage process of the ZKDX1001 is depicted in the flowchart in *figure 5* below.
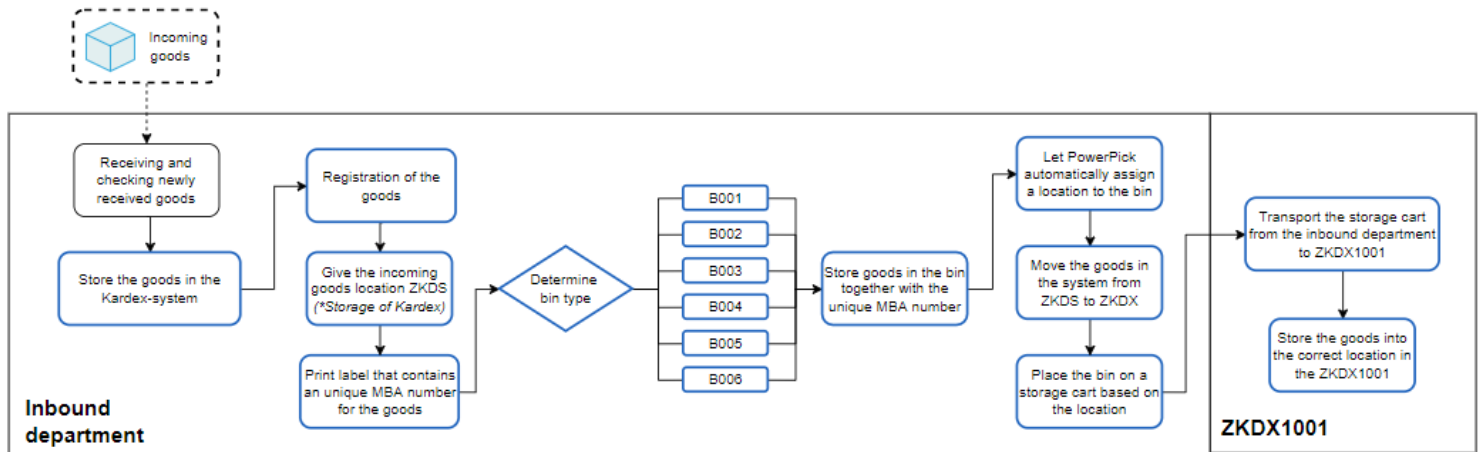
Figure 5 - Flowchart of the ZKDX1001-zone storage process

The storage process starts as soon as the decision is taken to store the newly arrived materials inside the ZKDX1001. From there on an employee of the inbound department checks whether the delivered materials match with the waybill and the order placed by Benchmark. When the wrong products and/or wrong quantities have been received, the goods are then transferred to inspection for a second check. In case the delivered materials pass the initial check they are registered into the system as received. The location of these materials is temporarily set to *ZKDS1001*, which indicates that the materials are waiting to be stored into the ZKDX1001 location.

Following the registration of the materials into the system an internal tracking label is printed with the help of the *Bridgelogix* software. This internal tracking label contains information such as the quantity, material number and the warehouse location, which is ZKDX1001 in this case. The most important piece of information on the tracking label is the unique MBA number. This MBA number is used to internally track the batch of goods inside Benchmark. This MBA number is especially important since Benchmark uses FIFO storage for their materials. Following the FIFO storage, goods with a different MBA number cannot be stored at the same location in the ZKDX1001.

Next, a decision is made in which bin type the materials are placed. As mentioned before there are six different bin types in which the materials can be placed. The materials are placed in the bin type that is optimal, which means there is as little free space as possible. The aim is to store all the goods into a single bin to save warehouse space. However, in exceptional cases (e.g., when not all parts fit into a single bin) two or more bins can be used to store the materials. It is also possible that a particular bin type is not available, in this case another bin type may be used. Determination of the optimal bin type(s) to store the materials is done by the employees of the inbound department. Important to note here is that each bin has a unique reference number. Upon putting the materials into the bin, the inbound department employee also stores this unique reference number into the system. Doing this ensures that the *PowerPick* software always knows which materials are stored inside a specific bin.

The last step of the process at the inbound department is to determine a location for the bin in one of the eight VLMs. This is done with the help of software provided by *Kardex Remstar*, named *PowerPick*. The *PowerPick* software is able to communicate with the eight VLMs and can therefore automatically search for empty bins inside the VLMs. Based on the bin type in which the goods are

stored the software is therefore able to assign an empty location in the ZKDX1001 to the filled bin. After a location is determined the employee places the bin on a storage cart depending on the VLM the bin is being stored in. In the system the location of the bin then updated to match the number on the storage cart on which it is stored. This storage cart is used to transport the bins to the ZKDX1001 location later on.

After placing the bin on a storage cart the storage process continues at the location where the eight VLMs are located, which is the ZKDX1001 location. When the storage cart is entirely loaded with bins it is retrieved by employees of *warehouse 1000*, who transport the storage cart to the ZKDX1001 location. Here the specific number of the storage cart can be entered into the *PowerPick* software on the display of the VLM. This display shows the material number, the location in the VLM where the bin is stored and the specific number of the bin that is stored. Furthermore, there is also a small display that shows the location where the bin should be placed on the tray in red. On this display bins at yellow locations contain goods, whereas the bins at a green location are empty.

This display is used to make storage of the bins into the VLM more convenient and less sensitive to errors. Storing a bin is done by removing the empty bin from the VLM and placing the filled bin at that location. Storage of a bin is confirmed by scanning the barcode on the stored bin. After completion, the following bin that should be stored is automatically displayed. The empty bin that is removed from the VLM is placed on the storage cart. Later on, the storage cart with empty bins is transported back to the inbound department.

2.2.3 – Storage process general warehouse

Although the general warehouse is not the primarily focus of this thesis research a brief introduction is given into the storage process of this general warehouse. As mentioned before this process is also shown in *Appendix A.5* and is depicted by the orange rectangles. Initially the storage process of the general warehouse is similar to the process of the ZKDX1001. The storage process of the general warehouse starts as soon as the decision is taken to store the newly arrived materials inside the general warehouse. Materials stored in the general warehouse are often the bigger materials or materials for which there is no demand yet in the upcoming months.

Next an employee of the inbound department checks whether the delivered materials match with the waybill and the order placed by Benchmark. In case something is not correct the goods are transferred to inspection, where a second check takes place. When everything is correct the employee registers the delivered materials into the system Benchmark uses. Following this registration into the system the materials get an internal tracking label. Just as at the ZKDX1001 process this tracking label contains data such as quantity, material number and of course the unique MBA number. Just like for the ZKDX1001 location Benchmark also uses a FIFO storage policy for their general warehouse, hence the unique MBA number is also important here.

After making sure that the materials can be tracked inside facility of Benchmark the following step is to decide on the exact storage location. The decision on the location of the materials is based on the dimensions of the materials and the current available locations in the general warehouse. Different then for the ZKDX1001 storage process this decision is made by the employees, and not by automatic software. Following this decision, the materials should be stored at the pick-up location of the inbound department. Here the employees of *warehouse 1000* pick-up the materials and transfer them to the location they need to be stored in. Arrived at the specified location the employees store the materials, often by using a forklift truck.

2.2.4 – Deviations in the storage process

In an ideal world the storage process at Benchmark takes place like explained in the previous two sections. However, since Benchmark is currently dealing with some storage capacity issues, recently there have been moments in which there were deviations from the optimal storage process. In this section the occurrence of these deviations is briefly explained.

During times in which the occupancy rate of the ZKDX1001 is really close to 100%, for instance above 98%, the decision can be made to not store certain materials there. This are materials that normally are stored inside the ZKDX1001 based on their characteristics. However, because these materials have no demand in the upcoming 2 to 4 weeks the decision is occasionally be made to prioritize storage of other more urgently needed materials. In this case the materials that are normally stored inside the ZKDX1001 are stored elsewhere. Ideally these materials are then stored inside the general warehouse. However, here Benchmark is also dealing with capacity issues, so this is not always an option. Instead, these materials are often stored on a pallet inside the inbound department for the time being. This decision has to be made occasionally to ensure that materials with demand in the upcoming 1 to 2 weeks can always be stored inside a VLM.

Because of a high occupancy rate, it may be the case that of a certain bin type only a few bins are still available. Typically, this are the B003 or B004 bins since their overall amount is lower. To deal with this the employees at the ZKDX1001 location can use the compacting method. With the compacting method the employees are looking for bins that are largely empty. If a bin is largely empty the materials of that specific bin can possibly be placed into smaller bin, which frees the larger bin. For example, if a B003 bin is largely empty its materials can be placed into a smaller B002 bin. By doing this an extra B003 becomes available. Although the compacting method seems like a great method to free some space it is a very time-consuming method. Therefore, the compacting method is only used if the availability of a certain bin type becomes critical.

Another deviation may occur if certain materials arrive later in Almelo than initially scheduled. Most of the times this is not a big issue since the delay in arrival time is often small. However, occasionally the production process for which these materials are necessary has already started or is about to start. In that case the materials are urgently needed such that the production can continue according to schedule. Materials that are urgently needed for production are placed on a list that is shown on a screen in the inbound department. As soon as materials from this list arrive at the inbound department they are immediately delivered to the relevant production department. So, materials that are urgently needed for production are not stored into *warehouse 1000* first.

2.3 – Storage location decision

As mentioned at the beginning of this chapter there are two locations inside *warehouse 1000* where materials can be stored, the ZKDX1001 and the general warehouse. In this section more insight is given into the decision on where to store incoming materials.

As explained earlier, materials that are already familiar to Benchmark already have a designated storage location. For these materials a decision on their assigned storage location has already been made earlier. These materials are therefore be stored at the same location as happened previously. In case certain materials arrive at Benchmark for the first time they get location 00New. This 00New location indicates that a decision should still be taken on the optimal storage location. This decision process is further explained below.

Generally speaking, there are no clear boundaries for the decision process on where to store materials. The only boundary is of course the size of the bins, if the incoming materials do not fit into any of the bin-sizes they are always be stored in the general warehouse. Besides that, there are no clear boundaries that are considered during the decision process. In general, all materials that fit inside one of the available bin-sizes are stored inside one of the VLMs at the ZKDX1001. This is done

because a VLM is a really efficient method of storage since a lot of items can be stored on little floor space. Next to that a VLM also ensures a faster picking process later on. Other materials that do not fit into one of the bin-sizes are stored on one of the pallet racks inside the general warehouse. Important to note here is that if the decision is made to store a certain material at, for example, the ZKDX1001 location that all materials of the same type are also stored at the ZKDX1001 location in the future.

An exception of this decision process is made for some of the so-called Kanban-items. Initially most of these Kanban-items were stored inside the ZKDX1001 since they fit perfectly into one the bin-sizes. However, recently the decision has been made to remove some of the Kanban-items from the ZKDX1001 location to free some much-needed space. Currently, there is still a debate going on whether this was a well thought decision. However, for the time being these Kanban-items are now being stored at another location at Benchmark.

2.4 – The picking process

Next, in this section the picking process used by Benchmark at the ZKDX1001 location is explained. As mentioned before there are eight different VLMs at this location from which the assorted items are collected. These VLMs are positioned in adjacent pairs run by a single order picker who is ideally picking in an alternating way. Having these VLMs work in pairs ensures that the order picker is spending less time waiting for the VLM to bring forward the next tray. The eight VLMs present at the ZKDX1001 location are divided into four different pairs, each with a single order picker. Therefore, there are a total of four pick locations at the ZKDX1001 location. Each of these pairs of VLMs is operated with the use of single computer screen that is located between both VLMs. See *figure 6* below and *figure 16* in *Appendix A.1* to get an idea of the layout of the ZKDX1001 location. The different colors in the figure indicate the pairs of VLMs that operate simultaneously, here the abbreviation *SH* refers to *Shuttle*. The gray object on *figure 6* below is a cart on which all items of a certain work order are stored, this is explained later on in this section.
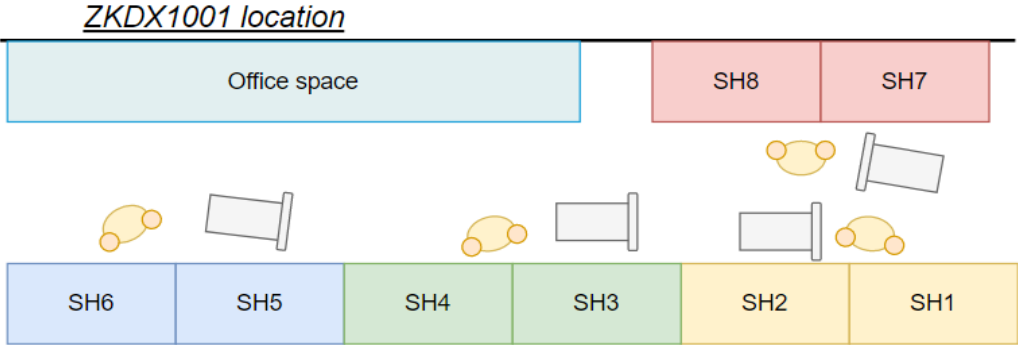
Figure 6 - Overview of the ZKDX1001 location

Picking at the ZKDX1001 location is done on the basis of unique work orders. Such a work order contains all the items that are needed by the manufacturing department for a certain customer order. At the start of the picking process a list containing everything that is in the work order is placed on an empty cart. One of the four order pickers takes this cart to his pick location to start picking the items that are in its pair of VLMs. To start the picking process the order picker simply enters the unique number of the work order into the computer screen that is between the VLMs. The adjacent pair of VLMs both then automatically start bringing forward the first tray on which an item from the work order is stored. The order picker picks the required items from one of the trays, after which a confirmation is given by scanning a barcode. These picked items are stored onto the drivable cart. The VLM from which the items are picked then stores the tray and, if possible, retrieve the next tray. In the meantime, the order picker moves to the adjacent VLM and picks the required

items from that tray, once again a confirmation is given by scanning a barcode. This VLM then also stores the tray and, if possible, retrieve the next tray. This process continues until all the items that are on the work order are picked from that pair of VLMs. It is also possible that only one of the two VLMs is still operating, this is the case if all remaining items are stored in one of the two VLMs. In this case the order picker has no other choice than waiting for the storage and retrieval of the trays.

After all the items that are on the work order are picked from an adjacent pair of VLMs, the drivable cart is moved to the next pick location. The drivable carts are always moved clockwise, this way the next order picker always knows which work order to work on next. From there on the next order picker continues with picking items of that work order from another pair of VLMs. As soon as the fourth and final order picker finished its picking tasks picking of the work order is finished. The drivable cart is then stored at the ZKDX1001 location, next to the office space, waiting to be picked up by an employee from the manufacturing department.

The picking process explained above is the 'normal' picking process. However, on an average day, there are multiple occasions on which an employee of the manufacturing department needs additional materials. Additional materials are needed in case of a mistake in the 'normal' picking process or because certain material has broken. In case additional materials are required from the ZKDX1001 location these are picked during the 'normal' picking process. Ideally this happens in between picking different work orders. Picking of these additional materials has no significant effect on the overall picking process and is therefore not considered during this thesis research.

2.5 – Current degree of insight into ZKDX1001

In the following section the final two sub-questions are answered. Therefore, this section gives an insight in the current degree of insight Benchmark currently has into the occupation rate of the ZKDX1001 location. Furthermore, this section discusses the initial occupation rate of the ZKDX1001 over the past few months.

As mentioned before Benchmark makes use of the *PowerPick* software to keep track of the situation inside the eight VLMs at the ZKDX1001. This software decides at which empty location a new bin is stored and also decides which bin is used for a picking action. To make these decisions *PowerPick* uses a large dataset that contains information on all the available storage locations inside the eight VLMs. This large dataset is continuously updated if new materials are stored or when materials are picked. Furthermore, it is also regularly checked whether the dataset correctly represents the actual situation. This is done through random counting checks. So, the dataset that *PowerPick* uses is reliable and gives a good picture of the actual situation in the ZKDX1001. Therefore, Benchmark uses this dataset from *PowerPick* to gain insight in the occupancy rate of the ZKDX1001.

This dataset is exported out of the *PowerPick* software daily to create an Excel-file that contains all the relevant data. This Excel-file is created every weekday and is available on the general server of Benchmark in Almelo. This Excel-file is currently used by Benchmark to get insight into the current situation of the ZKDX1001. A screenshot of this Excel-file can be viewed in *Appendix A.6*.

The most valuable information for Benchmark to get a clear insight is in the *Material* column and the *Bin* column. An empty cell in the *Material* column indicates that the corresponding location is empty. Furthermore, if a cell in the *Material* column is filled with the number of a material this indicates that this location is currently occupied. Based on the bin type in the *Bin* column the number of occupied and empty locations can be counted per bin type. However, since the dataset contains information about over 10.000 locations the most convenient method to count this is by using the built-in *CountIf* function of Excel.

Such a tool was already available at the beginning of this research. This tool is able to automatically calculate the percentage of empty locations per bin type. The tool works fairly simple, the only thing the user needs to do is pasting the most recent dataset into the correct Excel-sheet. Once that is done the tool uses the *CountIf* function of Excel to automatically count the occupied and the empty

locations. This information about the location is presented on a dashboard on a separate Excel-sheet, see *Appendix A.7* for a screenshot of this dashboard. This dashboard is able to give a quick overview of the current situation based on the most recent data out of the *PowerPick* software. Besides this tool there are also some employees at Benchmark that created their own little tool to be able to get an overview of the empty locations inside the ZKDX1001. But in general, these tools all use the same method to extract the relevant data from the exported dataset.

2.6 – Current occupancy rate ZKDX1001

Based on the exported dataset and the *CountIf* method insight into the current occupancy of the ZKDX1001 can be given. The first phase of this research is conducted in the months of December 2021 and January 2022. Therefore, in these two months a lot of data is collected about the occupancy rate inside the ZKDX1001. In these two months the occupancy rate is determined on every Monday and every Wednesday. As explained earlier this occupancy rate is based on the dataset that is exported out of *PowerPick* daily. For this research, the overall occupancy rate is considered, as well as the occupancy rate per different bin type. In *figure 7* the overall occupancy rate and the occupancy rate of the different bin types at various points in time during those two months are shown.
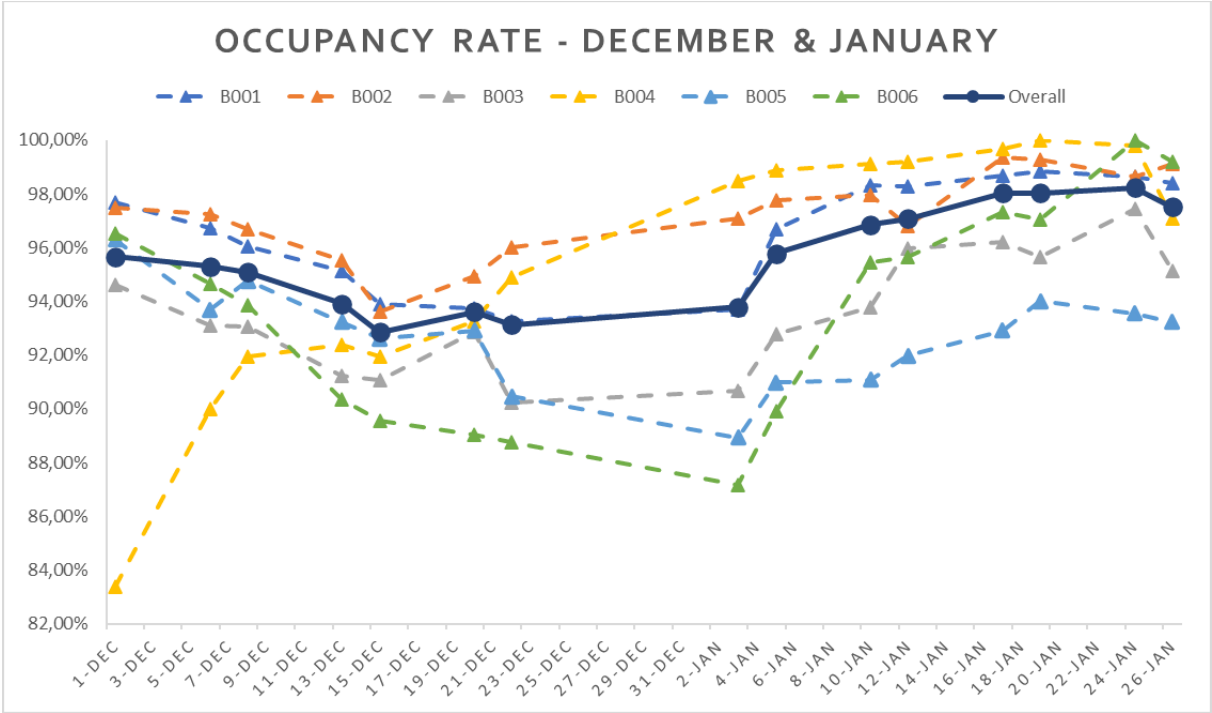
Figure 7 - Occupancy rate of ZKDX1001 in December & January

In this graph there are a total of seven different data lines that all represent a percentage of bins that are occupied with materials. The dark blue solid line represents the overall occupancy rate of the ZKDX1001 over time. Whereas the six dashed lines each represent the occupancy of a different bin type. Based on the graph the conclusion can be made that at first the overall occupancy rate declines towards the end of December. However, during January the overall occupancy rate of the ZKDX1001 slowly starts increasing again. The reason for this decline towards the end of the year is that Benchmark wants to minimize their inventory because of the ending of their fiscal year. Furthermore, less production orders are scheduled during the end of December and the beginning of January because of the holidays. Less production orders mean that less materials are needed, leading to a decline of the occupancy rate.

After the holiday season is over the usual business continues at Benchmark. The regular production orders continue, for which materials are needed. The arrival of all these materials at the beginning of January results in a rising occupancy rate. During the end of January, the situation at the ZKDX1001 even became quite critical with an overall occupancy rate above 98%. But on the 26th of January the overall occupancy rate drops a bit, especially for the B003 and B004 bins. The reason for this is that less orders arrived on the two days prior to this date. However, the reason for the sharp decline for the B003 and B004 bins is that Benchmark used a method called compacting on the 25th of January.

On days where the occupancy rate of a certain bin type becomes critical, so close to 100%, the employees of the ZKDX1001 location can use the compacting method. The compacting method is already briefly introduced in section 2.2.4. Based on this graph it is clear that the compacting method is used at the end of January to lower the occupancy rate of the B003 and the B004 bins. Before the 26th of January, the occupancy rate of both bin types was increasing and becoming critical, the B004 even reached an occupancy rate of 100%. But because the compacting method was used on the 26th the occupancy rate of the B003 and B004 had a sharp decline. Which can clearly be seen when looking at the gray and yellow dashed line towards the end of the graph. The data behind the graph illustrated in *figure 7* can be found in *table 9* in *Appendix A.8*, for a more in-depth overview.

2.7 – Conclusion

Based on the previous sections within this chapter the initial conclusion is that the current warehouse process being used by Benchmark is fairly complex. There are multiple factors that have to be considered during the storage process of incoming materials. Such as the fact that incoming materials have to be stored in separate batches, making it possible that a certain item has multiple storage locations. Furthermore, there are multiple deviations from the normal storage process because of the current high occupancy rate. By using VLMs for the storage of their fast-moving materials, Benchmark can pick these materials quickly. However, based on initial research there is still room for improvement within the picking process. Since Benchmark does not want to deviate from their current storage process the optimization is focused only on the picking process.

Furthermore, the current insight that Benchmark has into the occupancy rate of the ZKDX1001 zone, as well as other relevant KPIs, is really minimal. There is some insight into the current occupancy rate with the help of a tool, but this tool is not really user friendly. Because of this the data about the occupancy rate is not easily available. The current occupancy rate is also the only KPI in which Benchmark has insight currently. So, with regards to the insight into the various KPIs of the ZKDX1001 zone there is still room for improvement.

3. Improving the insight

The third chapter of the thesis research answers the second research question. The main goal of this second research question is to improve the insight that Benchmark has into the occupancy rate of their ZKDX1001 zone. Therefore, this chapter contains the following sections that discuss the various actions that are taken to improve the insight of Benchmark:

3.1 – Relevant KPIs ZKDX1001   3.3 – Dashboard current situation
3.2 – Available data ZKDX1001   3.4 – Conclusion

3.1 – Relevant KPIs ZKDX1001

This section discusses the most relevant KPIs of the ZKDX1001 zone that Benchmark would like more insight to. These KPIs are presented on the dashboard that is explained in *section 3.3*. The KPIs mentioned in this section only focus on the capacity issues of the ZKDX1001 zone. Of course, there are also other KPIs that are important for a warehouse, such as the percentage of picked orders. But for this thesis research only the KPIs that focus on the capacity issues in the warehouse are relevant. These KPIs have been determined based on multiple interviews and meetings with employees involved.

3.1.1 – The occupancy rate

Already mentioned a lot in this thesis is the occupancy rate, which is the most important warehouse KPI for Benchmark. In the case of Benchmark, the occupancy rate depicts the percentage of bins that are filled. Therefore, the occupancy rate gives clear information about the current capacity issues of the ZKDX1001 zone. For this thesis research a distinction is made between the overall occupancy rate and the occupancy rate per bin type. The overall occupancy rate depicts the percentage of all the bins that are filled with materials. Whereas the occupancy rate per bin type is used to show the percentage of bins that is filled for a specific bin type. See *figure 8* below for the formulas of the overall occupancy rate and the occupancy per bin type.

$$Overall\ occupancy\ rate = \frac{Filled\ bins}{Total\ number\ of\ bins}$$

$$Occupancy\ rate\ of\ bin\ B00\# = \frac{Filled\ B00\#\ bins}{Total\ number\ of\ B00\#\ bins}\quad , where\ \# \in (1\dots6)$$

Figure 8 - Mathematical formulas of the occupancy rate

3.1.2 – Bins with no demand

Another important KPI for Benchmark to have an idea of the capacity issues at the ZKDX1001 zone is the number of bins without demand. Whether or not there is demand for a certain bin is decided based on the material inside the bin. When there are no production orders scheduled in the upcoming 12 months for which the material is needed, this means the bin has no demand. It may seem strange to have this as a KPI since, in theory, only materials that are needed for production should be in the warehouse. However, based on initial research came forward that there are multiple bins at the ZKDX1001 zone that contain material for which there is no demand. Reasons for this are a phased-out product or the material being safety stock. Despite the reason one could argue whether these materials need to be stored inside a VLM. Therefore, with the capacity issues in mind, having an idea of the bins for which there is no demand is interesting for Benchmark to know.

3.1.3 – Bins per customer

The third and final KPI in which Benchmark should have more insight is the number of bins that are in use per customer. A bin being in use for a certain customer means that the material inside that bin is used during production for that certain customer. Based on the bins per customer it is possible to calculate the percentage of the bins that is in use by a certain customer. This percentage can be

compared with the percentage that the customer contributes to the yearly turnover. For example, there could be a customer that is using 30% of the bins while only contributing 5% to the yearly turnover. A customer like this is responsible for a large part of the capacity issues while only contributing little. Therefore, the bins in use per customer is a helpful KPI to keep track if customers use a reasonable amount of storage space.

Furthermore, this KPI is helpful at the moment a certain customer decides to stop the collaboration with Benchmark. In that case this KPI can give a clear overview of the number of bins that are in use by this particular customer. This way Benchmark is able to immediately know the effect of this leaving customer on the occupancy rate of the ZKDX1001.

3.2 – Available data ZKDX1001

The previous section mentioned a total of three KPIs that are important for Benchmark to get a better insight in the current situation at the ZKDX1001 zone. This section explains the available data that is used to determine the values of each of the three KPIs.

The data needed to determine the **overall occupancy rate** and the **occupancy rate per bin type** has already been briefly introduced in section 2.4. The information in the columns *Material* and *Bin* can be used to determine the occupancy rate. As explained earlier the *CountIf* function of Excel can be used to determine the various occupancy rates.

Next, to determine the number of **bins with no demand** another dataset is needed. In the *RapidResponse* software a dataset is available that contains demand data for every material that is used for production. For different time periods the demand for a certain material is given, based on the planned production orders. In this case the focus is on the demand in the upcoming 12 months. Materials for which the demand in the upcoming 12 months is equal to zero are picked out of this dataset. This list of materials without demand can be compared to the exported dataset from *PowerPick* to determine the number of bins with no demand.

Finally, the **bins per customer** can also be determined based on the exported dataset from the *PowerPick* software. Each type of material that is stored at Benchmark has a unique reference number. The first three characters of this reference number indicate for which final customer the material is used during production. For example, the *ABC* in the reference number *ABC1234_567_89101-LF* indicates that this material is used for the production of the fictive customer *ABC*. This unique reference number is also stored in the exported dataset in the *Material* column. By looking at the first three characters of this reference number the end customer of a specific material can be determined. This way it is possible to count the number of bins that are in use for each customer.

3.3 – Dashboard current situation

Finally, in this section the dashboard that improves the insight into the current situation is presented. This dashboard gives Benchmark a clear overview of the most relevant KPIs, as introduced in the previous section. The dashboard is created with Excel and VBA such that all employees of Benchmark are able to easily run the dashboard on their computer. Besides that, the data that is being used to determine the values of the KPIs is already in an Excel-format. Therefore, creating a dashboard in Excel saves computational time since transforming the data is not necessary.

A screenshot of the final dashboard is found in *figure 9*, and a larger version is also available in *Appendix B.1*. Here one can see that the dashboard is divided into four main parts. There is a part for each of the three relevant KPIs and a place where the user can upload the data.
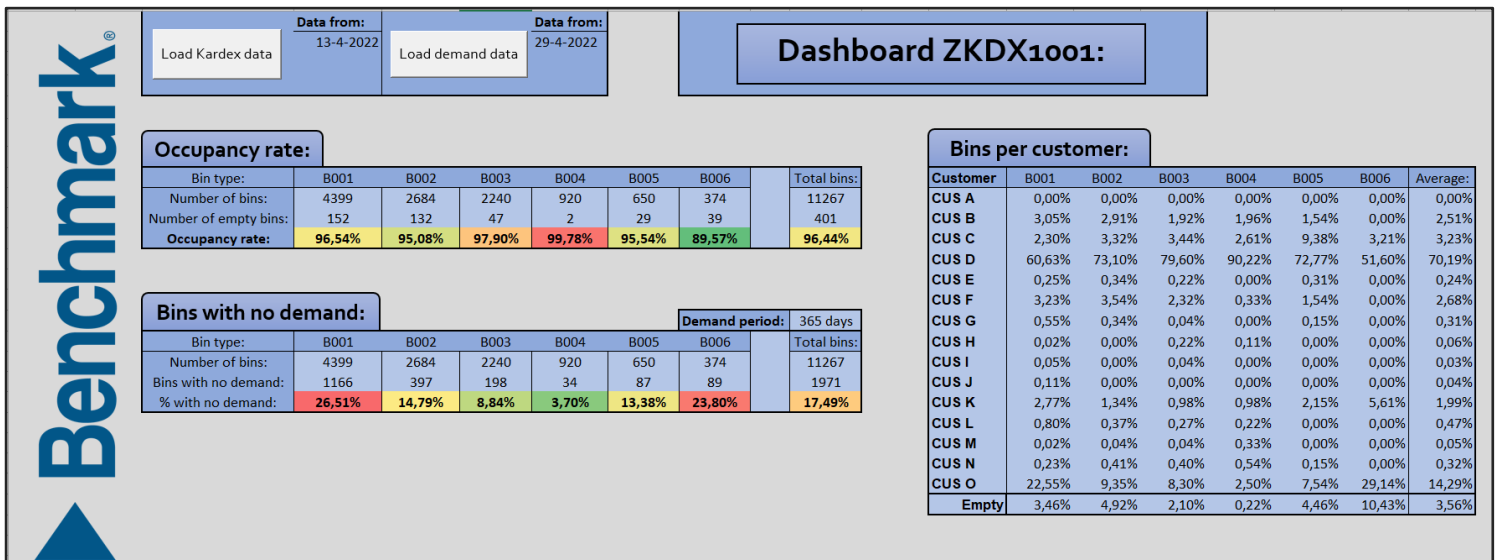
Figure 9 - Overview of dashboard of the ZDKX1001 zone

Dashboard ZKDX1001:

Load Kardex data — Data from: 13-4-2022
Load demand data — Data from: 29-4-2022

Occupancy rate:

Bin type:	B001	B002	B003	B004	B005	B006	Total bins:
Number of bins:	4399	2684	2240	920	650	374	11267
Number of empty bins:	152	132	47	2	29	39	401
Occupancy rate:	96,54%	95,08%	97,90%	99,78%	95,54%	89,57%	96,44%

Bins with no demand: — Demand period: 365 days

Bin type:	B001	B002	B003	B004	B005	B006	Total bins:
Number of bins:	4399	2684	2240	920	650	374	11267
Bins with no demand:	1166	397	198	34	87	89	1971
% with no demand:	26,51%	14,79%	8,84%	3,70%	13,38%	23,80%	17,49%

Bins per customer:

Customer	B001	B002	B003	B004	B005	B006	Average:
CUS A	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
CUS B	3,05%	2,91%	1,92%	1,96%	1,54%	0,00%	2,51%
CUS C	2,30%	3,32%	3,44%	2,61%	9,38%	3,21%	3,23%
CUS D	60,63%	73,10%	79,60%	90,22%	72,77%	51,60%	70,19%
CUS E	0,25%	0,34%	0,22%	0,00%	0,31%	0,00%	0,24%
CUS F	3,23%	3,54%	2,32%	0,33%	1,54%	0,00%	2,68%
CUS G	0,55%	0,34%	0,04%	0,00%	0,15%	0,00%	0,31%
CUS H	0,02%	0,00%	0,22%	0,11%	0,00%	0,00%	0,06%
CUS I	0,05%	0,00%	0,04%	0,00%	0,00%	0,00%	0,03%
CUS J	0,11%	0,00%	0,00%	0,00%	0,00%	0,00%	0,04%
CUS K	2,77%	1,34%	0,98%	0,98%	2,15%	5,61%	1,99%
CUS L	0,80%	0,37%	0,27%	0,22%	0,00%	0,00%	0,47%
CUS M	0,02%	0,04%	0,04%	0,33%	0,00%	0,00%	0,05%
CUS N	0,23%	0,41%	0,40%	0,54%	0,15%	0,00%	0,32%
CUS O	22,55%	9,35%	8,30%	2,50%	7,54%	29,14%	14,29%
Empty	3,46%	4,92%	2,10%	0,22%	4,46%	10,43%	3,56%

On the top left of the dashboard there are two buttons for the user to upload relevant data. The leftmost button is clicked to upload the newest exported dataset from the *PowerPick* software. Next, the button on the right is used to upload the exported demand dataset from *RapidResponse*. After uploading any of these files the dashboard automatically updates the values for the relevant KPIs. Furthermore, next to both buttons the user can see the dates of the dataset that are being used.

The most important part of the dashboard is the part that shows the values of the **occupancy rate** KPI. As mentioned, this KPI contains both the overall occupancy rate as the occupancy rate per bin type. Besides the occupancy rate this part also contains information about the number of empty bins and the total number of bins at the ZKDX1001 zone.

Next, there is a part that shows the values of the **bins with no demand**. On this part of the dashboard the user can view the number of bins that have no demand based on a certain demand period. This demand period can be altered by the user with the help of a dropdown list. In total the user can select six different demand periods between 7 up to 365 days. As soon as another demand period is selected the values on the dashboard updates accordingly.

The final part on the dashboard is reserved for the **bins per customer**. This part shows the percentage of bins that are in use by a certain end customer. On the dashboard only customers are shown that have materials stored at the ZKDX1001 zone. In case Benchmark attracts a new customer for which materials are stored at the ZKDX1001 zone, this customer should be added manually. In the future it would be great to update the dashboard such that this is performed automatically.

3.4 – Conclusion

Chapter three presents a clear insight in the process behind the creation of the dashboard of the ZKDX1001 zone. Based on section one and two the conclusion is that there are three KPIs that are interesting for Benchmark of which plenty data available. These data can be used to create a dashboard that improves the insight of Benchmark into the ZKDX1001 zone by a large extend. Most importantly, this dashboard is easy to use such that insight into relevant KPIs can be obtained by the various employees at any moment.

4. Forecasting the occupancy rate

The fourth chapter of this report discusses the third phase of the thesis research. The focus of this third phase is on improving the insight into the future situation of the ZKDX1001 zone. This chapter therefore introduces the reader to the forecast model that is able to give the user a forecast of the future occupancy rate at the ZKDX1001 zone. This fourth chapter consists of the following sections:

4.1 – Current insight into the future

4.2 – From supply to occupied bins

4.3 – From demand to empty bins

4.4 – Overview of the forecast model

4.5 – Conclusion

4.1 – Current insight into the future

The current insight Benchmark has into the future occupancy rate of their ZKDX1001 zone is really minimal. Benchmark however would like to have a better understanding of their occupancy rate in the upcoming 6 to 12 months. Before thinking about improving this insight it is important to understand the degree of future insight Benchmark has right now.

4.1.1 – Insight into the future occupancy rate

As mentioned, currently the insight into the future occupancy rate is really minimal. But in fact, there is no insight into the future occupancy rate of the ZKDX1001 zone. The only information that Benchmark has about the occupancy rate at the ZKDX1001 zone is the current occupancy rate. This means that Benchmark has no idea what they can expect in the future regarding the occupancy rate at the ZKDX1001 zone. Because of this Benchmark is unable to steer on the occupancy rate KPI when looking at the future.

The lack of insight into the future occupancy rate makes it difficult to make certain decisions, and even more difficult to support them with concrete data. Recently Benchmark made the decision to acquire two new VLMs, so that the total number of VLMs at the ZKDX1001 zone is increased to ten. This decision was made based on the fact that the current VLMs at the ZKDX1001 zone are getting full and the overall occupancy rate is getting close to 100%. However, in the future Benchmark would like to make such a decision on forecasts of their future occupancy rate.

4.1.2 – Insight into the future demand and supply

While Benchmark has no insight into their future occupancy rate, they do have insight into their future demand and supply of items. This section explains the insight Benchmark currently has into their demand and supply. The insight into the future demand and supply is essential when creating a model that forecasts the future occupancy rate.

The insight into the supply and demand comes from the ERP-system that is used by Benchmark. Within this ERP-system there is a so-called *time-phased planning overview* for each item, which is fairly similar to the well-known *Material Requirements Planning (MRP).* The overview contains all the future demand and supply of an item in chronological order. The ERP-system of Benchmark has the possibility to combine the demand and supply of all their items into one *time-phased planning overview*. After removing all items that are not stored within the ZKDX1001 zone this overview can easily be exported to an Excel-file. See *figure 28* in *Appendix C.1* for an insight into this exported Excel-file. This Excel-file can then be used as input data for the forecast model of the ZKDX1001 zone.

4.2 – From supply to occupied bins

As mentioned in the previous section the exported *time-phased planning* dataset is used to get an insight in the bins that are getting occupied because of the supply. The first step for the model is to retrieve the period for which the forecast is made. The start date is equal to the current date, whereas the end date is put in by the user of the model. All the supply data outside of this period is removed from the dataset. Next, the model also needs data about the quantities that can be stored within each of the bin-types for a certain item. This dataset is created by looking at five years (2017-2022) of historical data of the ZKDX1001 zone. Based on this historical data it is possible to estimate the quantities that can be stored within the different bin-types. This quantity can also be zero, meaning that this item cannot be stored in this type of bin. See *figure 29* in *Appendix C.2* for an overview of this dataset and a more detailed explanation.

Following this input data, the model can start determining the number of bins that are occupied by the supply in the given period. Since Benchmark uses the FIFO policy, each of the incoming supplies has to be stored within a different bin. The model starts by selecting the first incoming supply and the corresponding item. Then the model retrieves the quantities that can be stored in each bin-type for the specific item from the earlier mentioned dataset. For each of the six bin-types the model computes the *fill-rate* based on the incoming supply. The bin-type that has a *fill-rate* that is the closest to 100% and is at most 100% is the optimal bin to store the supply. This process is then repeated by the model for the remaining supplies in the period. For a more detailed insight in this process see the flow diagram in *figure 30* in *Appendix C.3*.

There are however two exceptions to the above-described process. In case the supply is larger than any of the six retrieved quantities, the supply is stored in the bin-type with the largest quantity. This continues until the supply is lower than the largest retrieved quantity, the remaining supply then follows the above-described process. The other exception is in case there is not yet historic data about a certain item. In this case the model determines the bin-type based on the historic probabilities that supply is stored within a certain bin-type. See *table 2* for the historic averages that each bin-type is used, these probabilities are used in this case.

B001	25,3%
B002	24%
B003	27,9%
B004	14%
B005	6,5%
B006	2,3%

Table 2 - Historic averages of bin-types

4.3 – From demand to empty bins

The following section introduces the reader to the method that is used to determine the number of empty bins based on the demand over a certain period. The dataset used to determine the demand is the exported Excel-file of the *time-phased planning overview* that has been mentioned in the previous section. Next, the exported dataset of *PowerPick* is used to get an insight into the current inventories at the ZKDX1001 zone.

Based on these two datasets it is possible to forecast the bins that get empty after a certain period. This period is decided upon by the user by the changing the input values, which is discussed in section 4.4. The first step is to determine the total demand for each of the items in the given period. Following that the dataset of the ZKDX1001 zone is first sorted on the items, and then on the storage date. This ensures that identical items are grouped together based on the FIFO process that is followed by Benchmark. The forecast model then takes the demand in the period for one of the items. This demand is compared to the quantity that is stored within the bin(s). There are three options that are considered by the model:

1. <u>The demand is less than the quantity in the bin.</u>
   In this case the remaining demand is zero. The quantity of the bin is equal to the initial quantity minus the demand. This means that no (extra) empty bins are created by this demand and the model continues with the next item.
2. <u>The demand is equal to the quantity in the bin.</u>
   The outcome in this case is fairly simple, both the remaining demand as the remaining

quantity is equal to zero. The model increases the count of empty bins of the specific bin-type with one. Following that, the model continues with the next item.

3. <u>The demand is more than the quantity in the bin.</u>
Finally, in this case the quantity within the bin is equal to zero. This creates an empty bin of the specific bin-type. Next, the remaining demand is equal to the initial demand minus the quantity within the bin. The model then continues with the next item.

The process described above is performed for all of the items that have demand. See also *figure 31* within *Appendix C.4* for a detailed flow diagram of this process. Normally the above process continues until the demand of each of the items is equal to zero. However, in exceptional cases it might be the case that not all demand for a certain item can be fulfilled by the inventory.

4.4 – Overview of the model

The next section of this chapter finally presents the overview of the model that has been introduced in the previous chapters. As mentioned this model is able to forecast the future occupancy rate of the ZKDX1001 zone based on certain datasets. The forecast consists of a prediction of the bins that will be occupied and of the bins that will be empty. Giving the initial situation at the ZKDX1001 zone these forecasts combined form the forecast of the occupancy rate.

The dashboard of the model, see *figure 10* below, consists of three main parts. These are the input form, the output and the statistics. The values on the input part of the dashboard are entered by the user before starting the run of the model. Here the user can enter the end date of the forecast period, but also the percentage of demand and supply from the dataset that is actually met. Next, the user can also select whether compacting (*section 2.3*) is considered by the model. After entering the relevant input values the user can start the forecast model by pressing *Run forecast* on the top-left of the dashboard.
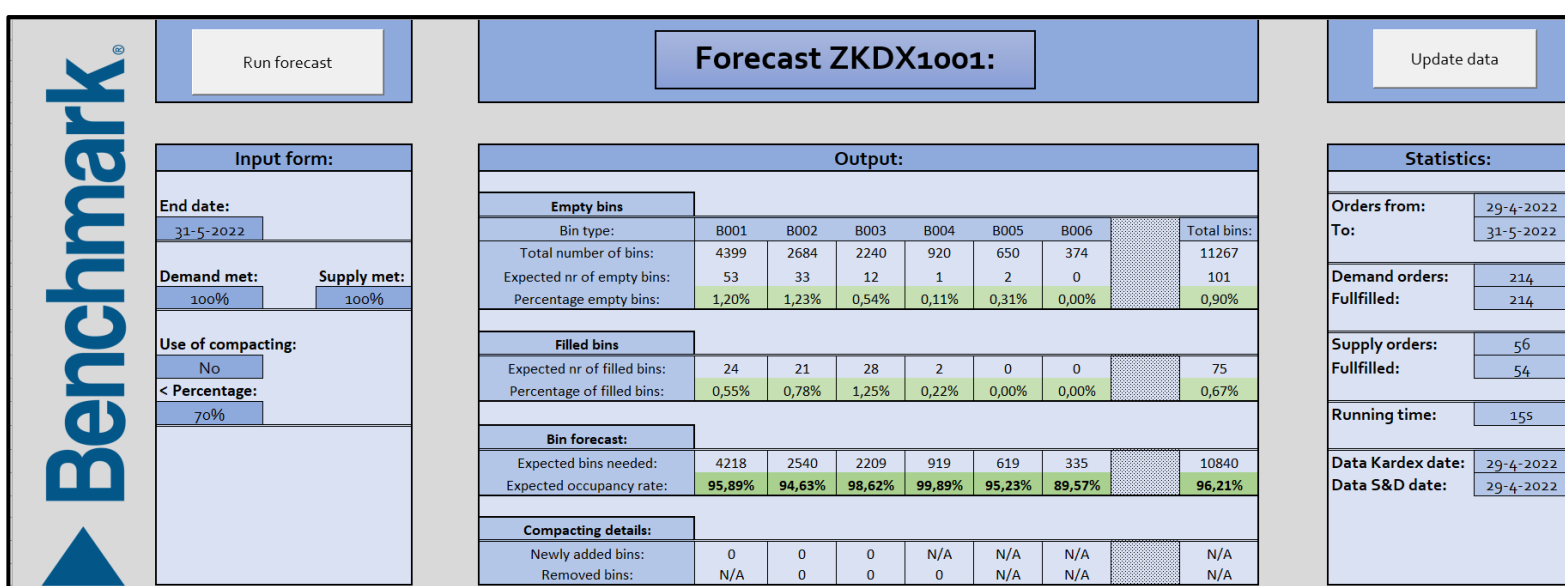
Figure 10 - Overview of the forecast model

After a short while of computation time the results of the forecast model is presented on the output part of the dashboard. Here the user can view the forecasted number of new empty bins and the forecast number of new occupied bins, per bin-type. Together these forecasts form the expected occupancy rate of the ZKDX1001 zone at the given end date. This expected occupancy rate is also shown for each separate bin-type. In case compacting is considered the dashboard also shows these outcomes on the dashboard. Finally, the dashboard also shows a few relevant statistics that give the user more background information about the forecast that is made.

4.5 – Conclusion

The fourth chapter presents the reader a dashboard to get insight into the future situation at the ZKDX1001 zone. The fact that Benchmark has a clear overview of their future demand and supply made it possible to forecast the future occupancy rate. Both these demand and supply are used by the model to forecast the number of empty and occupied bins. With these expected empty and occupied bins, the model creates a clear forecast of the expected occupancy rate after a certain period. Importantly, the model is also fairly easy to use such that Benchmark can still use it for years to come.

Finally, it came forward that there are occurrences in which the demand for an item is higher than its current inventory and incoming supply. This can also be the case in real-life for Benchmark, leading to a delay in production. In the forecast model this also was not an issue since the quantity of a bin could not get below zero. So, this occurrence has no direct effect on the outcome of the forecast.

5. Literature review

The fifth chapter of the report is about the literature review, which is the fourth phase of the thesis research. Within this chapter literature is presented about the typical characteristics of a VLM and how to incorporate this in a mathematical model. Next, this chapter contains a section that briefly discusses previous research towards the storage process of Benchmark. Finally, various literature sources are presented that could be used to optimize the picking process at Benchmark. The fifth chapter therefore contains the following sections:

5.1 – Characteristics of a VLM   5.4 – Optimization techniques
5.2 – Optimal storage policy for Benchmark   5.5 – Conclusion
5.3 – Reducing the completion time

5.1 – Characteristics of a VLM

As already mentioned before the VLMs present at Benchmark are from the company *Kardex Remstar*. More specifically Benchmark has eight *Kardex Remstar Shuttle XP 250/500* modules. This type of VLM is specifically designed for the storage and picking of small-scale goods, which is exactly what Benchmark uses it for. In this section an insight is given into the advantages of such a VLM based on a literature review. Furthermore, in this section a throughput model is presented that is able to represent a VLM system, which enables testing.

5.1.1 – Advantages of a VLM

A VLM can be described as an enclosed system of trays that are vertically arranged on both sides of the system with an extractor device placed in the center, see *figure 10*. With one simple action, such as scanning a barcode or a click on the display, the system automatically delivers the desired tray to the picking location. Therefore, VLM system works according to a part-to-picker principle, as also mentioned by De Koster et al. (2007). An important aspect of the VLM is its modular design. This modular design provides the possibility to add or remove trays and/or shuttles, whenever requirements of the customer change. Currently, still few scientific papers are available about VLMs, which was also the conclusion of Dukic et al in 2015 during their literature review. However, according to Bettini et al. (2005) a VLM is fairly similar to AS/RS systems. Therefore, to get more knowledge about other advantages of a VLM, a look is taken into scientific papers on AS/RS systems.

Figure 11 - Inside view of a VLM

AS/RS systems have been around for multiple decades and are widely used within distribution and manufacturing environments. While it requires higher investment costs, these AS/RS systems have various advantages over non-automated systems. Advantages are floor space savings, increased reliability and reduced picking times (Roodbergen and Vis, 2009). Especially efficient use of floor space and reducing the picking times have become important in recent years due to the growth in e-commerce. (Dukic et al., 2015)

Order picking is the most expensive activity within a warehouse. Close to 55% of a typical warehouse total operating costs are caused by order picking (Tompkins et al., 2010). The most crucial factor in these order picking costs is the travel time, so the time in which the picker is moving between locations. Following Tompkins et al. (2003) about 50% of the order picker's time is spend travelling. Or to cite Bartholdi and Hackman (2005) 'travel time is waste. It costs labor hours, but does not add value.' Usage of an AS/RS system, such as a VLM, can drastically lower these travel times through usage of the part-to-picker principle. Furthermore, according to Modula, a well-known manufacturer of VLMs, a VLM can provide floor space reduction up top 90%. Next, Kardex Remstar also gives two examples in which usage of their VLMs managed to reduce the warehouse floor space with 70% and 84%.

5.1.2 – A mathematical model of a VLM-system

This section of the literature review discusses a mathematical model that could be used to represent the VLMs at Benchmark. The goal of such a mathematical model is to be able to compute the values of various important KPIs, such as the total picking time. The mathematical model presented in this section is introduced by Nicolas, Yannick & Ramzi in 2018.

Mathematical model Nicolas, Yannick & Ramzi
Despite the lack of papers regarding storage and picking with a VLM, Dukic et al. (2015) concluded that there are in fact various mathematical models that describe the process of a VLM. As mentioned this section discusses the model introduced in 2018 by Nicolas, Yannick & Ramzi. This mathematical model is able to compute the total completion time for picking a set of N customer orders from single or multiple VLM(s). The goal of their research was to provide optimization models for order batching inside a single or multiple VLM(s). Order batching is the process of regrouping customers' orders into batches. These batches should then be collected from the VLM(s). The method used for order batching has a significant effect on the overall performance of a warehouse, since it directly effects the efficiency of order picking.

To perform experiments with their optimization models for order batching they needed to have a throughput model that represents a single and multiple VLM(s). Therefore, Nicolas et al. present a mathematical model that is able to calculate the total completion time for picking a set of N customer orders. Both a mathematical model for a single VLM is presented, as a model for a system with multiple VLMs. The mathematical model that describes a system with multiple VLMs reflects the situation of Benchmark the best, and is therefore further explained.

Mathematical model multiple VLMs:

The goal of this mathematical model is to compute the total completion time C to pick B batches, in the case of multiple VLMs. To give a formal definition of this mathematical model

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- **V** = {1 .. V}: Set of indices for all VLMs, where **V** is the total number of VLMs
- **N** = {1 .. N}: Set of indices for the customers' orders
- **S**: Batch size, the maximum number of orders to put in a batch. In practice, the batch size is generally a constant parameter.
- **B** = {1 .. B}: Set of indices for all batches. Where **B** is the number of batches to be created. Is based on the total number of considered orders and the numbers of order per batch, with B = [N / S] where [.] is the ceiling function.
- K_v = {1 .. K_v}: Set of indices for trays in VLM v.
- K^b_v: Number of trays that have to be visited on VLM v for batch b.
- **W**: Total waiting time of the picker. (This is the time when the picker is available, but has to wait for a tray)
- **P**: Total picking time. This is the time during which the picker is collecting items from the trays
- **C**: Total completion time for all batches, **C** = **W** + **P**
- W^b: Picker's waiting time associated with batch b.
- P^b: Picking time associated with batch b.
- C^b: Completion time associated with batch b, $C^b = W^b + P^b$
- $W^b_{l\,v}$: Picker's waiting time in front of the l-th tray of VLM v that is visited for batch b.
- $P^b_{l\,v}$: Time required to pick items from the l-th tray of VLM v associated with batch b.
- $C^b_{l\,v}$: Completion time for the l-th tray of VLM v associated with batch b, $C^b_{l\,v} = W^b_{l\,v} + P^b_{l\,v}$
- $L^b_{l\,v}$: Number of order lines that have to be collected on the l-th tray of VLM v for batch b.
- **p**: Picking time of one order line from a given tray when this tray is available.
- **r**: Time required by the VLM to store the current tray and extract the next one.

Based on the definitions above, we have the following relations:

(1) $C = W + P = \sum_{b=1}^{B} W^b + P^b = \sum_{b=1}^{B} \sum_{l=1}^{K_v} \sum_{v=1}^{V} (W_{l\,v}^b + P_{l\,v}^b)$

(2) $C = \sum_{b=1}^{B} C^b$

(3) $W = \sum_{b=1}^{B} W^b = \sum_{b=1}^{B} \sum_{l=1}^{K_v} \sum_{v=1}^{V} W_{l\,v}^b$

(4) $P = \sum_{b=1}^{B} P^b = \sum_{b=1}^{B} \sum_{l=1}^{K_v} \sum_{v=1}^{V} P_{l\,v}^b$

Using the above notation of the mathematical model one is able to compute the completion time C to pick B batches in the case of V VLMs. However, in the mathematical model mentioned above Nicolas et al. assume that both p, the picking time, and r, the storage time, are a constant for each item. These two parameters are of course not staying constant over time in reality.

In reality the picking time p will slightly vary for each picking action. Reasons for this are the quantity, the size of the items and the type of operations to be performed after collecting the items (e.g., labeling and/or scanning items before putting them into bins). However, Nicolas et al. argue that these factors are intrinsic to each warehouse and are difficult to estimate in practice. Furthermore, they mention that, according to a reliable French editor of warehouse management systems; *KLS Logistic Systems*, the variation in value of p between the different picking actions is not significant. Based on these reasonings Nicoles et al. decided to simplify their model and assume a constant value for p.

Next, the assumption used in the mathematical model is that the time required by the VLM to store the current tray and collect the next one has a constant value. According to Nicolas et al. this is a realistic assumption since the vertical moving speed of a VLM is high, close to 2 m/s according to Kardex Remstar, whereas the horizontal speed is much lower. This indicates that the time to collect a new tray depends on the horizontal movement. Therefore, Nicolas et al. concluded that it is justified to assume a constant value for r.

Mathematical model Meller & Klote
Next to the model of Nicolas et al. presented above there are more mathematical models in literature that describe the process of a VLM. One of those is the model introduced by Meller & Klote in 2004. Their model also makes it possible to compute the expected throughput time of storing/picking a batch of items from a VLM. Due to the fact that this model is less applicable to the current situation of Benchmark it is not discussed in detail in this section. However, in *Appendix D.1* the reader can find a detailed overview of the model of Meller & Klote.

5.2 – Optimal storage policy for Benchmark

As mentioned, in 2014 research was performed to determine the optimal storage assignment policy for Benchmark. This research was performed by Jansman in cooperation with Benchmark. At the time of this research Benchmark only just invested into the first six VLMs for their ZKDX1001 zone. So, at that moment the VLMs were still relatively new, as was the storage policy that was being used at the time.

Therefore, the aim of the research of Jansman was to perform research towards the optimal storage assignment policy for Benchmark. For this research Jansman compared the following three storage assignment policies:

1. Fixed locations: Each item has a fixed number of locations inside the VLM system where it can be stored. *This is the storage assignment policy that was being used by Benchmark at the time of the research.*

2. <u>Random storage policy</u>: This policy uses software that randomly assigns a location for each of the items that arrive. Assigning a location is done based on the bin type the items are placed in. *This is quite similar to the working method that Benchmark uses nowadays*.

3. <u>VDL-policy</u>: The final policy is based on the storage assignment policy used at VDL-ETG in Almelo. This policy also uses several fixed locations for each item. To store items into the VLM system with this policy a list of items is scanned. The *Kardex*-software then automatically chooses a sequence to store these items such that as little movements as possible are performed. For this policy it is also possible to let multiple VLMs work simultaneously which makes the storage process even faster.

Following these definitions Jansman performed an AHP-analysis to compare the three different methods of working. To compare these three storage assignment policies with each other Jansman used a total of five different criteria, each with their own weight factor. Each of the policies was assigned a score for each criterion, see *table 3*. This table is a translated version of the table in the research of Jansman, since that table is in Dutch.

	Fixed locations:	Random storage policy:	VDL-policy:	Weight factor
1. Number of actions:	0.61	0.10	0.29	0.07
2. Probability of human mistakes:	0.16	0.76	0.08	0.57
3. Speed of storage:	0.11	0.55	0.34	0.09
4. Speed of picking:	0.60	0.20	0.20	0.15
5. Flexibility and use of space:	0.09	0.82	0.09	0.12
Final score:	**0.24**	**0.63**	**0.14**	**1**

Figure 12 - Outcomes of Jansman's AHP-analysis

Based on this AHP-analysis Jansman concluded that the random storage policy would be the best storage assignment policy out of the three options. Main reasons for this are the fact that the random storage policy scores best on the speed of storage, probability of human mistakes and the flexibility and use of space. Following this Jansman advised Benchmark to implement the random storage policy, since this would be the most efficient policy. Today Benchmark is still using a storage policy that is closely related to this random storage policy.

The main shortcoming of this research is the fact that the three storage policies that are compared are focused on improving the storage speed. Although the speed of picking is also one of the five criteria, the main idea behind each of these storage policies is not to improve the picking speed. All three storage policies used by Jansman focus on storing a set of items as quickly as possible. Due to this shortcoming the storage policy that Benchmark currently uses is far from optimal when looking at the picking speed since currently the items are placed randomly inside the VLMs.

In literature there are plenty of storage policies that Jansman could have used of which the focus would also have been on improving the speed of picking. For example, using a class-based storage policy would lead to an increase in the speed of picking. However, currently Benchmark is not really willing to change their storage policy anymore. Therefore, the main focus of this research from now on is on optimizing the picking policy giving the current storage method that is used.

5.3 – Reducing the completion time

As just mentioned in the previous section Benchmark is not really willing to change the storage policy they currently use for the ZKDX1001 location. The other option to improve the speed of picking and thus reducing the total completion time is to use a different picking policy. Currently Benchmark uses the FIFO policy and the tray number that is brought forwards follows an ascending order. Changing the sequence in which the items are picked from the VLM might reduce the total completion time. This section of the literature review briefly discusses methods that could be used to improve the speed of picking. Some of these methods are straightforward and practical, while other methods are more theoretical.

One approach to optimizing the picking process is the use of time and motion studies. This method involves analyzing the time it takes for employees to complete the task of picking items, and identifying ways to eliminate unnecessary movements or steps that could be hindering productivity (Roth et al., 2014). This method is closely related to the lean theory that tends to eliminate all waste from the process by removing non-value adding activities (Rother and Shook, 2003).

Another method that is straightforward but has proven to be effective is the Pareto analysis. This method involves identifying the 20% of items that account for 80% of the picking activity, and give priority to these items by changing the layout of the warehouse or storage space. By prioritizing the most frequently picked items, this method can reduce the distance that employees need to travel to pick items, which will improve the efficiency (Wu et al., 2017).

Finally, simulation modeling is another method that can be used to optimize the picking process. This method involves creating a computer model of the picking process and simulating different scenarios to identify the most efficient configuration (Wang et al., 2019. Simulation modeling allows managers to evaluate different layouts, picking methods, and equipment configurations before implementing them in the real world, thereby reducing the risk of costly mistakes.

5.4 – Optimization techniques

Because of their NP-hardness the optimization problems mentioned in the previous section cannot be solved efficiently. To deal with this NP-hardness there are two optimization techniques that are commonly used: approximation algorithms and local search methods. Approximation algorithms tend to find provable near optimal solutions, often by searching for an upper or lower bound of a global optimum (Willamsion & Shmoys, 2010). Closely related to these approximation algorithms are the approximation heuristics. These heuristics present good, but not near optimal, solutions by following a certain pre-determined set of steps (Festa, 2014). These not near optimal solutions found by using a heuristic are often used as a starting point of a local search method. Local search methods sequentially explore the entire solution space. This is done by creating neighboring solutions and evaluating their solution values (Kleinberg & Tardos, 2005).

5.4.1 – Simulated annealing methods

One of the most used local search methods is the simulated annealing method. This algorithm is especially useful to escape from a local optimum and constantly find better neighboring solutions. For a more in-depth explanation of this method see *Appendix D.*2. This section illustrates the working of simulated annealing by applying it to the NP-hard parallel machine problem.

As previously mentioned optimizing the picking process of Benchmark is a NP-hard problem, so finding an optimal solution in polynomial time is not a possibility. One approach to solving this problem is therefore using the simulated annealing method. Simulated annealing can be used to find a near-optimal solution by iteratively improving a candidate solution. At each iteration, the method randomly selects two jobs and swaps their positions on the schedule. If the resulting solution has a lower completion time, it is accepted. If not, it is accepted with a certain probability

that decreases as the temperature decreases. By doing this the simulated annealing method is able to explore a large part of the solution space without getting stuck in a local optimum.

Several variations of simulated annealing have been proposed to solve NP-hard problems, including the parallel simulated annealing algorithm and the hybrid simulated annealing genetic algorithm. The parallel simulated annealing algorithm uses multiple processors to generate and evaluate multiple candidate solutions simultaneously. The goal, and also main advantage, of the parallel simulated annealing algorithm is that it speeds up the search process and is able to explore different parts of the solution space simultaneously (Ram et al., 1996). Exploring different parts of the solution space simultaneously leads to a more diverse set of solutions, and therefore a faster path to the optimal solution. However, parallel simulated annealing also has some limitations. The number of instances and the computational resources required to run them can increase significantly with the size of the problem. Additionally, communication issues between different instances can affect the overall performance of the algorithm. Therefore, the effectiveness of parallel simulated annealing algorithm depends on the problem size and the resources available for computation (Li, Wang, & Jin, 2017).

The hybrid simulated annealing genetic algorithm on the other hand is a combination of simulated annealing with a genetic algorithm. In the context of a parallel machine problem, the algorithm generates an initial set of candidate solutions using a heuristic method. Then, it applies a genetic algorithm to evolve and improve the quality of the solution set, followed by the simulated annealing method to explore the solution space and search for the optimal solution. By combining these two algorithms, the hybrid approach can efficiently explore a wide range of solutions, leading to a better overall performance (Mahapatra & Singh, 2014).

5.4.2 – Creating neighbor solutions

As explained the simulated annealing methods finds better solutions by exploring the entire solution space. Exploring this solution space is done by constantly creating new neighbor solutions. These neighbors are created by making minor changes to the current solution. This newly created neighbor is evaluated and compared to the current solution. The most frequently used operators to create a neighbor solution within a production schedule according to Nayeri et al. (2019) are:

- A - Swap operator: a randomly chosen production order is swapped with another randomly chosen production order to get a schedule change.
- B - Inversion operator: a certain number of consecutive production orders is selected, and their order is inversed to create a schedule change.
- C & D - Move operator: in this case a random production order is moved in front or after another randomly selected production order. Here there are two options; a left-shift, meaning that the production order is moved before the second selected production order or a right-shift, meaning that the production order is moved after the second selected production order

In *figure 13* below one can see an illustration to get a better understanding of these most commonly used operators. There are of course also many other operators that can be used, however the above mentioned are used most frequently within previous literature research.
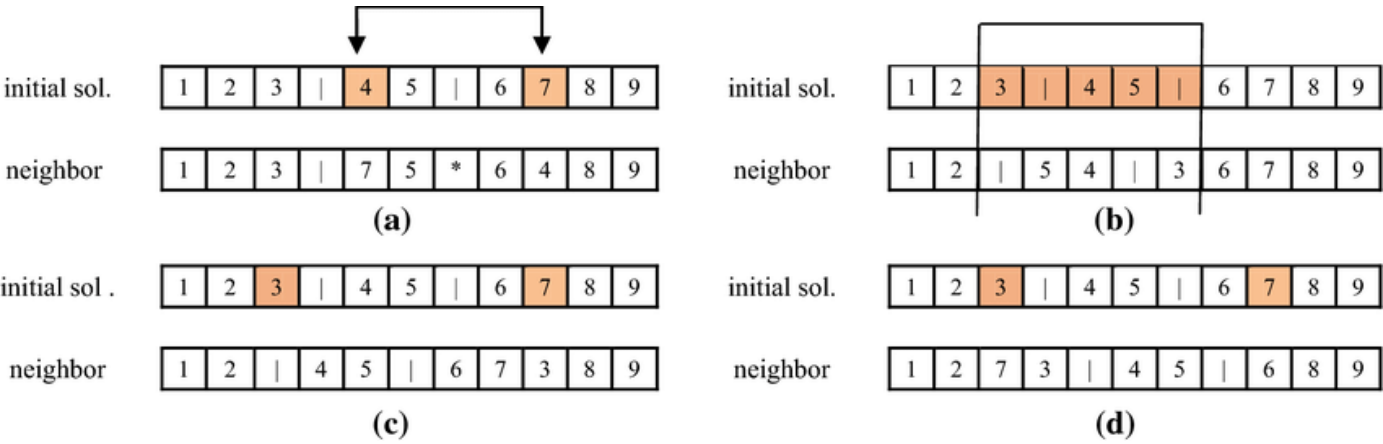
Figure 13 - Illustration of four commonly used operators (Nayeri et al., 2019)

5.5 – Conclusion

Despite the lack of papers discussing VLMs in general, and mathematical models of a VLM more specifically, the conclusion is that it is definitely possible to create a mathematical model of a VLM. In the first section the mathematical model of Nicolas et al. is discussed, this mathematical model is able to compute the completion time of picking a batch of items on a single or multiple VLM system. Another mathematical that is considered is the one of Meller & Klote, however the conclusion is that the one of Nicolas et al. is more applicable to the situation of Benchmark.

Next, the second section presents the thesis research performed by Jansman on the storage process of Benchmark. Although this research has shortcomings, the outcomes of this research are part of the reason Benchmark incorporated the random storage policy. This storage policy is something Benchmark is currently not really willing to change. The conclusion therefore is that the main focus of this thesis research is on optimizing the picking policy from now on.

In the third section of the literature review the situation at Benchmark is introduced as a NP-hard problem. Since this is a NP-hard problem and cannot be solved within polynomial time alternative optimization techniques are needed. Therefore, the fourth section discusses various literature sources about optimization techniques that could be used. One of those optimization techniques presented is the local search method, of which simulated annealing is the most known. The literature presented about optimization problems and the application of simulated annealing is helpful during the improvement of the picking process in the next chapter.

6. Models of the situation at Benchmark

The sixth chapter of this thesis report presents the improvement model that is created to improve the picking policy at Benchmark such that the total completion is minimized. Computing the completion time is done with the help of a mathematical model. To present both the mathematical model as the improvement model, the sixth chapter contains the following sections:

6.1 – Current situation at the ZDKX1001 zone   6.3 – The improvement model
6.2 – Mathematical model of a VLM   6.4 – Conclusion

6.1 – Current situation at the ZKDX1001 zone

In the current situation Benchmark has a total of eight VLMs in which items are stored in six different sized bin types. These six different sized bin types are divided over all the eight VLMs, meaning that each VLM contains bins of all six types. Inside each of these VLMs there are multiple trays on which the bins are stored. The number of bins on a single tray depends on the size of the bin. In general, each tray only contains bins of a single type, though there are some exceptions. After arrival, the incoming materials are stored in an appropriate bin inside one of the eight VLMs. So, for the mathematical model it is considered that the required items could be divided over all the eight VLMs. The mathematical model furthermore uses the assumption that each material has a fixed location, or multiple fixed locations, within the ZKDX1001 zone. The locations of the materials within the ZKDX1001 zone cannot be changed by both the mathematical- and improvement model.

As mentioned in *section 2.4* the eight VLMs are divided into four adjacent pairs, leading to a total of four picking stations. Each of these four-picking stations is served by a single order picker. Each of these picking stations can therefore be viewed as a multiple VLM system, with two VLMs and a single order picker. Meaning that currently the ZKDX1001 zone consists of four identical multiple VLM systems. Since these VLM systems are identical this means that a mathematical model should be created that describes a multiple VLM system with two VLMs and a single order picker. To compute the total completion time of picking a work order one could simply take the sum of the completion time of the four VLM picking stations.

6.2 – Mathematical model of a VLM

In this section the mathematical model, that represents the situation at the ZKDX1001 zone, is introduced. This mathematical model is based on the multiple VLM model from Nicolas et al. (2018), which is explained in detail in *section 5.1.2*.

6.2.1 – Mathematical model of a single picking station

Within this mathematical model each of the four picking stations is viewed as a separate picking station. This way the multiple VLM model from Nicolas et al. can be used to compute the completion time to pick all the required items at a single picking station. The mathematical model presented in this section is a model for a single picking station. To compute the total completion time of picking a work order this mathematical model is used for each of the four picking stations. The total completion time is then computed by taking the sum of the outcomes of all four picking stations. See below for the definition of the mathematical model for a single picking station:

Parameters:
V – {1 .. V}, Set of indices for the VLMs, where V is the total number of VLMs.
N – {1 .. N}, Set of indices for the items in a work order. Where N is the total number of items.
T$_v$ – {1 .. T$_v$}, Set of indices for the number of trays in VLM V, referred to with index *t*.
K$_v$ – Number of trays that have to be visited on VLM *v* for a work order
PickTime – Picking time of a single item from a given tray when this tray is available.
StoreTime – Time required by the VLM to store the current tray and extract the next one.

Continuation of the mathematical model:

W – Total waiting time of the picker for a work order. (This is the time when the picker is available, but has to wait for a tray)
P – Total picking time for a work order. This is the time during which the picker is collecting items from the trays
C – Total completion time to pick a work order, **C** = **W** + **P**

From this follows:
W_t^v – Picker's waiting time in front of the *t-th* tray of VLM *v* that is visited for a work order
L_t^v – Number of order lines that have to be collected on the t-*th* tray of VLM *v* for a work order
P_t^v – Time required to pick all items from the *t-th* tray of VLM *v* associated with a work order
C_t^v – Completion time for the *t-th* tray of VLM *v* associated with a work order, $C_t^v = W_t^v + P_t^v$

Based on the definitions above, we have the following relations:

(1) $P = \sum_{v=1}^{V} \sum_{t=1}^{K_v} P_t^v$

(2) $W = \sum_{v=1}^{V} \sum_{t=1}^{K_v} W_t^v$

(3) $C = W + P = \sum_{v=1}^{V} \sum_{t=1}^{K_v} (W_t^v + P_t^v)$

In the case of Benchmark there will be two adjacent VLMs that are working at the same time. This leads to the following formulas to compute the picking- and waiting time of the order picker:

(a) $W_t^1 = max(StoreTime - (L_{(t-1)}^2 * PickTime + W_{(t-1)}^2) ; 0)$

(b) $W_t^2 = max(StoreTime - (L_{(t-1)}^1 * PickTime + W_{(t-1)}^1) ; 0)$

(c) $P_t^v = L_t^v * PickTime$

In the mathematical model above, formulas 1 and 2 are used to determine the picking- and waiting time of an order picker for a single batch. Calculating the picking time is done by simply taking the total sum of picking times of each tray *t* that is brought forward from VLM *v*. This is described by formula 1. Calculation of the waiting time is done in a similar fashion, just take the total sum of the waiting times for each tray *t* from VLM *v*. The 2nd formula in the mathematical model shows this method. Finally, formula 3 in the mathematical model can be used to calculate the completion time of picking a work order, this is equal to the sum of the total waiting- and picking time.

However, to be able to calculate both the picking- and waiting time of the order picker one should first compute the individual picking- and waiting times per tray and VLM. Since there are only two adjacent VLMs working simultaneously at each picking location the logic behind the formula the calculate the waiting time is quite straightforward. Formulas *a* and *b* are used to calculate the waiting time of the order picker at respectively the first and second VLM. Both these formulas are almost similar, therefore explaining one is sufficient.

In an ideal situation the order picker is constantly switching between both VLMs. Upon arrival at the next VLM to pick the next items are two options. Ideally the next tray is already extracted by the VLM. Meaning that the order picker can start picking immediately, in this case there is no waiting time. The other option is that the VLM is still busy with storing the latest tray and extracting the next one. In this case the order picker has to wait for this next tray, and thus experiences waiting time. This waiting time is equal to the *StoreTime* of the current VLM minus the time the order picker spend at the previous VLM. This time spend is equal to the waiting time and total picking time at the previous VLM. By taking the maximum of both these options the mathematical model is able to compute the waiting time at both VLMs for each tray *t*.

Finally, formula c is used to calculate the picking time for each tray t that is extracted from one of the VLMs. This picking time is simply equal to the *PickTime* times the number of order lines that are picked from tray t.

6.2.2 – Example of the mathematical model of a single picking station

In this section a short example is given to further explain the mathematical model of a single picking station. This example consists, just like the real situation, of two VLMs each with two trays and a single picking station. For this example, a fictive work order of in total five different items is used, meaning that there are also five order lines. The items in this work order have the following characteristics:

Item	VLM-number	Tray-number
Item A	1	1
Item B	1	2
Item C	1	2
Item D	2	1
Item E	2	2

Table 3 - Input of the example work order

This set of items gives us the following values of the various parameters for the work order:

$$K_1 = 2, \ L_1^1 = 1, \ L_2^1 = 2 \quad and \quad K_2 = 2, \ L_1^2 = 1, \ L_2^2 = 1$$

In *figure 14* below an illustration is given how the completion time for this work order is computed. First both VLMs start with extracting the first tray, the waiting time of the order picker is then equal to the *StoreTime*. After waiting the order picker collects item A from the correct bin, after which VLM 1 starts storing this tray. The order picker then moves to the second VLM, here the picker immediately collects item D from the correct bin.

Following this the order picker moves back to the first VLM to pick items B & C. Here the order picker experiences waiting time if the time required to extract the second tray of VLM 1 (which is the *StoreTime*) is larger than the time elapsed to pick item A & D (which is two times the *PickTime*). If the tray is ready the order picker collects both items B & C from the correct bins. After this there are no more items from work order b stored in VLM 1.

Finally, the order picker needs to move back to the second VLM to collect the final item E. Here it again depends on the time required to extract the second tray of VLM 2 whether the order picker experiences waiting time. In case the tray is already extracted upon arrival there is no waiting time and item E is immediately collected. Else, the waiting time is equal to the time required to extract the second tray minus the waiting- and picking time spent at VLM 1. After item E is collected, the entire work order b is picked and the total completion time at this single picking station is known.
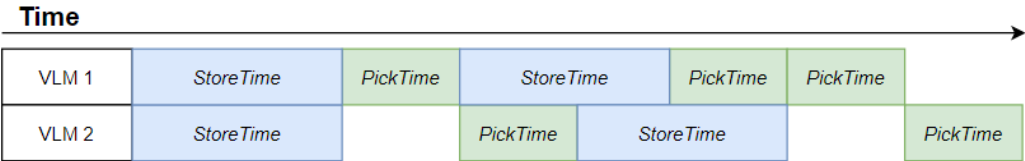

Figure 14 - Overview of the store and pick times

6.2.3 – Values of the parameters

For the mathematical model to correctly represent the situation at Benchmark, the values of the parameters *StoreTime* and *PickTime* are the most important. As mentioned in *section 5.1.2*, Nicolas et al. assume a constant value for both the *StoreTime* and the *PickTime*. In reality both these parameters will of course slightly vary over time. Especially the *PickTime* may vary based on the quantity, the size or the different operations that are performed after picking. However, to keep it feasible to create a mathematical model of the ZKDX1001 zone some assumptions and simplifications are made. Therefore, both parameters are assumed to have a constant value during each experiment. These constant values also makes it also more reasonable to compare the results of different experiments since no randomness is involved.

To get insight into realistic values for both these parameters, multiple measurements have been performed within the ZKDX1001 zone. In total ten measurements have been performed for both the *StoreTime* and the *PickTime*. The outcomes of these experiments are pictured in *table 4*. Based on these measurements the initial conclusion is that the values of both parameters are dependent on several factors. Therefore, the values are slightly different for all the measurements that have been performed. Based on the results of the measurements in this section the experiments are performed with a range of different values for both the *PickTime* and the *StoreTime*. Based on the outcomes the *PickTime* gets values of 20, 30 and 40 seconds, whereas the *StoreTime* gets values of 30, 40 and 50 seconds.

	StoreTime (s)	PickTime (s)
Observation 1	34,4	22,5
Observation 2	46,9	25,7
Observation 3	36,4	38,3
Observation 4	39,7	32,1
Observation 5	44,5	30,2
Observation 6	41,7	41,3
Observation 7	42,2	36,4
Observation 8	42	22,7
Observation 9	36,4	24
Observation 10	39,5	38,4
Average:	**40,37**	**31,16**
Standard deviation:	**3,89**	**7,17**

Table 4 - Outcomes of the observations

6.2.4 – Mathematical model with multiple picking stations

With the mathematical model of a single pick station and the values of the various parameters known, it is possible to create a mathematical model that represents the situation at Benchmark. This mathematical model is able to compute the total completion time of picking all the items of a work order at the four picking stations. The mathematical model is therefore used in the improvement model that is presented in *section 6.3*.

To compute to total completion time the model takes the sum of the completion time of each of the four single picking stations. See below for the formal definition of the mathematical model with four picking stations:

Parameters:
A – Set of indices for each picking station, referred to with index a. Current set: $\{1, 2, 3, 4\}$
C_a – Total completion time to pick items from a work order at picking station a, $C_a = W_a + P_a$
TotCom – The total completion time to pick a work order from multiple picking stations

To compute the C_a, W_a and P_a for each individual picking station the mathematical model of a single picking station should be used.

From this follows the following formula for the total completion time of picking :

$$TotCom = C_1 + C_2 + C_3 + C_4$$

6.3 – The improvement model

Next, an improvement model is created to improve the picking policy over all four different picking stations. The goal of this model is to reduce the total completion time of picking a set of items from the ZKDX1001 zone at Benchmark. Here the total completion time is computed with the help of the earlier introduced mathematical model. The model aims to reduce the completion time by using the alternative storage locations of certain items. As mentioned before each item can have multiple storage location, selecting an alternative location might reduce the completion time. This however means that the FIFO-policy currently used by Benchmark is no longer followed by this improvement model. In the section below this improvement model is explained in more detail. For an overview of the improvement model see *Appendix E.1*.

6.3.1 – Creating an initial solution

The improvement model consists of two separate steps, first an initial solution is created which is used as the starting point of the simulated annealing step. However, before starting the improvement model the user first selects values for the input variables of simulated annealing. Next, the user enters a list of all the items that need to be picked, internally at Benchmark this is referred to as a work order. Based on this input the first step of the improvement model can begin, which is creating an initial solution with the help of the FIFO-policy. This initial solution follows the FIFO-policy of Benchmark, so for each item the *oldest* location inside the ZKDX1001-zone is selected. See below for a brief overview of the steps followed to create this initial solution.

Steps to create an initial solution:

1. Sort the dataset of the ZKDX1001-zone on the *input date* in a descending order, such that the oldest *input date* is on top.
2. For each item in the work order search for the first storage location in the dataset. Select this location since this is the oldest location.
3. Use the mathematical model to compute the total completion time of the initial solution.

6.3.2 – Improving with simulated annealing

The next step in the improvement process is to improve the picking locations with the help of simulated annealing. The idea behind this local search method has already been explained in detail during *section 5.4.1*. Therefore, the main focus of this section is on explaining the method used to create neighbor solutions.

To create a neighbor solution first a random item is selected from all the items in the work order. This has to be an item that has at least two different storage locations within the ZKDX1001 zone, otherwise another item is chosen. The model then searches for all other locations the selected item is stored at and randomly select another storage location. See below for a brief overview of the various steps followed to create a neighbor solution.

Creation of a neighbor solution:

1. Randomly select an item from the work order.
2. Retrieve all the alternative storage locations of this item inside the ZKDX1001-zone.
3. If the number of alternative storage locations is equal to zero, return to step 1.
4. Randomly select one of the alternative storage locations.
5. Replace the current storage location with the alternative storage location in the work order.

These neighbor solutions are used by the simulated annealing method to improve the picking locations of a work order such that the completion time is minimized. The model computes the completion time of each neighbor solution based on which there is a certain probability that the neighbor solution is accepted. By analyzing a substantial amount of different neighbor solutions, the improvement model is able to reduce the completion time. In the end, the model presents the user with the values of each improved solution that was found in the process and also the best solution that is found. In the next chapter multiple examples of the way these results are presented can be viewed.

6.4 – Conclusion

The main conclusion of the first two sections is that it is possible to create a mathematical model that represents the situation at the ZKDX1001 zone. This mathematical model is based on a model first introduced by Nicolas et al. in 2018. Based on the values of the *PickTime* and *StoreTime* this model is able to compute the completion time of picking a set of items at a single picking station. Summing the completion times of all four separate picking stations makes it possible to compute the total completion time of picking all items of a work order.

This mathematical model being able to compute the completion time makes it possible to create an improvement model. The goal of this improvement model is to reduce the completion time of picking a work order by selecting alternative picking locations. As a starting point the model uses an initial solution, which is based on the FIFO-policy of Benchmark. Based on this initial solution the model then used simulated annealing to reduce the completion time. Based on initial findings the conclusion is that the model presented in this chapter is able to reduce the completion time at Benchmark. However, this needs to be validated with the help of experiments in the next chapter.

7. Experiments

The seventh chapter of this report describes the various experiments that are performed using the improvement model. The goal of these experiments is to validate the effectiveness of the model in reducing the total completion time of picking a work order. Therefore, this chapter contains the following sections:

7.1 – Experiment design
7.2 – Outcomes of the experiments

7.3 – Reducing the numbers of tray retrievals
7.4 – Conclusion

7.1 – Experiment design

The first section of this chapter explains the setup of the experiments to the reader. First, the work orders used for the experiments are briefly introduced. Secondly, the values of the various simulated annealing parameters that are used in the model are explained. Finally, the reader is introduced to the setup used during the experiments.

7.1.1 The work orders of the experiments

As mentioned before, the improvement model aims to improve the picking locations of a certain work order. During the experiments two different work orders, that each consist of a different bill of materials (BoM), are being used. These two work orders are used by Benchmark to produce end-products that have a frequent demand. One of these work orders is used for the production of a large cabinet, these large cabinets tend to have a large BoM. The other work order is used to produce a smaller cabinet, meaning that this BoM contains less materials. See *table 5* below for an overview of the frequency of these work orders and the number of materials in the BoM. For the materials in the BoM only items that are stored within the ZKDX1001 zone are considered.

Benchmark end-product	Nr. of materials in BoM	Demand
CABINET ORDER	92	5-6 per week
SMALL-BOX ORDER	31	4-5 per week

Table 5 - Overview of the BoM-items of both work orders

7.1.2 – Values of the parameters

Within the improvement model there are various parameters that have an influence on the outcomes. The most important are the *PickTime* and the *StoreTime* since these reflect the actual situation within the ZKDX1001 zone at Benchmark. The optimal values of both of these parameters has already been discussed in *section 6.2.3*. Based on the findings in that section the experiments are performed with a range of different values for both the *PickTime* and the *StoreTime*. The *PickTime* has values of 20, 30 and 40 seconds, whereas the *StoreTime* has values of 30, 40 and 50 seconds.

Next, a decision is made about the values of the various parameters that are used as input for the simulated annealing method. In total there are four different parameters involved in the simulated annealing method, the cooling factor (α), Markov chain length (M) and the start- and end temperature (T & E). The starting temperature makes sure that the acceptance ratio at the start is equal to 1. The end temperature on the other hand is such that the acceptance ratio is close to 0 when this temperature is reached. The cooling factor is chosen such that the graph of the acceptance ratio is decreasing slowly. Finally, the Markov chain length is based on a trade-off between the runtime and the number of alternative solutions explored.

See *table 6* for an overview of the values of the simulated annealing parameters.

Table 6 - Values of the SA-parameters

	AIR DIST.	WSRC
Start temperature (T)	100	100
End temperature (E)	15	15
Cooling factor (α)	0,95	0,95
Markov chain length (M)	50	25

7.1.3 – The experimental setup

In the following section the reader is introduced to the setup of the experiments. First, both the *PickTime* and *StoreTime* parameter having three different values means that a total of nine experiments is performed per work order. Secondly, the input values of the simulated annealing method are based on the values determined in the previous *section 7.1.2*. As mentioned, the values of the simulated annealing parameters are slightly different depending on the work order.

In both cases the initial solution, which is the current solution of Benchmark, is compared to the final solution found by performing the simulated annealing method. These different solutions are compared on the total completion time, which is the time needed to pick a certain work order

7.2 – Outcomes of the experiments

The next section of this seventh chapter presents the results of the experiments that have been performed with the improvement model. As mentioned, a total of nine experiments are performed for each of the two work orders, leading to 18 experiments in total. This section presents the results, starting with the *Cabinet Order* experiments, followed by the results of the *Small-Box* experiments.

7.2.1 – Results of the Small-Box Order experiments

The outcomes of the nine experiments that have been performed for the *Small-Box Order* work order can be viewed in *table 7* below. This table shows the total completion time of the initial solution, which is based on the FIFO location of the items. Next, the table presents the completion time of the final solution together with the percentage the completion time decreased compared to the initial solution. Finally, this table also shows the total run time of each of the experiments. In *Appendix F.1* the results of the nine experiments are presented in more detail.

Experiments Small-Box Order:	Initial completion time (s):	Improved completion time (s):	% decrease:	Run time (s):
1. *PickTime = 20, StoreTime = 30*	960	800	-16,7%	416
2. *PickTime = 20, StoreTime = 40*	1140	940	-17,5%	434
3. *PickTime = 20, StoreTime = 50*	1350	1120	-17,0%	496
4. *PickTime = 30, StoreTime = 30*	1170	990	-15,4%	370
5. *PickTime = 30, StoreTime = 40*	1350	1130	-16,3%	383
6. *PickTime = 30, StoreTime = 50*	1530	1270	-17,0%	417
7. *PickTime = 40, StoreTime = 30*	1470	1270	-13,6%	399
8. *PickTime = 40, StoreTime = 40*	1560	1360	-12,8%	405
9. *PickTime = 40, StoreTime = 50*	1740	1460	-16,1%	473

Table 7 - Outcomes of the Small-Box Order experiments

To give more background, the results of one of the experiments is discussed in more detail. *Figure 15* pictures the value of the total completion time of picking the work order over time for the second experiment. In this figure one can clearly see the effect of using a local search method. Initially the total completion time of picking the work order is quite high, but through exploitation of solutions the overall completion time is slowly reduced. To explore the entire solution space and avoid getting stuck in a local optimum it is however also possible that a solution with a higher completion time is accepted.
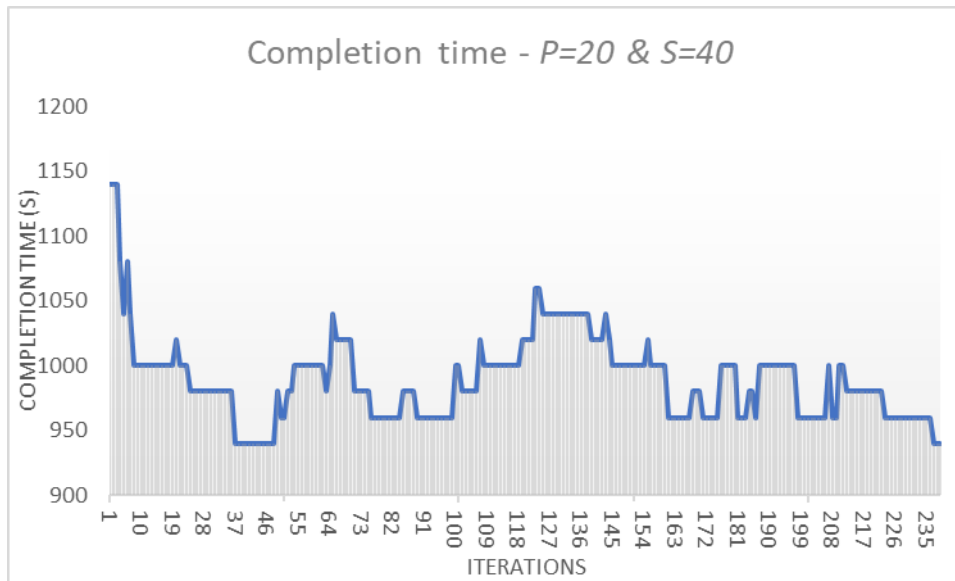
Figure 15 - Total completion time against the number of iterations

In the end the simulated annealing method managed to reduce the total completion time to a total of 940 seconds, which is a reduction of 200 seconds. The optimization model was able to reduce the completion time by reducing the number of trays to pick from 26 to 24. The model was able to do this by selecting alternative pick locations for a total of 8 items. In *figure 36* in *Appendix F.2* one can see the pick locations from the initial solution compared to the pick locations of the optimal solution.

7.2.1 – Results of the Cabinet Order experiments

Next, this section presents the outcomes of the nine experiments that have been performed for the *Cabinet Order*. The outcomes of these experiments are presented in *table 8* below. Furthermore, in *Appendix F.3* the results of the nine experiments are presented in more detail

Experiments Cabinet Order:	Initial completion time (s):	Improved completion time (s):	% decrease:	Run time (s):
1. *PickTime = 20, StoreTime = 30*	2370	2220	-6,3%	569
2. *PickTime = 20, StoreTime = 40*	2780	2580	-7,2%	604
3. *PickTime = 20, StoreTime = 50*	3250	2860	-12,0%	846
4. *PickTime = 30, StoreTime = 30*	2940	2670	-9,2%	908
5. *PickTime = 30, StoreTime = 40*	3350	3140	-6,3%	676
6. *PickTime = 30, StoreTime = 50*	3760	3430	-8,8%	549
7. *PickTime = 40, StoreTime = 30*	3730	3420	-8,3%	557
8. *PickTime = 40, StoreTime = 40*	3920	3760	-4,1%	551
9. *PickTime = 40, StoreTime = 50*	4330	3800	-12,2%	721

Table 8 - Outcomes of the Cabinet Order experiments

Based on the outcomes of the experiments the effect of the improvement model is once again pretty clear. It manages to reduce the completion time of picking all items between 5 to 10%. Therefore, the conclusion is that the improvement model is also helpful to reduce the completion time of picking larger work orders.

7.3 – Reducing the number of tray retrievals

The outcomes of the experiments presented in the previous section prove that the improvement model is able to reduce the completion time. However, to reach these outcomes the experiments required substantial computational times. In practice these computational times will not be feasible for Benchmark. Therefore, additional experiments are performed in which the objective of the model is to reduce the number of tray retrievals. The reasoning behind this is that having this objective requires less computational time, while still being able to find reasonable improvements. *Table 9* presents the outcomes of these experiments.

Experiments Small-Box Order	Initial solution:		Improved solution:			
Objective: Tray retrievals	Comp. time (s):	Trays:	Comp. time (s):	Trays:	% decrease:	Run time (s):
1. *PickTime = 20, StoreTime = 30*	960	26	860	22	-10,4%	178
2. *PickTime = 20, StoreTime = 40*	1140	26	1040	21	-8,8%	183
3. *PickTime = 20, StoreTime = 50*	1350	26	1230	21	-8,9%	194
4. *PickTime = 30, StoreTime = 30*	1170	26	1110	21	-5,1%	188
5. *PickTime = 30, StoreTime = 40*	1350	26	1230	21	-8,9%	178
6. *PickTime = 30, StoreTime = 50*	1530	26	1400	22	-8,5%	181
7. *PickTime = 40, StoreTime = 30*	1470	26	1400	21	-4,8%	187
8. *PickTime = 40, StoreTime = 40*	1560	26	1480	21	-5,1%	204
9. *PickTime = 40, StoreTime = 50*	1740	26	1680	22	-3,4%	188

Table 9 - Outcomes of the experiments with the objective of reducing the tray retrievals

The outcomes of the experiments show that the improvement model is able to reduce the number of tray retrievals. By doing so the completion time is also reduced by 5-10% compared to the initial solution. While this improvement is noteworthy, it is important to acknowledge that the decrease observed in *section 7.1.2* was more substantial. Furthermore, the run time in these additional experiments has been decreased by more than 50%. *Table 10* presents a clear comparison between the experiments that are performed with the different objectives.

	Reducing completion time		Reducing tray retrievals	
	Comp. time (s):	Run time (s):	Comp. time (s):	Run time (s):
Exp. 1	800	416	860	178
Exp. 2	940	434	1040	183
Exp. 3	1120	496	1230	194
Exp. 4	990	370	1110	188
Exp. 5	1130	383	1230	178
Exp. 6	1270	417	1400	181
Exp. 7	1270	399	1400	187
Exp. 8	1360	405	1480	204
Exp. 9	1460	473	1680	188

Table 10 - Comparison of the outcomes for both different objectives

7.4 – Conclusion

To validate the improvement model, a total of 18 experiments are performed. Based on the outcomes the improvement model is able to reduce the completion time by selecting alternative picking locations. The model is able to reduce the completion time by 10-20% in case of the *Small-Box Order* experiments, and by 5-15% in case of the *Cabinet Order* experiments. Therefore, this improvement model could be used by Benchmark in the future to reduce the time required for picking work orders. Especially for a work order with a large set of items a reduction of 10% is significant and will save serious costs. A potential downside of this optimization model is the computational time, which is already significant for a single work order. Especially considering the fact that on a regular day the warehouse of Benchmark is processing 80-100 work orders.

A possibility to reduce the computational time is to simplify the objective of the model. In *section 7.3* additional experiments are performed in which the objective is to reduce the number of tray retrievals. Based on these outcomes, the model is able to reduce the completion time by 5-10%. Furthermore, the run time in these additional experiments has been decreased by more than 50%.

8. Conclusions & discussion

The eight and concluding chapter presents an overview of the key findings and insights presented in the previous chapters. It summarizes the most significant challenges and opportunities in the current warehouse of Benchmark. Additionally, this chapter provides practical recommendations for improving the picking process that is currently in use. Finally, this last chapter discusses the effect of assumptions on the results and how further research could improve this research. This chapter contains the following sections:

8.1 – Conclusion   8.3 – Discussion & further research
8.2 – Implementation

8.1 – Conclusion

This research aims to answer the following research question:

> How can Benchmark **improve their insight** in the occupancy rate of their warehouse, both in the present and future, and use this insight **to improve their warehouse process?**

First, the third and fourth chapter of this research provide Benchmark with two different dashboard that can be used to improve their insight in the occupancy rate. The first dashboard is able to determine the current occupancy rate of the warehouse. This dashboard is based on an already existing dashboard of Benchmark, but is much more straightforward and therefore easier to use. The other dashboard is created from the ground up and is able to forecast the future occupancy rate based on the supply and demand. Since Benchmark has a good insight into their future supply and demand this dashboard is able to accurately predict the future occupancy rate. Therefore, it is recommended that Benchmark regularly uses this dashboard to notice a trend in the warehouse space that is needed.

Next, this research presents an improvement model that is able to reduce the total completion time of picking a work order from the warehouse. After performing 18 experiments the conclusion is that this improvement model can significantly reduce the overall picking time. By selecting alternative locations such that the number of trays and thus the store time is reduced the model can reduce the total completion time of picking a work order Based on the outcomes this model is able to reduce the total completion time by around 10 to 20%. Reducing the total completion time by at least 10% per work order is significant. This improves the efficiency of the warehouse of Benchmark and has a positive effect on the warehouse costs. A potential downside of the model is that the computational time is significant, but this is something that Benchmark can cope with by running the model overnight. Currently Benchmark already simulates their ERP-system overnight, this improvement model could be incorporated in this overnight simulation. Therefore, it is recommended to consider picking from alternative locations to improve the picking process at the warehouse of Benchmark.

To successfully implement the improvement model at Benchmark further research is necessary, especially to reduce the computational time. Based on the outcomes in *section 7.3*, using the number of tray retrievals as a simplified objective reduces the computational time of the model. However, using this simplified objective, results in a lower reduction of the completion time. Therefore, further research is needed before Benchmark can implement this simplified objective in order to reduce the computational time.

8.2 – Implementation

The main recommendation of the research is that Benchmark should consider using the improvement model to reduce the completion time of their picking process. However, in the current state this improvement model is not yet suited for use in practice, especially not for the scale of a company like Benchmark. The following section tends to list a few key steps that should be taken by Benchmark to successfully incorporate the improvement model in their picking process.

First, the improvement model must be designed to communicate with *PowerPick* in order to access the most recent data. This will enable the model to constantly retrieve data about the current situation within the ZKDX1001 zone. Secondly, the model should also be able to communicate with the ERP-system of Benchmark to gain an understanding of the active work orders and their bills of material. By integrating this information, the model can identify the work orders that are due to be picked the next day. During the overnight run, the model can then reduce the completion time of picking these work orders. Next, the model's outcomes must be presented in a way that the warehouse employees and *PowerPick* can use them. This requires careful consideration of the format currently used by both the warehouse employees and *PowerPick*. Ideally, the outcomes of the model would use this same format such that the current way of work can be maintained.

Finally, Benchmark needs to decide for which specific set of work orders the model can be used since the FIFO-policy is no longer followed. Furthermore, given the currently significant computational time, the model might not be able to incorporate all work orders within the overnight run. An idea here could be to prioritize work orders based on the average turnover rate of its items. Items with a higher turnover rate tend to have more alternative storage locations within the ZKDX1001 zone. Therefore, these work orders will have more options available for the model to reduce the completion time.

8.3 – Discussion

During this thesis research certain assumptions are made that have an effect on the outcomes of this research. This section briefly explains these assumptions and discusses their effect on the outcomes. Furthermore, this section discusses further research that can be done to improve this research and the improvement model.

8.3.1 – Assumptions & simplifications

First, the improvement model no longer supports the FIFO policy that Benchmark is currently using. This is however not an issue, since the largest customer of Benchmark does not demand Benchmark to use a FIFO picking policy. This specific customer is responsible for more than 70% of the used storage space at the ZKDX1001 zone, and responsible for an even larger percentage of the work orders. So, the improvement model is therefore useful in reducing the total completion time needed to pick work orders of this customer. A potential downside of no longer using this FIFO picking policy is that items from certain locations are less likely to get picked. Such a situation could occur in case this location is less ideal than the other locations this same item is stored at. This is not ideal for Benchmark, even more since certain items, such as batteries, have a shelf life. Therefore, to overcome this issue, the improvement model could be altered such that items on less ideal locations will be favored by the model. Furthermore, the shelf life of items should also be incorporated into the model, such that items never pass their expiry date.

Secondly, in the context of improving the picking process in a warehouse, it is essential to consider the picking time of each item. In reality this picking time is affected by numerous factors such as size and quantity. However, during this research the improvement model assumes the picking time to be the same for each item. This assumption is used as a simplification to ensure that the computational time of the improvement model stays feasible. Furthermore, having a constant picking time makes it easier to compare outcomes of the experiments since no randomness is involved. However, to

have a more realistic and reliable insight an addition to the improvement model would be to have variable picking times.

8.3.2 – Further research

A proposal to deal with variable picking times could be to assign weights to each item based on its level of difficulty to pick the specific item. For instance, items assigned with a weight of 1 would be considered easy to pick, resulting in a lower picking time in the model. On the opposite, materials assigned with a weight of 3 would be considered more difficult to pick, resulting in a higher picking time in the model. This approach would enable a more accurate representation of the real-life situation of the picking process. Therefore, incorporating weight-based picking time estimation into the improvement model is a promising direction for future research in this area.

Furthermore, the computational time of the improvement model is significant in its current state. Therefore, a good opportunity for further research is to explore the use of incremental completion time calculations in the improvement model. This means investigation should be performed into the most effective ways to break down the calculations into smaller, more manageable parts. Currently, the model performs an entire computation of the completion time for an alternative solution. Using incremental calculations enables the possibility to only perform a part of this computation. Overall, further research into the potential of incremental completion time calculations improves the efficiency of the improvement model while maintaining the accuracy.

Another way to reduce computational time is to simplify the objective to reducing the number of trays that are brought forward. The number of trays brought forward can provide a close approximation of the total completion time. By simplifying the objective in this way, calculations can be made simpler and quicker, leading to a significant reduction in computational time. However, it is important to note that simplifying the objective has an impact on the accuracy of the model's outcomes. Therefore, this approach should be carefully considered, and further research is necessary before implementation.

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Appendix A – Current situation

This appendix contains all the relevant information and data about the current situation at Benchmark in Almelo. The content of this appendix is discussed in the second chapter of this thesis report.

Appendix A.1 – Map of *warehouse 1000*
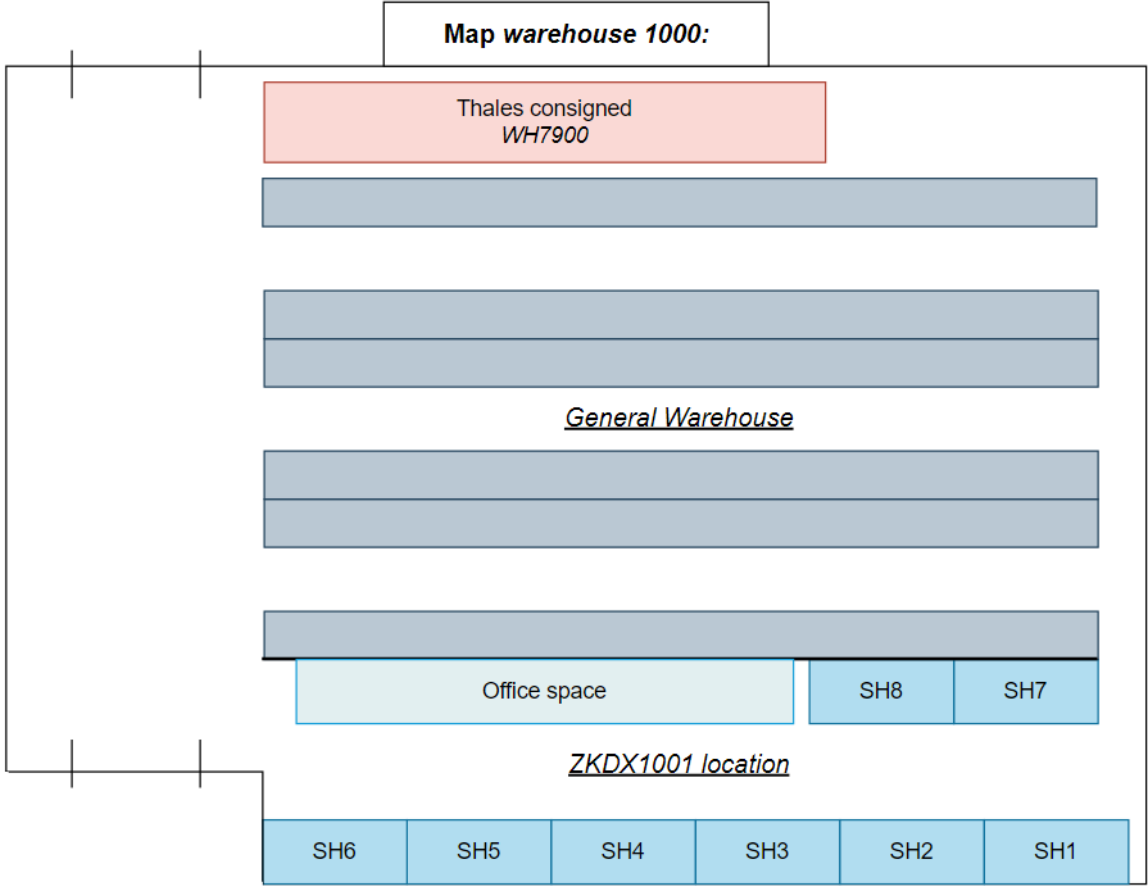
Figure 16 - Overview of warehouse 1000 at Benchmark

Appendix A.2 – Pictures of the process at the inbound department

Figure 17 - Empty bins stored at the inbound department

Figure 18 - Materials being stored into various bins

Appendix A.3 – Pictures of the ZKDX1001 zone

Figure 19 - Overview picture of the ZKDX1001 zone
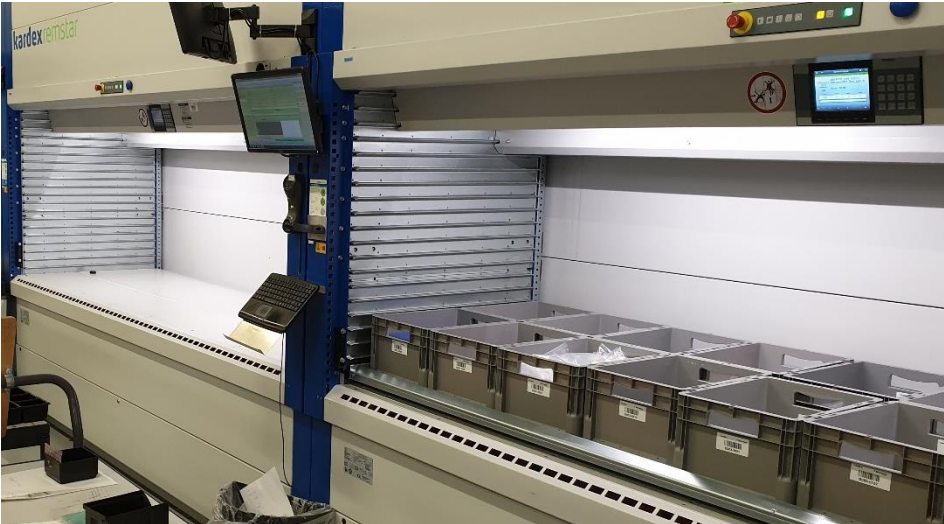
Figure 20 - Overview of a single picking station

Figure 21 - Bins on a tray inside a VLM

Figure 22 - A look inside a VLM at Benchmark

Appendix A.4 – Pictures of the general warehouse

Figure 23 - A lane between two pallet racks within the general warehouse

Appendix A.5 – Flowchart storage process of Benchmark

Figure 24 - Flowchart of the storage process at the ZKDX1001 zone and the general warehouse

Appendix A.6 – Dataset of the ZKDX1001 zone

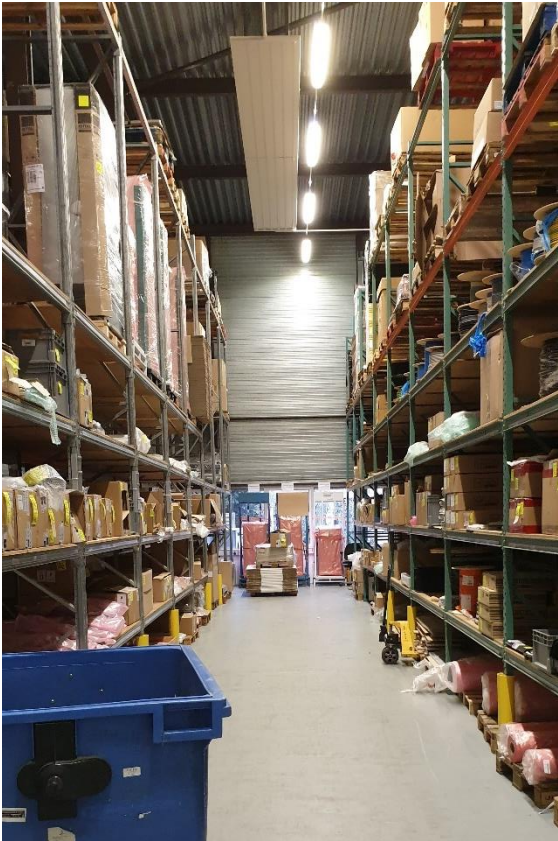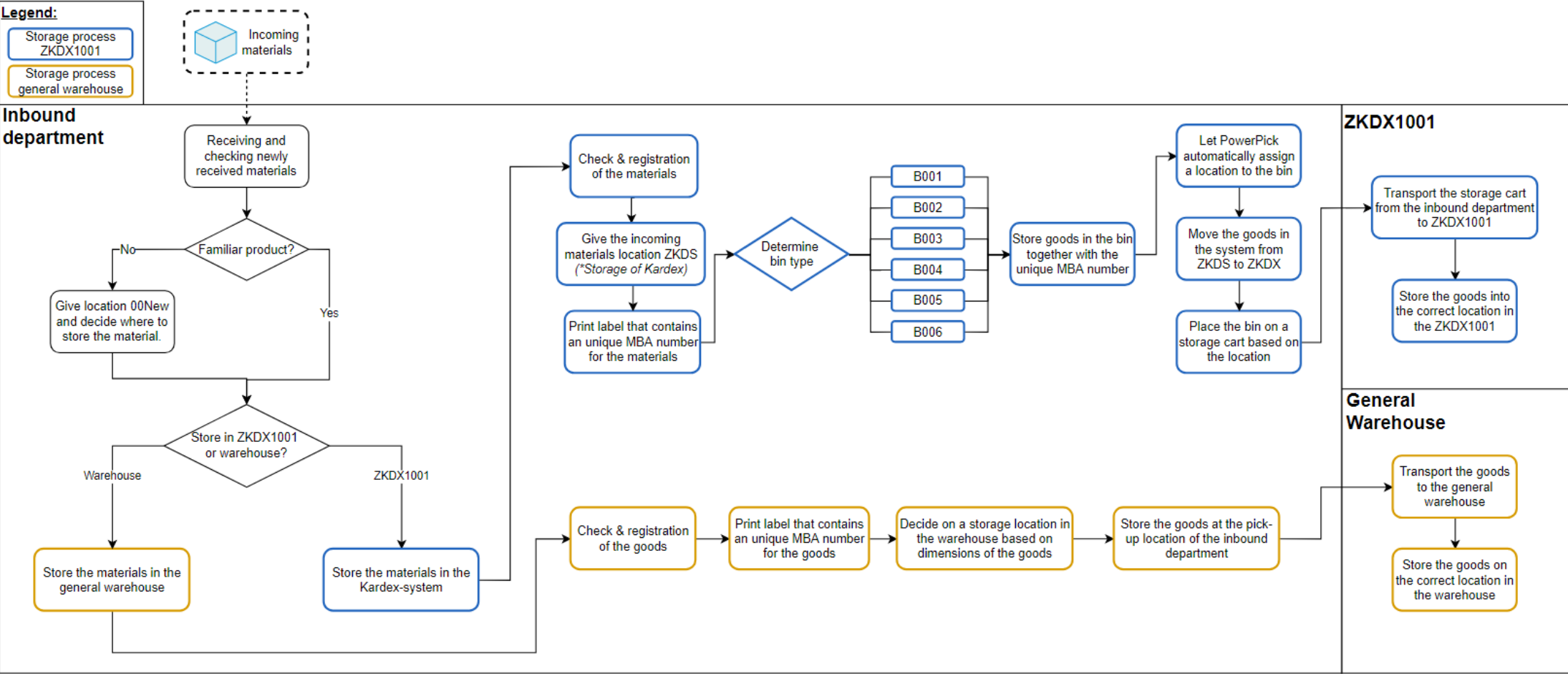|	A	B	C	D	E	F	G	H	
1	Location	Material	Information 1	Current quantity	Bin	Put date	Handling Unit	Lot	Count date
256	SH08-045-06-04				B002		B002-1606		
257	SH08-045-07-03				B002		B002-0293		
258	SH08-045-07-04				B002		B002-2108		
259	SH08-045-08-01				B002		B002-2721		
260	SH08-045-10-02				B002		B002-0888		
261	SH08-045-10-03				B002		B002-2972		
262	SH08-047-20-03				B001		B001-3556		
263	SH08-048-01-03				B001		B001-1704		
264	SH08-048-04-01				B001		B001-3644		
265	SH08-048-15-02				B001		B001-4183		
266	SH08-049-04-03				B001		B001-2063		
267	SH08-049-13-01				B001		B001-2724		
268	SH08-049-13-04				B001		B001-3703		
269	SH08-049-19-04				B001		B001-0441		
270	SH08-050-02-01				B001		B001-0084		
271	SH01-016-04-02	ABS6000_104_00121	LCD FERRITE	1000	B003	12-21-2021 7:35 AM	B003-0821	MBA426644	01-17-2022 7:29 AM
272	SH03-011-11-02	ABS6000_104_00121	LCD FERRITE	5	B001	08-25-2021 8:22 AM	B001-2225	MBA399602	01-17-2022 7:49 AM
273	SH03-017-06-02	ABS6000_104_00121	LCD FERRITE	100	B003	06-04-2021 3:12 PM	B003-0078	MBA400872	01-17-2022 7:54 AM
274	SH04-041-03-01	ABS6000_104_00121	LCD FERRITE	150	B003	10-11-2021 3:08 PM	B003-1153	MBA416823	01-17-2022 7:56 AM
275	SH07-039-04-02	ABS6000_105_00180	CON 9P PICOBLADE 51021-0900	1981	B001	08-12-2021 1:28 PM	B001-2461	MBA409302	01-24-2022 7:57 AM
276	SH01-009-06-02	ABS6000_105_00423	POWER INLET SOCKET	1	B002	09-22-2021 1:52 PM	B002-0216	MBA414541	02-07-2022 7:14 AM
277	SH07-015-07-02	ABS6000_105_00423	POWER INLET SOCKET	40	B003	09-30-2021 8:54 AM	B003-1119	MBA415524	02-07-2022 7:20 AM
278	SH07-044-02-04	ABS6000_105_00423	POWER INLET SOCKET	5	B001	11-19-2021 7:45 AM	B001-4374	MBA419822	02-07-2022 7:44 AM
279	SH07-044-17-02	ABS6000_105_00423	POWER INLET SOCKET	2	B001	11-19-2021 10:00 AM	B001-4036	MBA422294	02-07-2022 7:44 AM
280	SH01-008-10-01	ABS6000_105_00633	MOLEX 15134-0803 8 CIRCUIT WIR	43	B002	07-10-2021 8:58 AM	B002-0242	MBA406028	02-07-2022 7:13 AM
281	SH04-009-06-02	ABS6000_105_00633	MOLEX 15134-0803 8 CIRCUIT WIR	60	B002	01-31-2022 8:05 AM	B002-2922	MBA431400	02-07-2022 7:35 AM
282	SH04-010-03-02	ABS6000_105_00633	MOLEX 15134-0803 8 CIRCUIT WIR	100	B002	12-24-2021 8:13 AM	B002-1916	MBA427070	02-07-2022 7:39 AM
283	SH04-018-05-02	ABS6000_105_00633	MOLEX 15134-0803 8 CIRCUIT WIR	5	B003	05-01-2020 2:36 PM	B003-2097	MBA352320	02-07-2022 7:48 AM
284	SH02-044-06-03	ABS6000_105_00636	MOLEX 502380-1000 10 CIRCUITS	164	B001	11-12-2019 3:24 PM	B001-2416	MBA334524	01-17-2022 7:46 AM

Figure 25 - A snapshot of the exported dataset from PowerPick

Appendix A.7 – Available dashboard ZKDX1001 zone

8-11-2021
Dashboard Kardex Bezetting

Baktype	B001	B002	B003	B004	B005	B006	Totaal aantal bakken
Totaal aantal bakken	4159	2644	2240	920	650	374	10987
Totaal aantal lege bakken	49	19	97	0	39	11	215
Percentage lege bakken	1,18%	0,72%	4,33%	0,00%	6,00%	2,94%	1,96%

Materialen met meer dan 2 Lokaties   [Verversen]

Baktype	B001	B002	B003	B004	B005	B006	Totaal aantal bakken
Totaal aantal bakken	4159	2644	2240	920	650	374	10987
Lokatie besparing max 2 bakken	342	157	193	157	48	31	928
Besparing bij max 2 bakken	8,22%	5,94%	8,62%	17,07%	7,38%	8,29%	8,45%
Items met meer dan 2 bakken	211	121	105	91	30	12	570

Figure 26 - Currently available occupancy rate dashboard at Benchmark

Appendix A.8 – Occupancy rate ZKDX1001 zone in December & January

Date:	B001	B002	B003	B004	B005	B006	Overall:
1-dec	97,67%	97,47%	94,60%	83,37%	96,31%	96,52%	95,66%
6-dec	96,74%	97,24%	93,12%	90,00%	93,69%	94,65%	95,30%
8-dec	96,05%	96,67%	93,08%	91,96%	94,77%	93,85%	95,09%
13-dec	95,12%	95,54%	91,21%	92,39%	93,23%	90,37%	93,91%
15-dec	93,90%	93,61%	91,07%	91,96%	92,62%	89,57%	92,86%
20-dec	93,75%	94,93%	92,86%	93,26%	92,92%	89,04%	93,60%
22-dec	93,28%	96,03%	90,22%	94,89%	90,46%	88,77%	93,13%
3-jan	93,70%	97,09%	90,67%	98,48%	88,92%	87,17%	93,79%
5-jan	96,69%	97,77%	92,79%	98,89%	90,98%	89,90%	95,78%
10-jan	98,33%	97,96%	93,79%	99,13%	91,08%	95,45%	96,85%
12-jan	98,27%	96,79%	95,98%	99,19%	91,97%	95,67%	97,07%
17-jan	98,68%	99,36%	96,21%	99,67%	92,92%	97,33%	98,03%
19-jan	98,82%	99,28%	95,67%	100,00%	94,00%	97,06%	98,04%
24-jan	98,63%	98,64%	97,46%	99,78%	93,54%	100,00%	98,23%
26-jan	98,39%	99,13%	95,13%	97,07%	93,23%	99,20%	97,52%

Table 11 - Occupancy rate at the ZKDX1001 zone during December & January

Appendix B – Improving the insight

The content of this appendix is discussed in the third chapter of this thesis report. This appendix contains an overview of the dashboard that is created together with an instruction manual.

Appendix B.1 – Dashboard of the ZKDX1001

	Data from:		Data from:	
Load Kardex data	13-4-2022	Load demand data	29-4-2022	**Dashboard ZKDX1001:**

Occupancy rate:

Bin type:	B001	B002	B003	B004	B005	B006		Total bins:
Number of bins:	4399	2684	2240	920	650	374		11267
Number of empty bins:	152	132	47	2	29	39		401
Occupancy rate:	**96,54%**	**95,08%**	**97,90%**	**99,78%**	**95,54%**	**89,57%**		**96,44%**

Bins with no demand:

						Demand period:	365 days
Bin type:	B001	B002	B003	B004	B005	B006		Total bins:
Number of bins:	4399	2684	2240	920	650	374		11267
Bins with no demand:	1166	397	198	34	87	89		1971
% with no demand:	**26,51%**	**14,79%**	**8,84%**	**3,70%**	**13,38%**	**23,80%**		**17,49%**

Bins per customer:

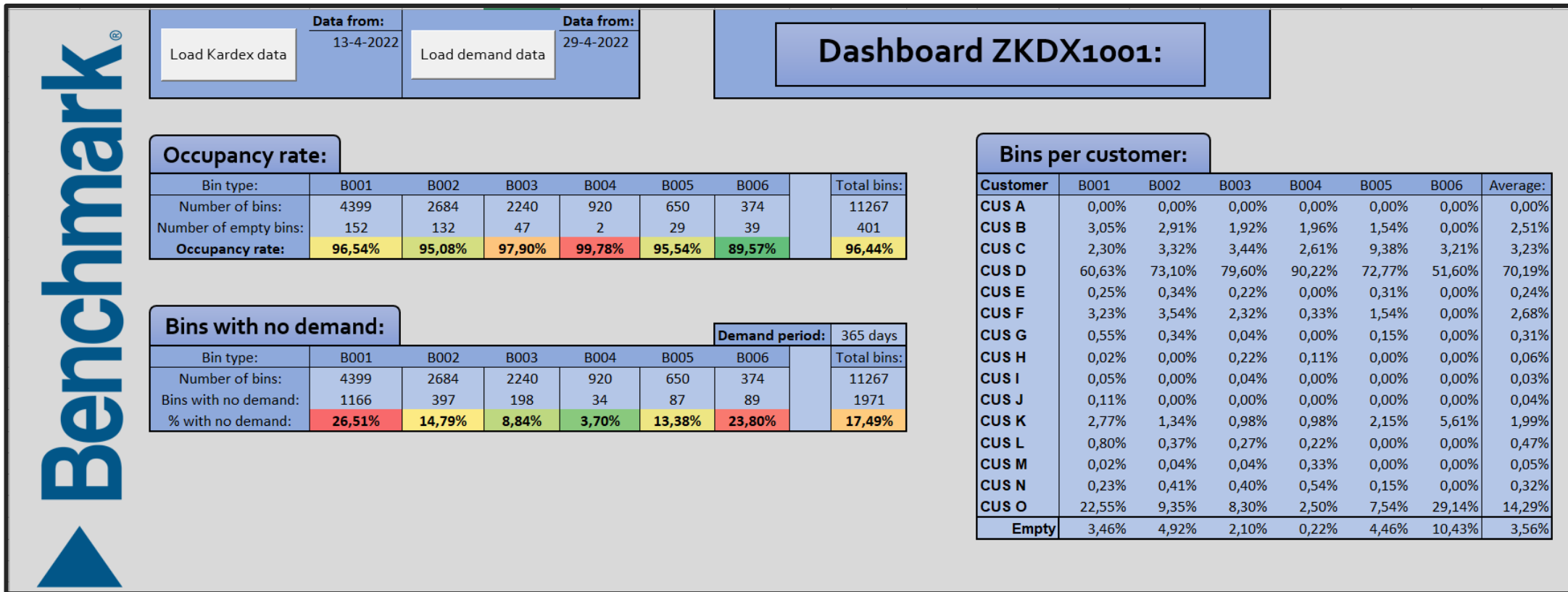| Customer	B001	B002	B003	B004	B005	B006	Average:
CUS A	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
CUS B	3,05%	2,91%	1,92%	1,96%	1,54%	0,00%	2,51%
CUS C	2,30%	3,32%	3,44%	2,61%	9,38%	3,21%	3,23%
CUS D	60,63%	73,10%	79,60%	90,22%	72,77%	51,60%	70,19%
CUS E	0,25%	0,34%	0,22%	0,00%	0,31%	0,00%	0,24%
CUS F	3,23%	3,54%	2,32%	0,33%	1,54%	0,00%	2,68%
CUS G	0,55%	0,34%	0,04%	0,00%	0,15%	0,00%	0,31%
CUS H	0,02%	0,00%	0,22%	0,11%	0,00%	0,00%	0,06%
CUS I	0,05%	0,00%	0,04%	0,00%	0,00%	0,00%	0,03%
CUS J	0,11%	0,00%	0,00%	0,00%	0,00%	0,00%	0,04%
CUS K	2,77%	1,34%	0,98%	0,98%	2,15%	5,61%	1,99%
CUS L	0,80%	0,37%	0,27%	0,22%	0,00%	0,00%	0,47%
CUS M	0,02%	0,04%	0,04%	0,33%	0,00%	0,00%	0,05%
CUS N	0,23%	0,41%	0,40%	0,54%	0,15%	0,00%	0,32%
CUS O	22,55%	9,35%	8,30%	2,50%	7,54%	29,14%	14,29%
Empty	3,46%	4,92%	2,10%	0,22%	4,46%	10,43%	3,56%

Figure 27 - Overview of the dashboard of the occupancy rate

Appendix C – Forecasting the occupancy rate

The content of this appendix is discussed in the fourth chapter of this thesis report. This appendix contains all the relevant figures/tables that have been useful in the creation of a dashboard to forecast the future occupancy rate. Furthermore, this appendix contains an overview of the dashboard that is created to forecast the future occupancy rate at Benchmark.

Appendix C.1 – Time-phased planning overview

See below for an insight in the exported Excel-file of the *time-phased planning overview* of Benchmark. As mentioned this Excel-file is exported from the ERP-system of Benchmark.

Part	Date	Supply	Deman
ABS6000_107_00145	29-4-2022	100,00	0,00
ABS6000_107_00145	29-4-2022	100,00	0,00
ABS6020_242_00521	29-4-2022	39,00	0,00
ABS6020_242_00551	29-4-2022	36,00	0,00
ABS6020_242_00641	29-4-2022	60,00	0,00
ABS6020_243_00051	29-4-2022	40,00	0,00
ABS6020_243_00061	29-4-2022	38,00	0,00
AIB7001_107_00003	2-5-2022	0,00	21,00
AIB4022_241_12371	3-5-2022	0,00	60,00
AIB4022_241_12371	3-5-2022	0,00	30,00
AIB4022_301_10491	4-5-2022	0,00	7,00
AIB7001_105_00006	4-5-2022	100,00	0,00

Figure 28 - Snapshot of the exported time-phased planning overview

Appendix C.2 – Bin quantities

Figure 29 below shows an insight into the dataset that is created for the quantities of an item that fit in a certain bin-type. As already mentioned in *section 4.2* this dataset is based on historic data of the last five years of the ZKDX1001 zone. Item C, highlighted in green, cannot be stored in a B001 bin based on this dataset. However, it can be stored in a B002, B003 and B004 bin as long as the quantities are below respectively 10, 50 and 180. Another example is item H, highlighted in blue, from this item no historic data is available. So, the bin-type of this item will be decided upon by using the historic probabilities as mentioned in *section 4.2*

Part	B001	B002	B003	B004	B005	B006
Item A	50	0	150	0	0	0
Item B	2000	0	0	0	0	0
Item C	0	10	50	180	0	0
Item D	0	50	250	0	0	0
Item E	500	0	0	0	0	0
Item F	1000	0	0	0	0	0
Item G	60	0	0	0	0	0
Item H	0	0	0	0	0	0

Figure 29 - Snapshot of the historic dataset of the optimal bin quantities

Appendix C.3 – Flow diagram of supply process

See below, in *figure 30*, for a flow diagram of the process that is being used to translate the incoming supply into occupied bins at the ZKDX1001 zone.
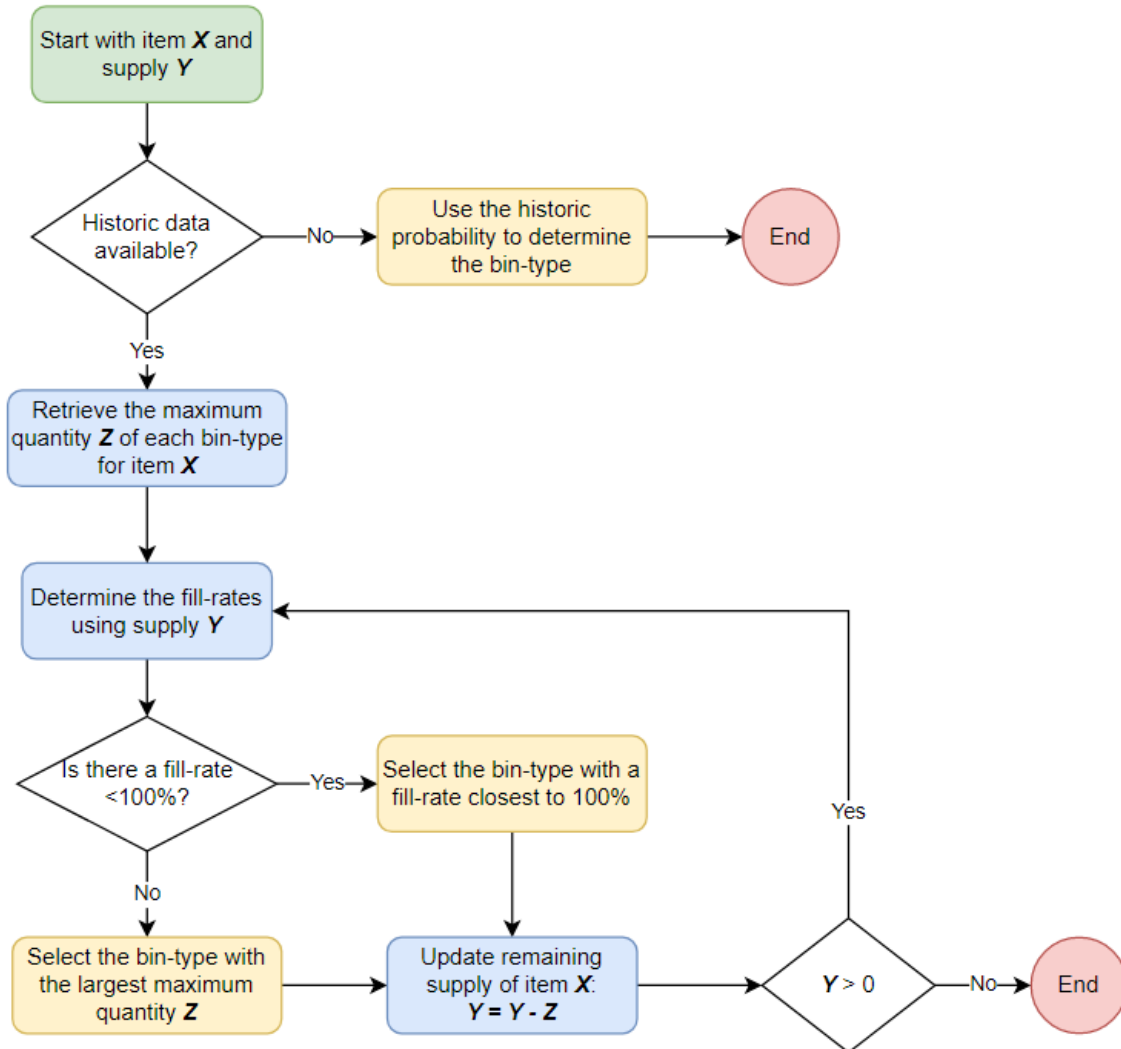

Figure 30 - Flow diagram of the process in case of supply

Appendix C.4 – Flow diagram of demand process

Figure 31 below contains a flow diagram that describes the process that is being used to translate demand into empty bins at the ZKDX1001 zone.
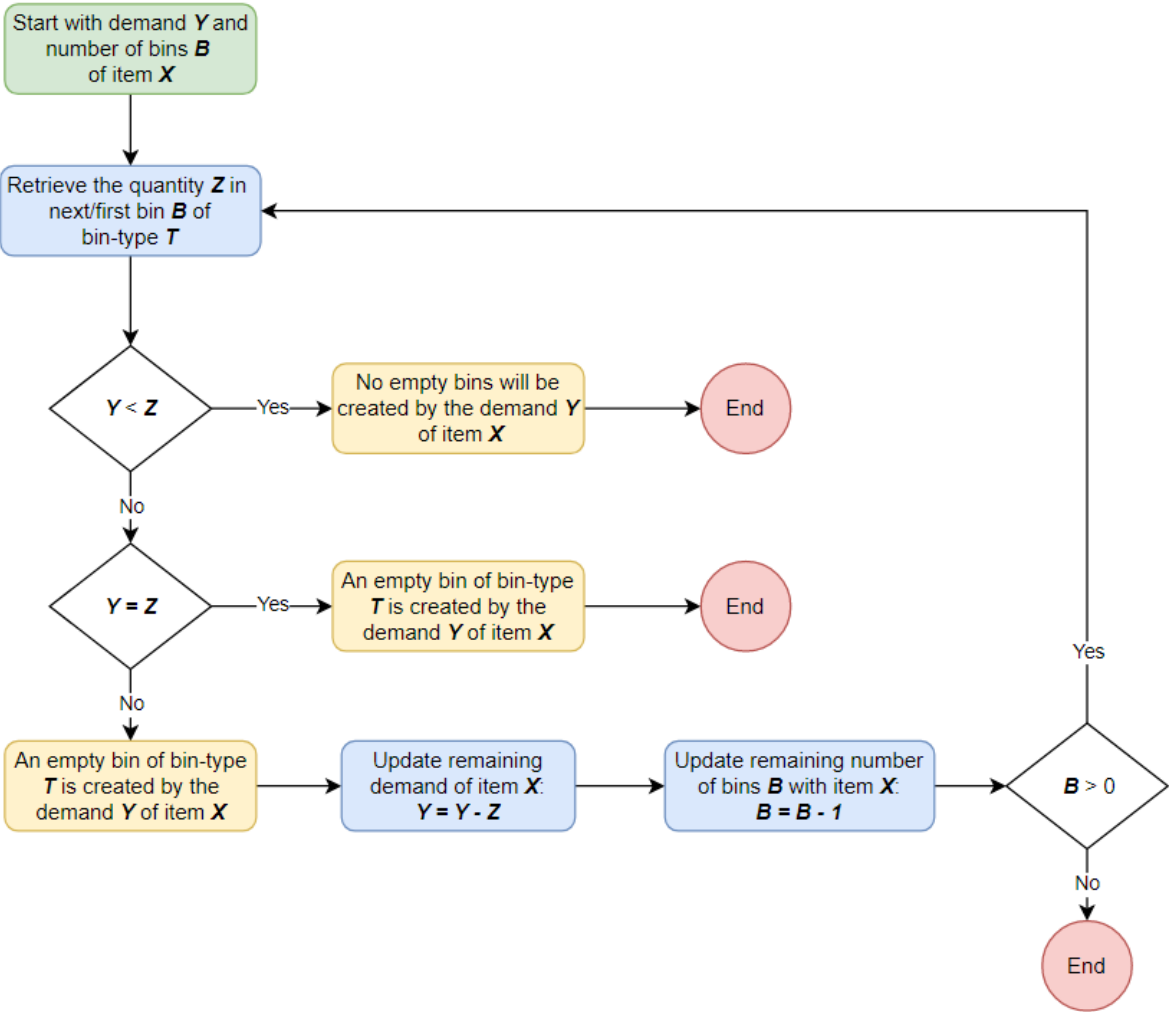

Figure 31 - Flow diagram of the process in case of demand

Appendix D – Literature review

The content of this appendix is discussed in the fifth chapter of this thesis report. This appendix contains an overview of the figures/tables of various literature sources that are mentioned in the fifth chapter.

Appendix D.1 – The mathematical model of Meller & Klote

This section contains the literature review towards the mathematical model of a VLM that has been introduced by Meller & Klote back in 2014. This mathematical model is briefly introduced in section 5.1.2 of the literature review.

Mathematical model Meller & Klote:
Despite the lack of papers regarding efficient storage inside a VLM, Dukic et al. concluded that there is in fact are multiple models for a single VLM. This model is introduced by Meller & Klote in 2004, with this model it is possible to compute the expected throughput time of storing or picking a batch of items. The single VLM model assumes a single VLM system with one pick location and one human picker picking or storing items. Based on a batch of items the model can compute the throughput time as a sum of the expected retrieval time and picking/storage time. Furthermore, the model also considers that a VLM always performs dual command cycles, except the first and last command. A dual command cycle means that a picker goes to the first location to store an item, then to a second

H – height of the VLM rack
h_1, h_2, h_3 – height of the VLM sections
v – velocity of the VLM crane
m – number of trays in a VLM system
n – number of items to pick
$t_{a/d}$ – delay time per VLM trip due to acceleration and deceleration
$t_{p/d}$ – delay time to pick up or deposit a tray
t_{oi} – expected travel time from picking opening to section i
t_{ij} – expected travel time between i and j
p_1, p_2, p_3 – probabilities of a storage/retrieval of a tray in each sector
p_{ij} – probability that dual command cycle stores a tray in i and retrieves a tray in section j
E[SC] – expected VLM crane travel time for single command
E[DC] – expected VLM crane travel time for dual command
T[SC] – expected VLM crane cycle time for single command
T[DC] – expected VLM crane cycle time for dual command
$E^V[R(n,m)]$ – the VLM retrieval time
$E^V[P(n,m)]$ – the picking time of the items
$E^V[T(n,m)]$ – the expected time to pick n items from m trays

Then we have the following expressions:

$$E(SC) = \sum_{i=1}^{3} 2t_{0i} * p_i$$

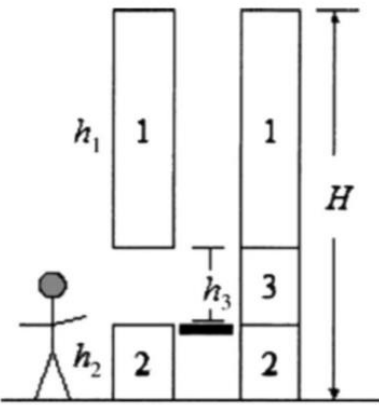$$E(DC) = \sum_{i=1}^{3}\sum_{j=1}^{3} (t_{0i} + t_{ij} + t_{0j}) * p_i p_j$$

$$T(SC) = E(SC) + 2t_{a/d} + 2t_{p/d}$$
$$T(DC) = E(DC) + 3t_{a/d} + 4t_{p/d}$$
$$E^V[R(n,m)] = T[SC] + (E[S(n,m)] - 1) * T[DC] + T[SC]$$
$$E^V[P(n,m)] = np$$
$$E^V[T(n,m)] = E^V[R(n,m)] + E^V[P(n,m)] = 2T[SC] + (1$$

location to pick an item before returning to the starting point (Pohl et al., 2009). In the case of a VLM this means that a tray is stored, then immediately a new tray is collected and returned to the pick location. The notation of the single VLM model of Meller & Klote can be found below, together with an illustration of a VLM.

The mathematical model presented above can only be used in case of a single VLM with a single picker. However, in practice, most of the warehouses will instead contain several VLMs working together. This was also noticed by Meller & Klote; therefore, they produced a model that is able to estimate the utilization of a picker in a system with several VLMs. This utilization can be used to determine the cycle time to pick a set of items. For this they use a closed queueing network model from Gelenbe (1975), which is described by Bozer & White (1996).

The same mathematical model that is described above is used, although with slightly different parameters. The number of VLMs inside the system will be denoted as c VLMs. Based on this c the order picker will work with 1/cth capacity. Such a representation is used by Bozer & White (1996) and can be seen in *figure 32.C*.
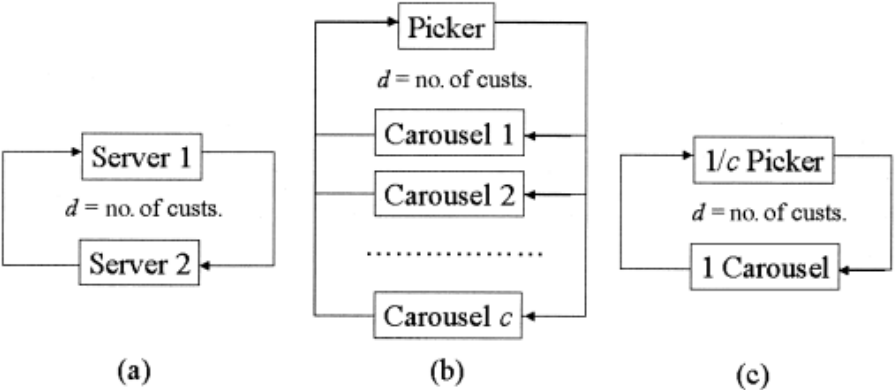

Figure 32 - Illustration of a closed queueing network model (Bozer & White, 1996)

The expected picker utilization is denoted as E[PU], the average rotation time between VLM stops as R and the average time spent picking at each stop equal to P. Both values of R and P are obtained from the single VLM model presented earlier in this section. Finally, the time for a picker to move from one VLM to the other is denoted by w. With these newly introduced parameters it is possible to determine the cycle time to pick a set of items from c VLMs. Therefore, the following definitions will be added to the single VLM model introduced earlier (see next page):

E[PU] – expected picker utilization
c – the number of VLMs inside the system
R – average rotation time between VLM stops
P – average time spent picking at each VLM stop
w – moving time between VLMs for a picker
W – average time the picker has to wait upon arriving at a VLM to start picking

Then we can calculate the expected cycle time and expected carousel utilization:

$$E^C[T(c,n,m)] = \frac{c}{E[PU]}\,(E[S(n,m)]\,(P+w))$$

$$E(CU) = \frac{(E[S(n,m)] * R)}{E^C[T(c,n,m)]}$$

To calculate the E[PU] we use the notation from Bozer & White (1996):

$$\lambda = 1/R$$
$$\mu = 1/[c((P+w)+W]$$
$$\rho = \lambda/\mu$$
$$\alpha = \lambda^3 V_R + c\mu^3 V_P$$
$$\beta = 2(\lambda - \mu)/\alpha$$
$$\Omega = \rho/(1 - \rho^2 e^{\beta(d(c)-1)})$$
$$E[PU] = 1 - \Omega[\frac{1-\rho}{\rho}]$$
$$W = (1 - E[PU])E[t']$$

Appendix D.2 – The simulated annealing method

The following section contains a more detailed explanation of the simulated annealing method that can be used to improve a solution of the parallel machine scheduling problem. This simulated annealing method is introduced in *section 5.4.1*

One of the most used local search methods is the simulated annealing method. This algorithm is especially useful to escape from a local optimum and constantly find better neighboring solutions. The algorithm starts with an initial solution, a starting temperature T and a cooling factor α. This initial solution is often created by using a heuristic, the values of the starting temperature and the cooling factor are decided upon by the user. Each iteration of simulated annealing starts with the creation of a new neighbor solution (see *section 5.4.2*) by slightly adjusting the current solution. If the objective value of this neighbor solution is better this neighbor solution is accepted, else the solution can be accepted based on a Boltzmann probability distribution. If a random number R is larger than the outcome of the Boltzmann distribution then the neighbor will be accepted despite being worse than the previous one. The algorithm uses this distribution to avoid getting stuck in a local optimum.

After evaluating M neighbor solutions, the temperature T is decreased by the cooling factor α. Here M is the Markov chain length, which value is decided upon beforehand by the user. In the beginning, when T is still high, most neighbor solutions should be accepted despite being inferior. Accepting a lot of inferior solutions at the start ensures that the entire solution space is evaluated. As the temperature gets lower generally only better solutions are accepted. This algorithm continues until the end temperature E is reached; a value that is also decided upon beforehand by the user. As soon as the end temperature is reached the simulated annealing algorithm stops running and presents the best-found solution. See *figure 33* below for a pseudocode of the simulated annealing method.

```
input  : s₀, T₀, T_c, α, SA_max
output: Best solution s*

1   numIter ← 0;
2   s* ← s₀;
3   s ← s₀;
4   T ← T₀;
5   while T > T_c do
6       while numIter < SA_max do
7           numIter ← numIter + 1;
8           s' ← GenerateNeighbor(s) ;
9           Δf ← f(s') − f(s*) ;
10          if Δf < 0 then
11              s ← s';
12              if f(s') < f(s*) then
13                  s* ← s';
14              end
15          end
16          else
17              Generate random number x ∈ [0, 1];
18              if x < e^{−Δ/T} then
19                  s ← s';
20              end
21          end
22      end
23      T ← T * α;
24      numIter ← 0;
25  end
```

Algorithm 1: SA algorithm pseudocode

Figure 33 - Pseudocode of the simulated annealing method (Zampriolli & Amaral, 2021)

In total there are four different parameters of which the value should be chosen beforehand, the cooling factor (α), Markov chain length (M) and the start- and end temperature (T & E). There is not a standard guideline for determining the values of the parameters in the algorithm. These parameter values have to be determined by performing multiple experiments. To decide on the optimal parameter values, one could use the acceptance ratio, which is the number of accepted solutions compared to the total evaluated ones. This acceptance ratio should be close to one at the start and slowly decline as the temperature decreases. When getting close to the end temperature this acceptance ratio should be reaching zero.

Appendix E – Improvement model

The following appendix contains content discussed in the sixth chapter of the thesis report. This appendix contains an overview of the improvement model.

Appendix E.1 – Overview of the improvement model

This section presents the reader with an overview of the improvement model. On the left the user can find the various input parameters such as the *PickTime* and the *StoreTime*. Next, below the orange-colored cells the user puts in all the items that are in the work order. Finally, the solution with the improved picking locations will be presented below the green-colored cells. Next to that the improvement model will also show the results of both the initial as the improved completion time.

Tool input:			Current picking locations:					Improved picking locations:			
PickTime (s):	30		Item:	Location:	Results:			Item:	Location:	Results:	
			ASM4022_430_06461-LF		Time spend picking:					Time spend picking:	
StoreTime (s):	50		ASM4022_430_06531-LF		Time spend waiting:					Time spend waiting:	
			ASM4022_438_39500-LF		Total completion time:					Total completion time:	
Simulated Annealing input:			ASM4022_438_39511-LF								
Start Temp:	100		ASM4022_438_42624-LF								
			ASM4022_438_77173-LF								
End Temp:	15		ASM0051_244_00341-P							Start!	
			ASM4022_430_06461-LF								
Alpha:	0,95		ASM4022_430_06531-LF								
			ASM4022_436_59191-LF								
Markov Chain:	10		ASM4022_438_39500-LF							Clear!	
			ASM4022_438_39512-LF								
Statistics:			ASM4022_489_20833-LF								
Runtime (s):	549		ASM4022_430_06461-LF								
			ASM4022_436_81252-LF								
			ASM4022_438_34078-LF								
			ASM4022_438_38922-LF								
			ASM4022_438_39500-LF								
			ASM4022_438_39511-LF								
			ASM4022_438_39512-LF								

Figure 34 - Overview of the improvement model

Appendix F – Experiments

The following appendix contains content discussed in the seventh chapter of the thesis report. This appendix contains a more in-depth insight into the outcomes of the experiments.

Appendix F.1 – Outcomes of the *Small-Box Order* experiments

This section provides a more in-depth insight into the outcomes of the experiments that have been performed with the optimization model of multiple picking stations for the *Small-Box Order* work order.
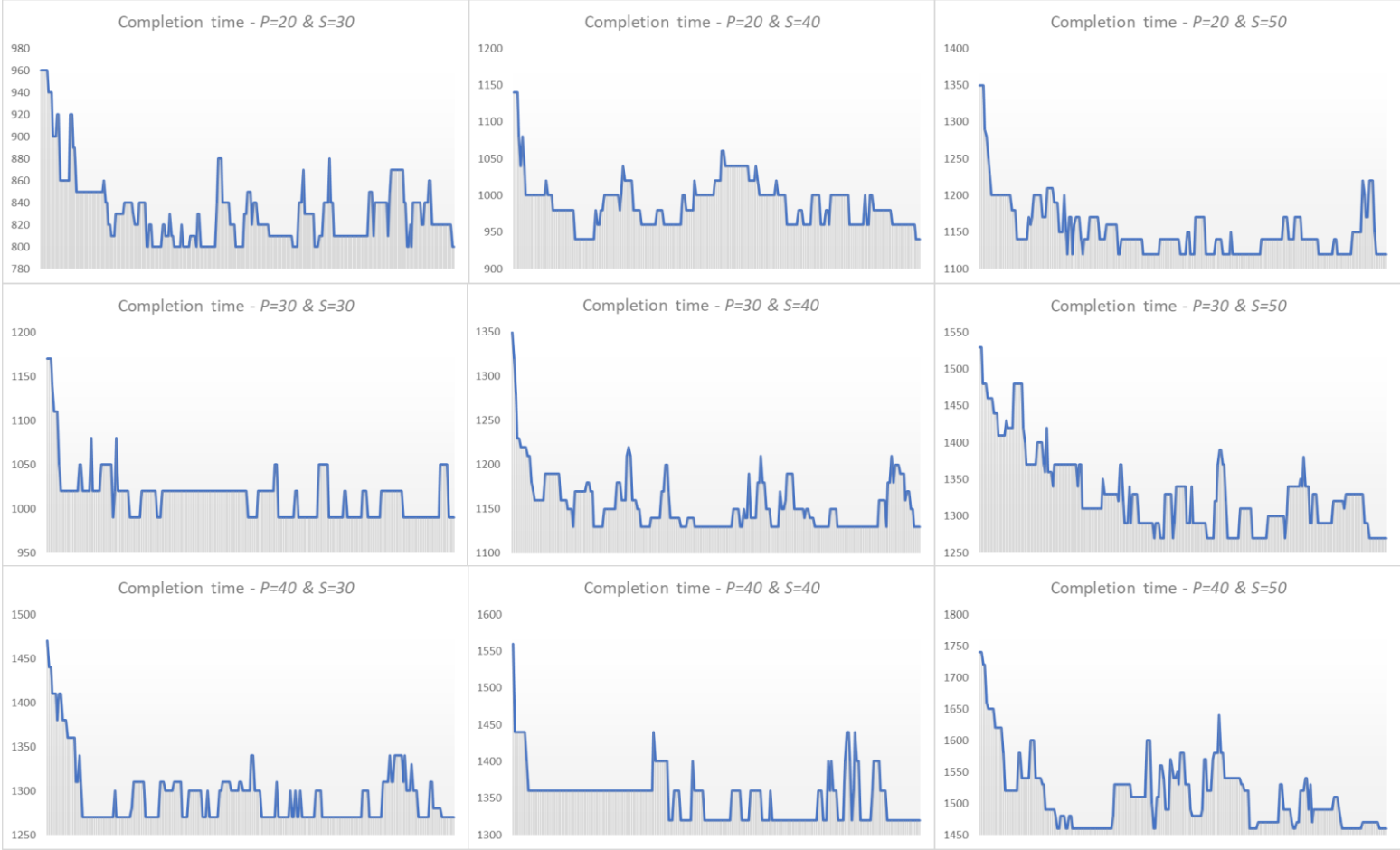

Figure 35 - Outcomes of the Small-Box Order experiments

Appendix F.2 – Differences in picking locations

The figure below presents the picking locations of the initial solution and the optimal solution. Highlighted in green are the differences in picking locations.

Item:	Location:	Item:	Location:
ASM4022_430_06461-LF	SH07-007-08-01	ASM4022_430_06461-LF	SH07-007-08-01
ASM4022_438_39500-LF	SH05-014-02-02	ASM4022_438_39500-LF	SH05-014-02-02
ASM4022_438_39511-LF	SH04-009-10-02	ASM4022_438_39511-LF	SH04-009-10-02
ASM4022_438_42624-LF	SH02-051-08-01	ASM4022_438_42624-LF	SH03-001-16-04
ASM4022_488_16871-LF	SH03-001-19-02	ASM4022_488_16871-LF	SH08-003-20-02
ASM4022_488_18781-LF	SH02-001-11-02	ASM4022_488_18781-LF	SH08-010-03-03
ASM4022_640_02451-LF	SH07-035-01-01	ASM4022_640_02451-LF	SH07-035-01-01
ASM0051_240_04422-LF	SH07-026-05-01	ASM0051_240_04422-LF	SH07-026-05-01
ASM4022_430_06461-LF	SH07-007-08-01	ASM4022_430_06461-LF	SH07-007-08-01
ASM4022_436_59191-LF	SH03-007-01-02	ASM4022_436_59191-LF	SH03-007-01-02
ASM4022_438_33894-LF	SH06-021-01-01	ASM4022_438_33894-LF	SH08-008-08-02
ASM4022_438_35085-LF	SH05-008-06-01	ASM4022_438_35085-LF	SH05-008-06-01
ASM4022_438_39500-LF	SH05-014-02-02	ASM4022_438_39500-LF	SH05-014-02-02
ASM4022_438_39512-LF	SH04-004-07-01	ASM4022_438_39512-LF	SH04-004-07-01
ASM4022_472_30271-LF	SH05-007-05-03	ASM4022_472_30271-LF	SH05-007-05-03
ASM4022_489_20833-LF	SH07-047-04-02	ASM4022_489_20833-LF	SH07-047-04-02
ASM4022_640_03151-LF	SH06-024-02-02	ASM4022_640_03151-LF	SH06-024-02-02
ASM4022_646_00002-LF	SH05-019-09-02	ASM4022_646_00002-LF	SH05-019-09-02
ASM4022_430_06461-LF	SH07-007-08-01	ASM4022_430_06461-LF	SH07-007-08-01
ASM4022_436_81252-LF	SH06-008-06-04	ASM4022_436_81252-LF	SH06-008-06-04
ASM4022_438_34078-LF	SH01-010-08-02	ASM4022_438_34078-LF	SH08-003-15-01
ASM4022_438_38922-LF	SH04-014-07-01	ASM4022_438_38922-LF	SH06-016-10-02
ASM4022_438_39500-LF	SH05-014-02-02	ASM4022_438_39500-LF	SH05-014-02-02
ASM4022_438_39511-LF	SH04-009-10-02	ASM4022_438_39511-LF	SH04-009-10-02
ASM4022_438_77173-LF	SH02-006-05-03	ASM4022_438_77173-LF	SH07-007-10-03
ASM4022_488_18781-LF	SH02-001-11-02	ASM4022_488_18781-LF	SH08-010-03-03
ASM4022_640_02471-LF	SH01-020-01-02	ASM4022_640_02471-LF	SH01-020-01-02
ASM4022_640_03531-LF	SH02-014-09-01	ASM4022_640_03531-LF	SH02-014-09-01
ASM4022_640_03571-LF	SH06-020-05-01	ASM4022_640_03571-LF	SH06-020-05-01
ASM4022_646_43461-LF	SH01-032-03-01	ASM4022_646_43461-LF	SH01-032-03-01
ASM4022_438_34639-LF	SH08-046-13-04	ASM4022_438_34639-LF	SH08-046-13-04

Figure 36 - Example of the differences in picking locations

Appendix F.3 – Outcomes of the *Cabinet Order* experiments

This section provides a more in-depth insight into the outcomes of the experiments that have been performed with the optimization model of multiple picking stations for the *CABINET ORDER* work
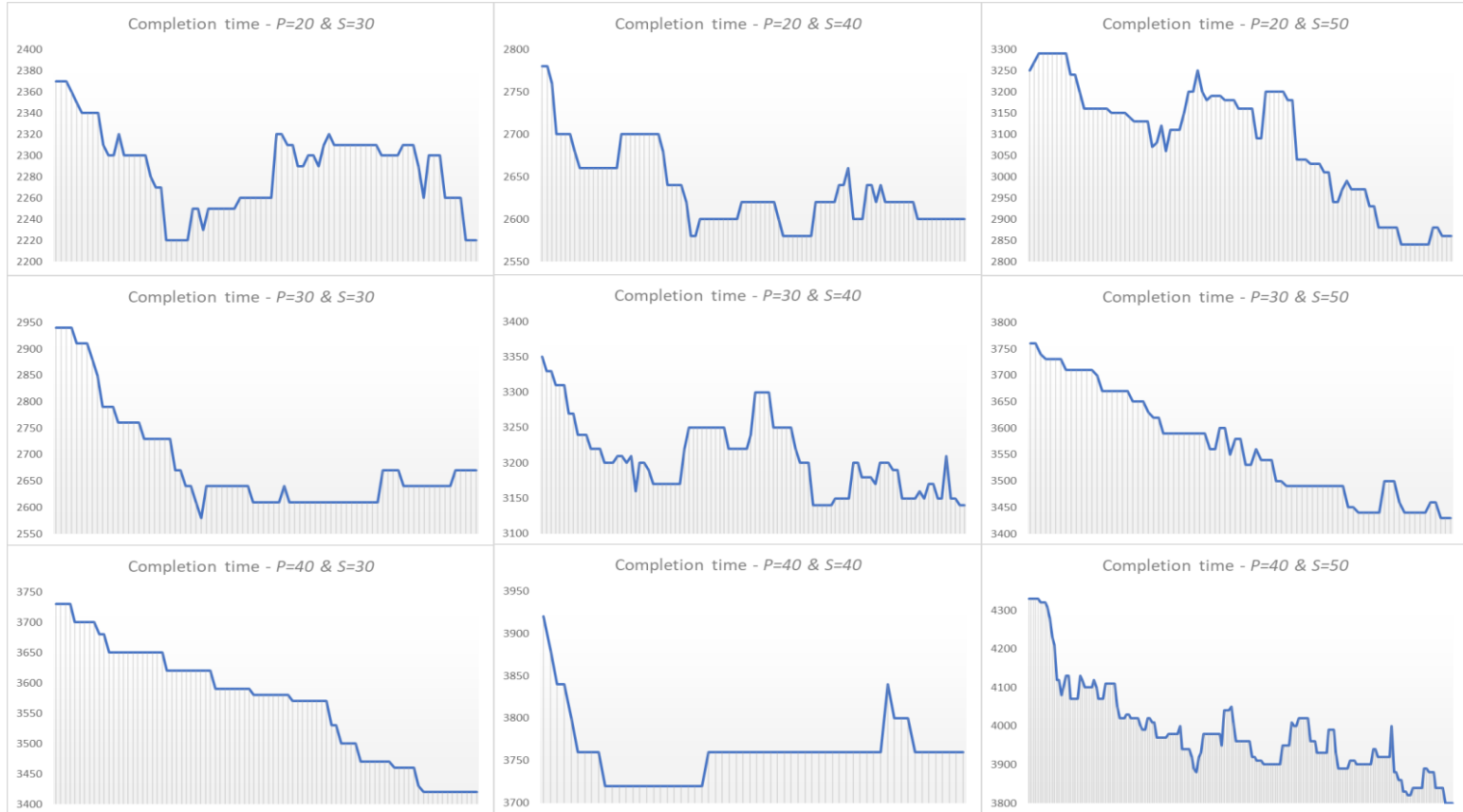

Figure 37 - Outcomes of the Cabinet Order experiments

order.