Dynamic storage allocation to optimize the utilization of storage capacity and handling efficiency

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Dynamic storage allocation
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storage capacity and
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Abstract
This study includes the development of a dynamic storage allocation strategy that maximizes the utilization of the storage capacity and the handling efficiency with a service level constraint. The development is the result of the initiated problem about exceeding the target occupancy rate of storage locations. The challenging characteristics of a third-party logistics provider in spare parts have led to a shift in performance measurement from an occupancy rate to a utilization rate of storage locations. A model has been developed that maximizes the average performance while including the costs for storage capacity and handling. Comparing different dynamic storage allocation strategies with diverse input characteristics has resulted into a best practice strategy. The results indicate that implementing this strategy will minimize overall costs.
Preface
This chapter is the final chapter that has to be added to my report to complete this master thesis project. Completing this makes an end to the journey as a student at the University of Technology in Eindhoven. During six years, my hard and soft skills are positively enhanced.

I hope you have enjoyed reading this report in the same way as I have enjoyed working on my project. It was a pleasure to work on my project at CEVA Logistics in Eindhoven. I liked to talk about the subject with the employees which resulted into useful insights for my project. Particularly, I want to thank the project engineering team of the customer Sandvik. They have made my graduation period an enjoyable one. Besides the engineering team, I especially would like to thank Annelies Verheijen and Patrick Tersteeg for their time and valuable input. Their experiences have enriched my knowledge and skills.

Furthermore, I particularly want to thank my first supervisor, Rob Broekmeulen. I really appreciate his amount of feedback to help me out when I got stuck. Especially his quick responses and clear communication ensured a pleasant cooperation. His experiences and knowledge provided non-subject related examples that were very useful to give me new insights. Moreover, I would also like to thank my second supervisor, Tugce Martagan. The feedback she gave me about the outline of the project has helped me to hand in a structured report.

My great life as a student could not be described as a great one without my fellow students. I would like to thank all of them for the amazing distractions. Besides the non-study related activities, I also liked the chats about my project that resulted into new insights from a different perspective. My friends from my hometown, my fellow exchange students, my roommates and my teammates of my basketball team have also been of great value by supporting me to do what I like.

Last but not least, I would really like to thank my parents, my family and my boyfriend who supported me along the way to pursue my goals in life. Without them, reaching this moment to write the final words of my master thesis project was impossible.

I wish you all the best.

Heleen van Delft

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**Management summary**

This report is the result of a master thesis project that is conducted at CEVA Logistics in Eindhoven. The focus of this report lies on the part of the warehouse that operates with spare parts for the customer with the largest volume: Sandvik.

**Problem statement**

As a third-party logistics (TPL) provider, the driving forces are cost savings and customer satisfaction. Especially in a spare parts environment, a TPL provider needs to be flexible to meet the customer demand. As a result, CEVA determined 85 percent as an optimal occupancy rate of storage locations to be able to satisfy customer demand. An occupancy rate that exceeds the target rate is observed and therefore, CEVA feels pressure to address this exceedance.

However, determining an optimal occupancy rate is based on several factors. In a spare parts environment where demand is unknown on beforehand, it is not beneficial to use the occupancy rate as a performance measurement. Therefore, the aim of this report has shifted from occupancy rate to utilization. When focusing on the utilization of storage locations, the travel distance is expected to decrease and the probability to meet the customer demand is expected to increase. From existing literature, it is not clear how to model these dependencies in such a challenging environment. This has led to the following research question:

*How can a storage allocation strategy be developed to maximize the utilization of storage locations, minimize the travel distance with a service level constraint?*

To answer this question, the following characteristics of CEVA are taken into account:

- Extremely diverse SKU characteristics;
- Increasing amount of different SKUs;
- Capacity is limited;
- Multiple locations per SKU;
- Unpredictable demand.

**Conceptual design**

The research question stated that three components have to be optimized simultaneously. The first component of maximizing the utilization of storage locations is expressed as a Dynamic Storage Allocation (DSA) problem that is formulated by Garey & Johnson (1979). Shortly, the goal of a DSA problem is to allocate all items with a certain arrival and departure time in the available storage sizes, where only one SKU can be stored at a storage location per time. The second component that has to be optimized is the travel distance. This component is added to the DSA problem to prevent that storage costs will decrease, but handling costs will increase significantly. As a TPL provider, customer satisfaction is very important. Therefore, a service level constraint is created to make sure that a certain service level will be achieved. As a result, the DSA problem has to be solved with an additional travel distance factor where a certain service level has to be achieved.

The main objective of the created DSA problem is based on the environment of the application of the problem. A distinction is made between three environments: a deterministic, a stochastic and a dynamic environment.

In a deterministic environment, modeling implies input with absolute certainty. However, arrival and departure rates of the future are unknown. In addition, solving this combinatorial optimization problem with extremely diverse SKU characteristics is impossible. In contrast to a deterministic environment...
environment, no valid knowledge about future information is available. In this study, the unpredictable demand is not purely dynamic which has resulted into the determination that the model is applied in a stochastic environment. In this environment, the objective is to maximize the average performance of the model.

**Formal model**

The objective is transformed into a mathematical model that minimizes the average costs with respect to storage locations and traveling time with a service level constraint. To prevent extremely worse outcomes of storage allocation strategies, key performance indicators are expressed: the average and standard deviation of utilization rate and the average and standard deviation of travel time.

**Results**

Steps to reach the objective are defined as: 1) Class rescheduling 2) Storage allocation strategy in a single –aisle. Following these steps, an arrival is first assigned to an aisle based on its class. As in the figure below, step 2 consists of the determination of the specific storage location within the aisle. The original route is the route to the occupied location where the same items as the arrivals are stored. The optional routes are the routes to empty locations in the aisle.

In the first step, the storage locations of the main storage areas are divided into 20% A, 30% B and 50% C storage locations, where A locations are the most favorable locations and C the least favorable in terms of travel time. The percentages have to be used as a starting point, since dynamic borders are suggested.

The second step has resulted into a recommendation of the storage allocation strategy. A simulation in MS Excel by using Visual Basic for Applications with different storage allocation strategies and different input parameters has led to unexpected outcomes. In addition to existing storage allocation strategies, such as Best Fit (BF), Worst Fit (WF), FIFO, LIFO, an extension is introduced with respect to the Best Fit strategy, namely the Best Fit with boundary level (BFb) put away strategy. This extension includes a check whether it is beneficial to store a SKU at an empty storage location even though the occupied storage location of that SKU is still sufficient for arrivals. In contrast to the expectations, the Best Fit strategy with a Farthest Fit pick strategy (BF-FF) has resulted into the lowest overall costs as is observed in the figure below.
Conclusion and recommendations

This study has demonstrated that focusing on the utilization rate of storage locations is beneficial in terms of overall costs including occupied storage locations costs. A model is formulated that maximizes the average performance. To conclude, it has resulted into the following short and long term recommendations:

- Invest in measuring all SKUs;
- Investigate whether it is still important to use a FIFO pick strategy;
- Investigate whether SKUs, especially SKUs of class E in the reach area, are still in the assortment of the customer;
- Reassign SKUs to only three classes where A SKUs are responsible for about 80%, B SKUs for about 15% and C SKUs for about 5% of the pick order lines;
- Reassign storage locations to only three classes;
- Assign put away order lines to storage locations that are larger than the size of the order line;
- Redesign the put away and pick strategy into a respectively Best Fit with Farthest Fit strategy;
- Perform pick frequency checks periodically.

Implementing the BF-FF strategy will result in 4.6% savings per SKU per year in storage location costs and 3.9% savings in overall costs per SKU per year for CEVA. In addition to these numbers, practical contributions can also be found in a decrease in relocation costs. The SKUs that need to be reallocated due to ABC classification changes are already close to its new class. In terms of theoretical contributions, this study has dealt with both storage locations as handling efficiency. Literature about storage allocation strategies with an objective with these two components is limited. Therefore, this study is an extension to existing literature which increases the academic relevance of this report. Furthermore, it is suggested in future research to further investigate the extension of the existing Best Fit strategy where the option to occupy an empty location is only considered if the initial travel costs overrule the costs for the extra location.
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List of abbreviations and definitions

Abbreviations

3PL  Third party logistic provider
BF   Best Fit
BFb  Best Fit with boundary
CF   Closest Fit
CU   Consumer Unit
DSA  Dynamic Storage Allocation
FF   Farthest Fit
FIFO First In First Out
HOPT High Order Pick Truck
I/O  Input and Output point
KPI  Key Performance Indicator
LIFO Last In First Out
PAL  Pallet
SKU  Stock Keeping Unit
SLA  Service Level Agreement
SMC  Sandvik Mining & Construction
TPL  Third-party logistics
WF   Worst Fit
WMS  Warehouse Management System

Definitions

BIN   Unit of space in the shelving area where units from maximum 45 kg are stored
Cut-off time Latest time until an order could be forwarded by the customer such that it will have a marshal by time at the same day it is forwarded
Dock time The exact date and time a SKU is scanned at an arrival dock
EURO Standard European pallet that can cover variable heights
Fragmentation Inability to reuse memory that is free
Interquartile Range Difference between the upper quartile (highest 25% = Quartile 3) and the lower quartile (lowest 25% = Quartile 1) of a data set
Marshalling Process of moving orders from the pack station to the location on a dock
Packing Process of checking, wrapping and confirming a picked order line
Peak week Every beginning of a month when stocks are replenished by the customer that results in a high number of sales orders
Picking Process of retrieving order lines from stock and deliver them to picking station
Put away Process of moving order lines from prepack to a storage location
Order Customer request which includes one or more order lines
Order line Customer order for a unique Stock Keeping Unit that can include multiple units
Upper fence “Upper limit” of data (= Quartile 3 + 1,5 * Interquartile Range), and any data outside this defined bound can be considered as an outlier
Top up Process of moving order lines from prepack to an occupied storage location
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1. Introduction
The first chapter serves as an introduction to the master thesis project in partial fulfillment of the requirements for the degree of Master of Science in Operations Management and Logistics. The first section of this chapter includes a description of the company background. This is followed by an introduction of the problem that is initiated by the company in Section 1.2. The last section includes the outline of this report.

1.1 Company background
The project has been executed at CEVA Logistics. CEVA Logistics was created as a result of the merger of TNT Logistics and EGL Eagle Global Logistics. They have expertise in automotive and tires; technology; consumer and retail; industrial; publishing; energy; aerospace; and healthcare. Within these market sectors, CEVA provides end-to-end design, implementation and operational capabilities in freight forwarding, contract logistics, transportation management and distribution management. In Figure 1 the integrated end-to-end service of CEVA is shown where three main departments can be identified: inbound, warehousing and outbound.

CEVA logistics has over 42,000 employees in 1,000 locations over 170 countries. The countries are located in four regions: Asia Pacific; Americas; Northern Europe; Southern Europa, Middle East and Africa.

Figure 1: CEVA end-to-end service portfolio

CEVA Eindhoven is a third-party shared-user global warehouse with seven main customers: Sandvik, Ericsson, Toshiba Medical Systems, Jacobs, Transitions, DAF, and ThyssenKrupp. Integrated supply chain management is performed separately for these customers by around 300 FTE’s. The focus of the project is on the customer with the largest volume of the Eindhoven site: Sandvik. Sandvik is an engineering group in materials technology, mining and construction. A part of their spare components is stored at CEVA Eindhoven since 2004. The components of Sandvik have a wide variety in size and weight. In this report, CEVA is used to refer to the part of the warehouse of CEVA Eindhoven that is used for all processes that are related to Sandvik.
1.2 Problem statement

In general, the main activity of a third-party logistics (TPL) provider is to manage, control and deliver logistic activities on behalf of a customer where at least transportation and warehousing are included (Hertz & Alfredsson, 2003). The driving forces of a TPL provider are cost savings and customer satisfaction (Bhatnagar, Sohal, & Millen, 1999). A TPL provider charges the customer a pre-arranged price with respect to storage space and handling costs. In general, a process of the TPL that causes more storage space and handling costs than expected results in lower profit for the TPL provider. The reason for this is that the customer will still pay the same pre-arranged price although the costs are higher. However, a process that uses the storage space and handling more efficiently leads to cost savings since the expected costs are lower and the TPL provider still gets the pre-arranged price. Therefore, it is important for a TPL provider to efficiently use the storage space and handling time. As mentioned by Bhatnagar et al. (1999), besides costs savings, customer satisfaction is also a driving force of a TPL provider. This means a TPL provider has to be flexible to meet the customer demand and the service deadlines. In a spare part environment, the demand is realized during the maintenance operation (Jalil et al., 2011). This makes it difficult to forecast the demand and consequently meet the customer demand and service deadlines. Therefore, CEVA has determined that some empty warehouse storage space is required to be able to deal with the unpredictable demand.

However, CEVA has indicated that they face problems with the storage performance. Several storage performance measurements are used in literature. For example in the paper of (Yun & Choi, 1999), the occupancy rate is defined as “… a percentage of the total storage level by a total yard capacity.” The occupation includes, according to Richards (2011), warehouse space, material handling equipment and storage equipment. To clarify the definition used in this report, the definition of the occupancy rate\(^1\) is formulated: The occupancy rate is the ratio between the number of occupied storage spaces and the number of total storage spaces. The occupancy rate of the storage locations in the warehouse should be, as determined by CEVA, 85 percent. As a third-party logistics (TPL) provider, CEVA feels pressure to meet the 85 percent target occupation rate to be able to store the arrivals. Though, CEVA has indicated a problem since the actual occupancy rate is higher than the target occupancy rate.

In contrast, most studies refer to the utilization rate as a measurement for the storage performance instead of the occupancy rate. For example, in Richards (2011) the amount of floor space utilized is measured or the cubic utilization of the building to make it more realistic. There seems to be a difference between the occupancy rate and the utilization rate. The difference is explained by an example in Figure 2 where every situation exists of two storage locations and two arrivals. The length of the arrow displays the average travel distance. In situation 1, the arrivals are stored separately and in situation 2 the arrivals are stored in only one storage location. When comparing these situations, the occupancy rate in situation 1 is higher than in situation 2, but the utilization rate in situation 1 is lower than in situation 2. In addition, the higher occupancy rate in situation 1 results in a higher travel distance. Another important difference between the two situations is the possibility that the storage locations are sufficient to store an incoming arrival. The storage locations are sufficient in both situations when an order arrives that is equal to or smaller than 6 items. However, the storage locations are only sufficient in situation 2 when an order arrives that is equal to or smaller than 10

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\(^1\) The term fill rate is used within CEVA; however this term is usually used as the long-run average fraction of demand satisfied immediately (Zhang & Zhang, 2007). In this report, the occupancy rate is used as defined. The term service level is used as the ratio between the arrivals that can be directly stored in the warehouse and the total number of arrivals.
items. From this example in Figure 2, it is expected that increasing the utilization of the storage locations might decrease the occupancy of storage locations, the travel costs and it might also decrease the probability that an arrival cannot be stored due to insufficient storage capacity. This last consequence is called the service level which is defined as: *The ratio between the arrivals that can be directly stored in the warehouse and the total number of arrivals.* As a third-party logistics provider, customer satisfaction is a driving force that results into a certain service level that has to be achieved.

![Figure 2: Comparison of two situations with a maximum storage capacity of 10 items](image)

To conclude, the main goal of this master thesis project is to increase the utilization of the storage locations and to decrease the travel distance where a certain service level has to be achieved.

This storage problem probably occurs in more situations where efficient use of storage space and handling time is required. This probability makes reaching the goal of the master thesis project even more crucial.

### 1.3 Research outline

In the first chapter, a description is provided of the company with a problem statement that is initiated by the company. The results of the executed literature review are provided in Chapter 2. This is followed by a detailed analysis of the warehouse process in Chapter 3. Consequently, a diagnosis is executed followed by the research questions in Chapter 4. This diagnosis and research questions have resulted into a design, including the formal model, which are both provided in Chapter 5. In addition, this is followed by the chapter about the results of this model with a discussion and the implementation (Chapter 6 and 7). Finally, the conclusion with contributions, limitations of the research and future research directions are listed in Chapter 8.
2. Literature review

To bridge the gap between the existing literature and possible solutions of the problem, the existing literature is discussed in this chapter. After this discussion, the gap is outlined that serves as scientific research goals of this project.

A variety of indicators are discussed in literature to measure the performance of logistics service providers. Firstly, the book of Ten Hompel and Schmidt (2007) gives general possible solutions with background information about warehouse management, for example, fundamentals of an operational optimization and the realization of warehouse management systems. Krauth et al (2005) specifically focus on the different streams of measurements between warehouse management indicators to measure the performance of a warehouse. A distinction is made between internal and external key performance indicators (KPIs). Internal management indicators are based both on the management point of view, such as effectiveness, efficiency, satisfaction and IT and innovation, and on the employee’s point of view. The external indicators are based on a customers and society perspective. In particular, the internal measurements concerning effectiveness and efficiency are useful for the master thesis. These measurements can be used to identify the existing problems within the warehouse. In Huiskonen (2001) the need for differentiating the methods between different types of spare parts is highlighted. Four control characteristics are discussed to differentiate the spare parts: criticality, specificity, demand pattern and value of parts. Criticality refers to the consequences caused by a failure of parts on the process when a replacement is not available and specificity is about the standardization of parts. Methods to solve the existing storage problems are widely discussed in literature. In this literature review, a distinction is made between existing models that can solve:

- Deterministic problems
- Stochastic problems
- Dynamic problems

2.1 Deterministic models

A deterministic procedure is presented by Accorsi, Manzini and Bortolini (2012) that concerns allocation and assignment issues. It demonstrates that restocking performance might not go together with picking performance in terms of travel distance. Heragu et al. (2005) examined besides storage size problems also other functional areas problems together with the product allocation problems. The result is a mathematical model to solve these problems simultaneously. Hausman, Schwarz and Graves (1976) have also dealt with optimal storage assignment problems. It can be concluded from their study that reductions in travel times are more likely to occur with a class-based assignment than with a random based assignment of items to locations. With a class-based assignment items are assigned to a class of storage locations according to the class of the item. A random based assignment assigns items randomly to storage locations and a dedicated storage policy assigns each item to a dedicated storage location in the warehouse. Van den Berg (1999) added to this conclusion of Hausman et al. that dedicated storage policy strategies require more storage space than class-based storage strategies. Randomized storage strategies require the smallest amount of storage space of the three main storage strategies. The study of Petersen, Siu and Heiser (2005) discussed new storage assignments that are based on ‘the golden zone’. The golden zone is the zone where items are located between the picker’s waist and shoulders. Results show that storage policies that take into account this concept generated significant savings (Petersen et al., 2005). Many companies use an ABC categorization to sort products. Fontana and Cavalcante (2011) determined in their paper a category for each item by using this categorization (‘subjective criteria to clients’) and also use ‘objective criteria relating to products’, for example profit per product. Another method to formulate classes is
the cube-per-order index (COI) that is based on the order frequency of an item and the condition of the storage space. This index is based on a calculation of all possible combinations of the products. When inserting a new product, it has to redo all these calculations in order to define the final categorization. In contrast to this method, the ABC categorization is not dependent of the new products (Fontana & Cavalcante, 2011). The ABC method together with product allocation is also used by Tippayawong, Sopadang and Patitad (2013) in a multi-commodity warehouse. They have reduced the travel time by 45 percent and the picking time by 42 percent by changing the layout and the picking system of the warehouse.

2.2 Stochastic models

Rosenblatt and Roll (1988) discuss factors that affect the relationship between the required capacity of a warehouse and the resulted service level in a stochastic environment. According to their analysis, factors that affect the required capacity are the order quantity, average daily demands with its variability, number of items and the reorder level. These factors together form the Nominal Capacity Requirement (NCR) that refers to the average required capacity conditional to random throughput factors. The model of Rosenblatt and Roll shows the relationship between the listed factors and the expected deviations from the NCR by a given service level. In the study of Cormier and Gunn (1999), the optimal storage capacity expansion schedule is determined by taking into account a demand growth and costs for inventory ordering, inventory holding and investment costs. The Karush-Kuhn-Tucker conditions are used to solve the nonlinear optimization problem within two time periods. The Karush Kuhn-Tucker (KKT) conditions are a variation of the Lagrange multipliers where these multipliers only deal with equality constraints and the KKT conditions also deal with inequality constraints (Mangasarian & Fromovitz, 1967). By executing these KKT conditions several times, an optimal discrete capacity expansion schedule is the result. Experiments have indicated that the time between two successive expansions is increasing when the demand of the products increases linearly, while the time between two expansions decreases when the demand increases exponentially (Cormier & Gunn, 1999).

In contrast, the study of Choi et al. (2005) has taken the available limited capacity as a constraint and constructed three heuristics to define the replenishment quantities. In their study, they have dealt with an unequal replenishment interval. The first heuristic uses a separate capacity for each product for replenishment (“nonintrusive heuristic”), while the second heuristic (“greedy heuristic”) uses the maximum capacity of the system to replenish products. The final sharing heuristic is a combination of the two heuristics where to each product an individual capacity is assigned. In contrast to the nonintrusive heuristic, the sum of these individual capacities may exceed the total warehouse capacity (Choi et al., 2005). A more recent and practical study is performed by Terlouw (2013) who developed a space allocation method for a forward area of a warehouse without taking into account the forecasts of the demand and where no specific location assignment strategy is used. It decides whether an item needs one or two locations. Each fast moving item will be checked before replenishment and slow moving items are checked periodically to deal with differing frequencies. Implementing these strategies showed a result of 45 percent improvements in the throughput rate of the order (Terlouw, 2013). An analysis by Eilon and Mallya (1985) has expanded the classical ABC analysis with a determination of the number of categories and how products should be assigned to these categories by taking into account the stochastic nature of the demand. A case study at an electronics company by Eilon and Mallya has resulted in savings in holding costs and improvements in administrative control and ordering processes.
2.3 Dynamic models
In reality, most of the order flows change dynamically over time. Therefore, it is important to adjust existing models to deal with changing requirements. Firstly, to analyze existing warehouse systems the study of Macro and Salmi (2002) describes the development of a universal storage simulation model and experiment with different storage options. In their paper, a medium volume warehouse with only 88 different stock keeping units (SKUs) and a medium volume warehouse with 3000 different SKU’s are examined. In both applications, an overcapacity is observed or is expected to be observed in the future. Possibilities to deal with changing requirements are described in Gu et al. (2007). One possibility is to relocate items with an expectation of an increasing arrival rate closer to the I/O point and one could reallocate based on uncertainty of incoming orders. This last possibility is also described by Roll and Rosenblatt when the allocated space seems to be insufficient to store the incoming product; some free space is created by shifting some stored products to another location. In literature, several others describe the dynamic storage location assignment problem. For example, Sadiq et al. discuss a relocation schedule based on cluster techniques (Gu et al., 2007). A storage-sizing problem with a dedicated storage policy is studied by Lee and Elsayed (2005). A nonlinear optimization model was constructed in order to minimize the overall cost. Since the conditions of the model are dynamic in time, results of their study can only be used as approximations for the design of storage space requirements. A simulation study of Galé, Oliveros and Silván (2002) had the aim to understand the effect of an automatic storage upon the occupied space in a non-automated distribution warehouse. It is concluded that, among other conclusions, a mixture of products within a shelf reduces the amount of required shelf space. Sadiq, Landers and Taylor (1996) remark that storage decisions must be based on correlated assignments, since some items are picked in conjunction with other items. Their paper describes a Dynamic Stock Location Assignment Algorithm (SLAA) that performs better than the cube per order index rule in environments with changing popularity and correlation of demand. A more recent study of Brands (2003) studied factors that influence the location of a SKU in a distribution center. It resulted that the weight and the category of a SKU has a significant influence. The height, the variable of the volume of a SKU and stacking categories seemed to be significant factors in a part of the distribution center. The number of SKUs picked and the density of a SKU did not have a significant influence on the location of a SKU. The study is performed at a grocery retailer in the Netherlands.

2.4 Gap in literature
The goal of this scientific research is to find a storage assignment methods to increase the utilization of storage capacity while also decreasing the travel distance. In literature, much information can be found about warehouse operations in a deterministic, stochastic or dynamic environment. Models that describe more specific situations are also found in literature which is useful when examining and optimizing the described storage problem. However, most of the existing literature has a primal objective. In more detail, none of the existing literature has an objective that focuses on maximizing the utilization of storage locations and simultaneously minimizing the travel distance in an environment where the demand is unpredictable.
3. Analysis

In Chapter 3 the current warehouse process of the company is discussed. Firstly, the storage operations in the warehouse are described including the implications of the initiated problem. After this, the assortment is analyzed by describing the characteristics of the deliveries and how these deliveries are grouped (Section 3.2).

3.1 Storage operation

A warehouse operation consists of four main standard processes: receiving, put away, picking and shipping (Van den Berg, 1999). In more detail, the process flow of the company can be divided into nine main stages (Appendix A):

- Unloading
- Sorting
- Prepack
- Put away
- Storage
- Picking
- Packing
- Marshalling
- Shipping

Important facts that are relevant for the storage operations are shown in Figure 3.

<table>
<thead>
<tr>
<th>Facts warehouse process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
</tr>
<tr>
<td>26,500 m²</td>
</tr>
<tr>
<td>Inbound lines</td>
</tr>
<tr>
<td>4,000 lines a week</td>
</tr>
<tr>
<td>Outbound lines</td>
</tr>
<tr>
<td>15,500 lines a week</td>
</tr>
<tr>
<td>Return lines</td>
</tr>
<tr>
<td>800 lines a week</td>
</tr>
<tr>
<td>SKU’s</td>
</tr>
<tr>
<td>63,000</td>
</tr>
<tr>
<td>Storage locations</td>
</tr>
<tr>
<td>Shelving</td>
</tr>
<tr>
<td>Vertical storage</td>
</tr>
<tr>
<td>Racking</td>
</tr>
<tr>
<td>Cabinets</td>
</tr>
<tr>
<td>Cantilever</td>
</tr>
<tr>
<td>Dangerous goods area</td>
</tr>
<tr>
<td>Ground locations</td>
</tr>
<tr>
<td>Outside storage</td>
</tr>
<tr>
<td>Cable rack</td>
</tr>
<tr>
<td>Archive storage</td>
</tr>
<tr>
<td>Block stacking</td>
</tr>
<tr>
<td>Ground locations</td>
</tr>
<tr>
<td>Total number of different locations types</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td>Total amount of unique locations</td>
</tr>
<tr>
<td>± 79,200</td>
</tr>
</tbody>
</table>

Figure 3: Factsheet warehouse process

The shelving and racking storage locations are called the general flow (± 98 percent of the daily business) and the others together are called the exception flow. Shelving within CEVA consists only of low-level shelving where a single platform rests on the floor and ladders are used to increase the accessibility of slow movers (Tompkins & Smith, 1988). Racking locations are divided into two different locations: HOPT (High Order Picking Trucks) and reach locations. The reach locations consist for about 90 percent of Euro pallet locations and the others locations are block pallet locations. In Figure 4, the layout of the warehouse is displayed with the main storage areas.
The relevant processes for this research, the put away, storage and picking process of the company, are discussed in more detail in the following sections.

3.1.1 Put away process

The put away process includes the movements of SKUs from the receiving area to the assigned storage location in the warehouse. The receiving area is used to temporarily store units that are checked and, only when needed, measured or/and pre-packed. The receiving area is also used to relocate SKUs within the warehouse when SKUs were originally assigned to a location that is proven to be not sufficient to store the incoming order lines. When a location is not sufficient, the troubleshooter operator will try to solve the problem and the order will get a new location.

Order lines are put away based on the dock date and dock time in order to achieve the target Key Performance Indicator (KPI) of the put away process. This KPI includes that 99.5 percent of all normal pre-alerted order lines have to be in stock within 24 hours. Heavy SKUs and SKUs that have to be prepacked in the woodshop have to be in stock in 36 hours with an agreed allowed deviation. The forecast is based on historical data and the information the company received from carriers. The information from carriers exists of the expected date and time of arrivals and the expected number of case packs, boxes and occasionally the expected order lines that will arrive.

The put away process makes use of reach trucks, High Order Pick Trucks (HOPT) and several trolleys (see Appendix B). Trucks can transport only one pallet, where a pallet for the reach area exists of only one SKU and a pallet for the HOPT area can exist of multiple SKUs. For this reason, a put away batch in the reach area exists of one location and a put away batch in the HOPT area exists on average of four locations. A put away batch within the shelving area has on average 20 locations. The put away operator has all relevant information about the SKUs such as the put away quantity and their assigned...
location. The put away operator decides the route between the locations in the put away batch. Order lines are put away or topped up randomly in the assigned storage location. In Figure 5, the put away rate per day is given for each area. It can be concluded that about 66.7 percent of the put away order lines are stored in the shelving area, since on average 600 order lines are put away in the shelving area per day and the other two areas have both about 150 order lines per day.

![Figure 5: Put away order lines per day over three months](image)

**3.1.1.1 Implications of the problem on the put away process**
The occupancy rate problem that is initiated by the company has consequences for the put away process. The travel time of the put away order lines has increased since order lines are assigned to suboptimal locations, as indicated by the company. This resulted in productivity losses of operators.

**3.1.2 Storage process**
The storage process includes the monitoring of the spare parts inventory. These parts are stored in different storage types over different areas of the warehouse. To indicate the performance of the storage process, the actual occupancy of the storage capacity is compared to the target occupation of the storage capacity. In general, it holds that the occupancy rate needs to be maximum 85 percent. As a result, 15 percent of all warehouse locations need to be empty to be able to efficiently store the incoming order lines and to rearrange units. The occupancy rates of all storage areas with their subareas are determined every week without a pre-arranged time. As can be seen in Figure 6, the target occupancy rate of only three subzones (BIN 47/12, BIN 22/12 and BIN 08/15) is met in August and for only one subzone (BIN 22/12) in October. The dimensions of these storage types are given in Appendix C.
In Figure 7, the average number of unique SKUs in stock is displayed over three years. It can be concluded that the number of unique SKUs stored in the warehouse has increased from the beginning of 2013 till the end of 2015 with about 12 percent (from around 57,000 SKUs to almost 64,000 SKUs). This increase in stock can also be a cause for the high occupancy rate. Stock levels might change due to closure of regional stock rooms. Furthermore, no peaks per month can be observed which means that there is not one month where the number of SKUs in stock is significantly higher than others months of the year. However, seasonality is observed in two of the three years since in those years one can observe an increase in SKUs from June until December.

Furthermore, it is observed from Table 1 that 12 percent of the SKUs have more than one location in the warehouse. Observable is that there are SKUs that are stored at 21 or more storage locations in the reach area.
11

Table 1: Frequencies of number of storage locations per SKU

<table>
<thead>
<tr>
<th>Number of unique SKUs</th>
<th>Number of locations</th>
<th>REACH</th>
<th>Shelving</th>
<th>HOPT</th>
<th>Cumulative percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.539</td>
<td>38.329</td>
<td>7.621</td>
<td></td>
<td>88.06 %</td>
</tr>
<tr>
<td>2</td>
<td>1.623</td>
<td>3.531</td>
<td>745</td>
<td></td>
<td>97.42 %</td>
</tr>
<tr>
<td>3 - 6</td>
<td>1.026</td>
<td>311</td>
<td>83</td>
<td></td>
<td>99.67 %</td>
</tr>
<tr>
<td>7 - 20</td>
<td>186</td>
<td>1</td>
<td>0</td>
<td></td>
<td>99.97 %</td>
</tr>
<tr>
<td>21 - 88</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td></td>
<td>100.00 %</td>
</tr>
</tbody>
</table>

3.1.2.1 Storage assignment algorithm
The storage assignment algorithm, also called the slotting algorithm by Petersen, Siu and Heiser (2005), ensures the assignments of SKUs to a warehouse storage locations. The storage assignment algorithm used for reach, shelving and HOPT locations can be basically divided into three parts (Appendix D):

1. Determination of the storage type of the put away line
2. Determination whether to top-up or put away to a new location
3. Determination of the exact location

1. Determination of the storage type of the put away line
The optimal storage type of a put away line with one SKU is determined based on the measured width, height, depth of the SKU and the volume and weight of the put away line. The algorithm checks the smallest possible storage type for the entire put away line regardless of the existing inventory.

2. Determination where to top-up or put away to a new location
After the optimal storage type of an put away line is calculated, the algorithm first tries to top-up at an existing location where already units of that SKU are stored. When no location of that SKU can be topped up due to the different reasons, the algorithm will determine a new location for the SKU. The different reasons are, for example, that the there is no inventory of the SKU available, no sufficient used locations are available or the country of origin is different from the available inventory. The algorithm will search for a new location based on the determined storage type and the class of a SKU. In Appendix D, the steps that are used to find the most suitable location are given. If no location is available with the correct characteristics, the algorithm will search for the next best locations. Order lines will go to a trouble shooter when no location has space sufficient to store this line. After this exception step, a new storage type will be assigned to the SKU and the storage location will be determined again.

3. Determination of the exact location
The exact location is determined easily when only one location of the determined type is available. When more locations with the correct characteristics are available the algorithm has to select an exact location to execute the put away activity. The best location is determined by taking into account the distance to the I/O point and the routing strategy. At the end, a dedicated storage location that is linked to a storage type is determined by the system for the put away line.
3.1.2.2 Implications of the problem of the storage process

The high occupancy rate that is observed has implications. It has forced the company to employ more operators, since on average 100 relocations per day are executed as a consequence of the high occupancy rate. When assuming around 900 put away order lines per day, about 11 (100/900) percent of the order lines need to be relocated to be able to store all arrivals. The relocations are for example to combine the inventory from two locations into one location and to reallocate the inventory from less favorable to favorable locations. In addition, the high occupancy rate has resulted into a lower utilization rate since order lines are stored in a suboptimal location size that is larger than the initial determined location size. Occupancy rate problems have also led to dangerous situations when for example having too many different SKUs at one location. Finally, an implication of the occupancy rate problem that is initiated by the company is the extra costs for building additional storage locations.

3.1.3 Picking process

The picking process includes the movements of SKUs from their storage locations to the assigned packing location in the warehouse.

The picking process starts directly when an order arrives and a pick batch is composed. The exact pick location of an order is selected based on the First In First Out (FIFO) method without taking into account the quantity and the zone within the area of the exact location.

Order lines are picked based on the cutoff time in order to achieve the target KPI of the pick process. This KPI includes that 99.5 percent of the forecasted order lines has to be available for shipment before the marshal time. The marshal time is “...the last possible point of time on a day until an order could be marshalled such that it will be on time regarding the service level agreement (SLA)” (Janssen, 2015). It seems that this target KPI is always reached for the picking process with an agreed allowed deviation.

The picking process of the company is based on order batching, according to De Koster, Le-Duc and Roodbergen (2007). Orders are grouped into a number of subset picking orders. All batches are composed based on highest priority and cutoff times of orders. As can be noticed from Figure 8, the picking process consists of about 60 percent shelving (2,000 of the 3,400 order lines), 30 percent HOPT (1,000 of the 3,400 order lines) and 15 percent reach (500 of the 3,400 order lines). A peak can be observed every beginning of the month when the demand is the highest. Stockroom replenishments for Sandvik take place every beginning of the month to reduce lead-times of critical parts.

![Figure 8: Total order lines of the picking process per day over three months](image-url)
3.1.3.1 Implications of the problem of the picking process
The initiated problem by CEVA about the occupancy rate is also a cause for productivity losses of the pick operators. The main consequence is the fact that order lines are not picked from optimal locations, since SKUs are not stored at the optimal locations. On average, more pick order lines are executed than put away order lines. Therefore, the productivity of pick operators decreases even more when SKUs are not stored at the optimal locations. In addition, when multiple SKUs are stored at one location, SKUs in front of the required SKU have to be removed first and consequently have to be stored at the location again. As a consequence of all the implications, the possibility of process delays in the entire production line has increased. When the process delays increase, it is more difficult to meet customer demand.

3.2 Assortment analysis
In the first part of this paragraph, the characteristics of deliveries are discussed (Section 3.2.1) and afterwards, the grouping of the delivered SKUs is described (Section 3.2.2).

3.2.1 Characteristics of deliveries
The spare parts that arrive at CEVA logistics are sent by their customer Sandvik. The analysis of the deliveries is based on data from the first of November 2015 until the end of January 2016. Deliveries within these three months differ a lot in their amount of units per delivery based on the fact that the maximum quantity is 54,900 units per order line and the minimum quantity is only one unit per order line. In Figure 9, the total receiving quantities per day are shown; while in Figure 10 the average delivery quantities are given with their standard deviations. There is no trend in the average delivery quantity over time, while it can be observed that the standard deviation quantity has the same trend as the average quantity. This means that on days with a high average quantity size per delivery, the standard deviation per delivery is also high. Especially around the second week of the month, it can be concluded that deliveries have the widest variety in quantities. Overall, the standard deviation ranges from 10 – 1,729 units. The interquartile range (IQR) per SKU is used as an indicator to determine whether a SKU has equal or non-equal levels (Analytical Methods Committee, 1989). If the interquartile range is higher than 1,35σ, the SKU levels are determined as non-equal. In addition, checks for normality (Kolmogorov-Smirnov in SPSS) showed that the put away and stock and pick levels of some sample SKUs are not normally distributed (Appendix E, Table 13 - 19). Therefore, it is assumed from these numbers that the arrival and departure numbers change dynamically and are difficult to forecast.

Figure 9: Total delivery quantities per day over three months
3.2.2 Grouping of deliveries

SKUs that arrive at CEVA are grouped into five different classes based on their pick ranking category in order to increase the picking efficiency. A SKU is grouped to a class based on the picking profile, picking frequency, SKU profile and the location ABC profile. The picking profile of a SKU includes the number of picks per year and the location ABC profile includes the available locations per location per class. In the past, CEVA used only the picking profile numbers to indicate which part of the SKUs contains 80 percent of all picks per year. This part was called the A category SKUs. The other SKUs that ensured the mid 15 percent picks and the last 5 percent picks were called, respectively, the B and C category items. The method used by CEVA was based on the classical ABC method (Eilon & Mallya, 1985). At this moment, the calculation of the class per SKU is based on three factors.

1. A factorization based on months a SKU is picked per year and the months a SKU is stored per year is included. This factorization has been taken into account to rank SKUs that are picked every month higher than SKUs that are picked occasionally;
2. A multiplication of the picks per month and a month factor is included to rank recent picks higher (Appendix F, Figure 31);
3. A factorization is used to rank new SKUs higher where the number of the factor is based on the months since a last pick is executed (Appendix F, Figure 32).

These three factors together with the SKU profile lead to a ranking of all SKUs where SKUs that are picked recently have a higher ranking. The SKU profile consists of the storage type a SKU should be allocated to which is based on the most used put away location of one year. When two locations are used with the same frequency, the system will select the largest storage location of these two. This profile is needed to assign the SKUs to an ABC category. Since each ABC category in an area has its own region with a different target occupancy rate, SKUs are assigned to these ABC categories according to their ranking and SKU profile while taken into account the target occupancy rate.

The ABC analysis is used within CEVA for three areas: shelving, HOPT and reach area. CEVA assigns new SKUs to the C-category SKUs. When a new calculation is executed to divide all SKUs to the classes, new SKUs can be reassigned to another class. However, this reassignment will not lead to a relocation of SKUs in stock.

In this study, the expression ‘class’ is used to refer to the grouping of SKUs in their ABC ranking category that can be A until E. The expressions ‘class’ is introduced in this study to distinguish between SKUs and treat different classes differently. In Figure 11 and 12, the occupancy rate per class of October 2015 is given to further examine the initiated problem.
As can be observed in Figure 11, E category SKUs in the HOPT area has the highest occupancy rate (above 95 percent). Besides this category, also at the locations of SKUs from category A and B have a high occupancy rate. Where the occupancy rate of A is significantly reduced during the period, the occupancy rate of B is again increasing. Based on the data of the month October, it can be concluded that SKUs from category E, B and A have a respectively high occupancy rate percentage for the HOPT area while A, B and C SKUs have a high occupancy rate percentage for the shelving area (Figure 12).

To summarize how received order lines are grouped, an example is given in Appendix F where SKU 1, 3 and 4 will reach together the target occupancy rate of the HOPT 20 area of class A SKUs. The ABC grouping method has resulted in a division of the SKUs where about 40 percent of the SKUs are assigned to the E class (Table 2).
<table>
<thead>
<tr>
<th>Class</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of SKUs on stock</td>
<td>13.959</td>
<td>16.286</td>
<td>15.817</td>
<td>10.103</td>
<td>35.869</td>
</tr>
<tr>
<td>Percentage of total stock</td>
<td>0,15</td>
<td>0,18</td>
<td>0,17</td>
<td>0,11</td>
<td>0,39</td>
</tr>
</tbody>
</table>

### 3.3 Summary of analysis

Three different warehouse processes are discussed in detail; the put away, storage and picking process. For each process, the implications of the initiated problem are discussed. It can be concluded that the average number of order lines per day in the put away process is significant lower than the average number of order lines per day in the picking process. Based on this, an important implication of the initiated problem are the productivity losses of picking operators.

The order lines that are received by the company are hard to forecast at SKU level, since the order lines that are received every day differ a lot in their amount. Therefore, it can be concluded that it is hard to forecast what will be received in the future. This conclusion shows the importance of efficient storage operations that can deal with fluctuations in the amount of incoming order lines over time.
4. Diagnosis

In this chapter, a diagnosis is made based on the information obtained by the analysis of the storage process. This diagnosis refers to the challenging characteristics of the storage process (Section 4.1). In Section 4.2, suggestions are provided that may result in a better storage process performance. As a result of these suggestions, a research question is formulated and translated into a research assignment. This is followed by the approach to address this research assignment (Section 4.3). Finally, the scope of the project is clarified in Section 4.5 which is followed by a summary of the diagnoses in Section 4.6.

4.1 Challenging characteristics

The storage process has to deal with some important characteristics that have resulted into a challenging problem. These characteristics are:

- **Multiple locations per SKU;**
  The storage assignment algorithm results in multiple locations per SKU (Table 1). In most cases locations of SKUs with multiple locations are not next to each other.

- **Incorrectly measured and pre-packed SKUs;**
  Not all SKUs are correctly measured (currently only 25 percent) and pre-packed.

- **Capacity is limited;**
  Due to constraints weight capturing.

- **Difficult to forecast the demand;**
  A spare part supply chain is generally characterized by a demand with a dynamic nature which means that the demand pattern is highly variable (Frazzon et al., 2014).

- **Risk of obsolescence of the spare parts is high;**
  In a spare part supply chain, a large number of SKUs is stored where there is a possibility that some of them are no longer useful, for example, by phasing out of a machinery of the customer (Saxena, 2003).

- **Increasing amount of different SKUs (Figure 7);**

- **Extremely diverse SKU characteristics;**
  The stored spare parts from Sandvik have a wide range in characteristics such as dimensions and weight.

4.2 Suggestions for problem solutions

The initiated problem by CEVA refers to an occupancy rate that is higher than the general target occupancy rate of 85 percent. However, a determination of the required storage capacity is dependent on several factors. Rosenblatt & Roll (1988) listed some of the major factors: number of different items stored, demand characteristics and the replenishment policy. Based on these factors, the storage capacity can be determined by a desired service level. In a warehouse that has the challenging characteristics as listed in Section 4.1, it is not beneficial to use one target occupancy rate for all kind of storage locations and SKUs. The diverse SKU characteristics with their unpredictable demand make it challenging to determine the nominal required warehouse capacity that reaches the desired service level. Therefore, the target occupancy rate of 85 percent is not a valid performance measurement.

In addition, only aiming for the target occupancy rate could suggest a solution that results in additional storage capacity. Increasing the number of storage locations and remaining the current storage processes will automatically result in a lower occupancy rate. However, when referring back to the main forces (i.e., cost savings and customer satisfaction) of a third party logistics provider, it is
necessary to efficiently use the handling time. Increasing the number of storage locations to reach the target occupancy rate will result in an increase in handling time. Therefore, it is suggested to maximize the utilization of the storage locations instead of minimizing the occupation of storage locations. When maximizing the utilization, also the travel distance has to be minimized in order to create cost savings. This results in the suggestion to create an objective that is based on the utilization of storage locations and the travel distance.

Moreover, it is suggested to implement a storage assignment policy that pursues the same objective. A class-based storage policy minimizes the throughput time and also maximizes the utilization of storage locations, according to Van den Berg (1999). Order lines will be assigned to a class based on the demand rates and a storage region is reserved for each class. To minimize the travel distance, a Cube per Order Index assigns SKUs to classes. This index is determined by dividing the storage volume by the turnover rate of a SKU (Van den Berg, 1999). The COI only determines the class of a SKU and not the exact location within a class. Since it is difficult to cluster the same SKUs together in the current warehouse, it is suggested to distribute the same SKUs across a class and not necessarily next to each other. In addition, it is recommended to create a small number of classes. In this way, the warehouse is divided into a small number of classes to decrease the complexity of the system. Different storage types are available in each class which already creates a kind of subclasses within each class. In case no previous demand rates are known, it should be assumed that these new SKUs have a relatively low demand rate (Terlouw, 2013).

Finally, it is suggested to use dynamic pick zones with dynamic borders of zones to be able to store the unpredictable and diverse SKUs in their determined class and still meet the service level. As a result, the number of storage locations per class can be modified.

4.3 Research question

After defining the forces of the company and a formulation of the problem statement, the initial objective to optimize the occupancy rate of storage locations is transformed into to the main goal of this research. The main goal is to maximize the utilization of storage locations, minimize the travel distance with a service level constraint. To be able to meet this objective, the research question of this master thesis project is:

*How can a storage allocation strategy be developed to maximize the utilization of storage locations, minimize the travel distance with a service level constraint?*

4.4 Research assignment

The formulated research question is translated into the following research assignment:

*Develop a storage allocation strategy that maximizes the utilization of storage locations, minimizes the travel distance with a service level constraint*
To approach this research assignment, sub assignments are formulated:

1. **Design a model that includes storage locations, handling and rejection costs**

To develop a storage allocation strategy that maximizes the utilization of storage locations, minimizes the travel distance with a service level constraint, a model is designed that focuses on the three relevant costs: storage locations, handling and rejection costs. The handling costs are the result of the traveled distance and the rejection costs are the result of the achieved service level.

2. **Determine the objective type of the model**

After the model is developed with the relevant costs, the objective type is determined which refers to the main objective of the final model.

3. **Identify storage allocation strategies based on utilization and travel distance**

The third sub assignment is formulated to identify different strategies to be able to reach the research assignment. The different strategies have as decision factor(s) utilization and/or travel distance. The service level cannot be determined as a decision factor for the storage allocation strategy, since determining a storage location based on the service level is not valuable. It is only valuable to determine a storage location based on the utilization and/or travel distance.

4. **Formulate key performance indicators for the storage allocation strategies**

To compare the strategies, key performance indicators are formulated. The results of the storage allocation strategies in terms of key performance indicators are compared to prevent worse case scenarios.

5. **Determine the best practice storage allocation that reaches the objective of the model**

After the model with its objective is formulated and the strategies are compared, the best practice storage allocation strategy is determined.

6. **Determine how the storage allocation with the best practice can be applied at the company**

The last sub assignment regards the actual implementation of the results. It determines the recommended implementations for CEVA for both short term and long term implementations.

After these six sub assignments are approached, the answer to the research question is given. As mentioned before, answering the question is not only valuable for CEVA but also for other companies that focus on efficiently using storage capacity and handling.

### 4.5 Scope

This section describes the scope of the master thesis project to clarify the boundaries of the project. This project focuses on a tactical level of the problem. Rouwenhorst et al. (2000) refer to the organizational problems of the warehouse, for example the dimensioning of the ABC zones and selection of the storage concept. In more detail, the scope of the problem can be identified as a storage location assignment based on product information (SLAP/PI). The physical location of the arriving SKUs has to be determined to minimize handling costs and maximize the space utilization (Tippayawong, Sopadang, & Patitad, 2013).
To achieve the goals of the project, it is also important to describe the part of the process that is out of scope. The current order arrival, packing and marshaling process are not taken into account. In addition, the current layout of the warehouse with the routing is served as input to make decisions. The order batching algorithm is also out the scope of this project. Even though the system of the company assigns multiple orders per batch, the project focusses on only one order per batch. This means that an operator always executes one single demand per time.

4.6 Summary of the diagnosis

The initiated problem by the company about the exceedance of the target occupation rate of the storage locations has to be solved by maximizing the utilization rate of storage locations, minimizing the travel distance with a service level constraint. A class-based storage policy with dynamic pick borders is suggested. To be able to solve the initiated problem the following research assignment is formulated: Develop a storage allocation strategy that maximizes the utilization of storage locations, minimizes the travel distance with a service level constraint.
5. Design

Chapter 5 includes the design of the model that leads to a storage allocation strategy that reaches the objective. The first sections discuss the components of the model, the objective, input and output of the model (respectively Section 5.1.1, 5.1.2, 5.1.3 and 5.1.4). Section 5.2 describes the principles that are fundamental for the design of the model. In Section 5.3 the formal model is formulated. Finally, Section 5.4 includes a description of the solution method.

5.1 Conceptual design

5.1.1 Components of the model

Suggestions for problem solutions are given in Section 4.3 which are translated into the goal of this master thesis report. Based on this goal, the components of the model are:

- **Maximize the utilization of storage locations**
- **Minimize the travel distance**

Maximizing the utilization of storage locations is formulated as a Dynamic Storage Allocation (DSA) problem (Garey & Johnson, 1979). The Dynamic Storage Allocation problem is expressed as:

\[
\text{Given a set with } A \text{ different SKUs to be stored where each SKU } a \in A \text{ having size } s(a) \in \mathbb{Z}^+,
\text{ an arrival time } r(a) \in \mathbb{Z}^+_0, \text{ a departure time } d(a) \in \mathbb{Z}^+_0, \text{ and a positive integer storage size } D.
\]

The problem consists of the allocation of all SKUs \(a\) with \(\sigma: A \rightarrow \{1, \ldots, D\}\) such that for every \(a \in A\) the allocated storage interval \(I(a) = [\sigma(a), \sigma(a) + 1, \ldots, \sigma(a) + s(a) - 1]\) is contained in \([1,D]\) and such that, for all \(a,a' \in A\), if \(I(a) \cap I(a')\) is nonempty then either \(d(a) \leq r(a')\) or \(d(a') \leq r(a)\).

A SKU is interpreted as a one dimensional array where \(s(a)\) is the volume of the SKU. The interval \(d(a) - r(a)\) is the period for which the SKU is stored at a location. The result is an assignment of SKUs to a storage location size \(D\) such that only one SKU is stored at a location per time.

The travel distance factor is added to the dynamic storage allocation problem to prevent that storage locations costs will decrease and handling costs will increase significantly.

As a third-party logistics provider, customer satisfaction is a driving force. The dynamic storage allocation problem stated that: ‘…for every \(a \in A\) the allocated storage interval \(I(a) = [\sigma(a), \sigma(a) + 1, \ldots, \sigma(a) + s(a) - 1]\) is contained in \([1,D]\)...’. To make sure, a constraint of the created dynamic storage allocation problem with a travel distance factor is added. In this way, solving the dynamic storage allocation problem has the additional constraint that a minimum determined service level has to be achieved.

5.1.2 Objective of the model

To determine the type of objective of the model, firstly the environment of the application of the model is described. After the environment of the application is determined, the objective of the model is formulated. From prior literature in Chapter 2, it becomes clear that a distinction between existing models of solutions can be made in three different environments:
- Deterministic environment
- Stochastic environment
- Dynamic environment

In a deterministic environment, modeling implies input with absolute certainty. However, as a TPL provider of spare parts, this information is not known and it is difficult to forecast the demand. When the input of the model is known, it is still not possible to solve the problem in a deterministic environment. The reason for this is that the model can be identified as a combinatorial optimization problem that refers to determining the optimal storage assignment strategy between all storage assignment strategies that satisfy the objective of the model (Papadimitriou & Steiglitz, 1982). Solving the combinatorial optimization problem with as input the extremely diverse SKU characteristics is impossible. Based on these two reasons, the unpredictable input and the combinatorial optimization problem, the model is not applied into a deterministic environment.

In contrast to a deterministic environment, a pure dynamic environment experiences continuous changes in such way that no valid knowledge about arrivals and departures can be obtained. In this dynamic environment, which also can be considered as an on-line environment, results of strategies can only be compared based on their worst case results. The unpredictable demand cannot be defined as purely dynamic; there is some knowledge about the arrivals and departures based on historical numbers. Therefore, decisions based on a worst case analysis would not result in the objective of the model. In a stochastic environment, arrivals and departures take place at random or with a certain distribution function. To conclude, determining the environment of application of the model as a deterministic environment is not possible, determining it as a dynamic environment leads to unrealistic results and therefore, the environment is determined to be stochastic. With this stochastic environment, the average performance of the model is evaluated and the objective is to maximize the average performance.

After the description of the environment with the objective of the model, the steps to reach the objective are discussed. It was suggested to use a class-based storage policy where SKUs are allocated to a class and are assigned to a location within in this class. While reaching the objective to find the average best performance, it has resulted into two required steps that lead to a decomposition of the focus from the total warehouse into a single aisle:

**Step 1** Class rescheduling

**Step 2** Strategy of a single-aisle

In the first step, all aisles of the warehouse are assigned to classes. In this way, when an order arrives and its class is defined, it can only be allocated to aisles with the same class. After classes are assigned to aisles, the storage allocation strategy within a single aisle is determined.

The determination of the storage allocation strategy of a single aisle is translated into a ‘hostel problem’, where: ‘The hostel consists of several floors with on each floor two rooms on both sides of the staircase. The exact arrival rate of the guests, their length of stay and the total number of guests is unknown on beforehand. When the guests arrive, only the total number of arriving guests and their arrival date is known and their number is always smaller than or equal to the total number of beds in a room. The question is which room should the arriving guests book?’
The following rules hold for determining the room for the arriving guests:

- There is no option to split arriving guests;
- All guests want to be as close as possible to the lowest floor.

Arriving guests can decide to book a new empty room or book an occupied room and share a room with other guests. The first option can result in extra costs in comparison with the second option, since there is a possibility that no new guest will arrive in the room in the future. This leads to higher costs for the guests that have already booked to the room, because the total costs are divided among fewer guests. However, the first option can result in lower travel time to the first floor. The rooms at the upper floors will be empty as much as possible, because all guests want to be as close as possible to the lowest floor. The problem is displayed in Figure 13.

![Figure 13: Hostel problem](image)

Examining this question in a stochastic warehouse environment has resulted into a storage allocation strategy that defines the exact storage location of arrivals and results into a maximization of the average performance of the storage process.

5.1.2 Input of the model
This section discusses the storage assignment strategies and input parameters of the model.

5.1.2.1 Storage assignment strategies
To determine the storage allocation strategy that reaches the objective of the model, different strategies are created based on a utilization factor and/or travel distance factor. On top of combinations of existing heuristics (Appendix G), a new heuristic is created based on the hostel problem. It is called ‘the Best Fit with boundary put away strategy and Farthest Fit pick strategy’ (BFb-FF). All input storage allocation strategies are given in Table 3 which is followed by a description of the operational behavior of each strategy.
Table 3: Input storage allocation strategies

<table>
<thead>
<tr>
<th>Strategy number</th>
<th>Strategy</th>
<th>Put away strategy</th>
<th>Pick strategy</th>
<th>Decision factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BF - FIFO</td>
<td>Best Fit</td>
<td>FIFO</td>
<td>Utilization</td>
</tr>
<tr>
<td>2</td>
<td>BF - LIFO</td>
<td>Best Fit</td>
<td>LIFO</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>BF - WF</td>
<td>Best Fit</td>
<td>Worst Fit</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>WF - FIFO</td>
<td>Worst Fit</td>
<td>FIFO</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>CF - FF</td>
<td>Closest Fit</td>
<td>Farthest Fit</td>
<td>Distance</td>
</tr>
<tr>
<td>6</td>
<td>BF - FF</td>
<td>Best Fit</td>
<td>Farthest Fit</td>
<td>Utilization and distance</td>
</tr>
<tr>
<td>7</td>
<td>BFb - FF</td>
<td>Best Fit boundary</td>
<td>Farthest Fit</td>
<td></td>
</tr>
</tbody>
</table>

1. **BF-FIFO**

This strategy checks for every put away order line whether the order line can be stored in the occupied locations from locations with the smallest to largest leftover. If no occupied location is sufficient, an empty location with the smallest travel distance is selected. The put away order line is stored in this empty location. For every pick order line, this strategy checks the occupied sufficient locations from locations with the earliest to the latest put away order line.

2. **BF-LIFO**

This strategy checks for every put away order line whether the order line can be stored in the occupied locations from locations with the smallest to largest leftover. If no occupied location is sufficient, an empty location with the smallest travel distance is selected. The put away order line is stored in this empty location. For every pick order line, this strategy checks the occupied sufficient locations from the locations with the latest to the earliest put away order line.

3. **BF-WF**

This strategy checks for every put away order line whether the order line can be stored in the occupied locations from locations with the smallest to largest leftover. If no occupied location is sufficient, an empty location with the smallest travel distance is selected. The put away order line is stored in this empty location. For every pick order line, this strategy checks the occupied sufficient locations from locations with the largest to the smallest leftover.

4. **WF-FIFO**

This strategy checks for every put away order line whether the order line can be stored in the occupied locations from locations with the smallest to largest leftover. If no occupied location is sufficient, an empty location with the smallest travel distance is selected. The put away order line is stored in this empty location. For every pick order line, this strategy checks the occupied sufficient locations from locations with the earliest to the latest put away order line.

5. **CF-FF**

This strategy checks for every put away order line whether the order line can be stored in the occupied locations from locations with the smallest to the largest travel distance. If no occupied location is sufficient, an empty location with the smallest travel distance is selected. For every pick order line, this strategy checks the occupied sufficient locations from locations with the largest to the smallest travel distance.

6. **BF-FF**

This strategy checks for every put away order line whether the order line can be stored in the occupied locations from locations with the smallest to largest leftover. If no occupied location is sufficient, an
empty location with the smallest travel distance is selected. The put away order line is stored in this empty location. For every pick order line, this strategy checks the occupied sufficient locations from locations with the largest to the smallest travel distance.

7. **BFb-FF**

This strategy checks for every put away order line whether the order line can be stored in the occupied locations from locations with the smallest to largest leftover where the utilization is lower than the boundary level. If no occupied location is sufficient and has a utilization rate that is lower than the boundary rate, it is checked whether an empty location has a smaller distance than the sufficient occupied location with the smallest leftover. If there is an empty location with a smaller distance, the put away order line is stored in this empty location. If there is no empty location with a smaller distance, the put away order line is stored in the sufficient location with the smallest leftover. For every pick order line, this strategy checks the occupied sufficient locations from locations with the largest to the smallest travel distance.

In existing storage allocation strategies, the system tries to store a put away order line in occupied locations as long as the inventory reaches the maximum capacity of the storage location. In the BFb-FF strategy, the system tries to occupy an empty location that has a smaller travel distance instead of fully utilizing occupied locations with a larger travel distance.

**5.1.2.2 Input parameters**

In addition to the storage allocation strategies, the input parameters are listed in Table 4.

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Period</strong></td>
<td>Time period over which the average performance will be calculated</td>
</tr>
<tr>
<td><strong>Storage locations</strong></td>
<td></td>
</tr>
<tr>
<td><em>Type</em></td>
<td>Number of different types of storage locations</td>
</tr>
<tr>
<td><em>Size</em></td>
<td>Maximum capacity of the storage locations types in items</td>
</tr>
<tr>
<td><em>Travel time</em></td>
<td>Travel time to each location from the I/O point</td>
</tr>
<tr>
<td><em>Total number</em></td>
<td>Total number of storage locations</td>
</tr>
<tr>
<td><strong>Put away order line</strong></td>
<td></td>
</tr>
<tr>
<td><em>Size</em></td>
<td>Size of a put away order line in items</td>
</tr>
<tr>
<td><em>Total number</em></td>
<td>Total number of put away order lines</td>
</tr>
<tr>
<td><strong>Pick order line</strong></td>
<td></td>
</tr>
<tr>
<td><em>Size</em></td>
<td>Size of a put away order line in items</td>
</tr>
<tr>
<td><em>Total number</em></td>
<td>Total number of put away order lines</td>
</tr>
<tr>
<td><strong>Service level</strong></td>
<td>Determined service level in percentages</td>
</tr>
</tbody>
</table>

**Number of different storage locations types**

In a situation where more than one storage location type is created, before each order line it is checked which types of locations are already occupied. Based on this determination, the system only checks a selection of the occupied and empty locations. After this, the strategy behaves as described in Section 5.1.2.1. The reason for this selection is to achieve a high utilization of storage locations and low occupancy of storage locations. When making a selection, the smallest empty storage locations serve as overflow locations and are only used when the larger locations are not sufficient. Preferable is to pick first from these overflow locations. In this way, the utilization and occupation of the storage location is optimized. The selection is as follows: When no occupied location is sufficient, the strategy selects the smallest empty storage location. If there are no occupied locations, the strategy selects the largest occupied storage location. For a pick order line, the strategy starts with picking
from the smallest locations to the largest locations. A situation where only one storage type is created behaves just as described in Section 5.1.2.1.

**Travel time to storage locations**
The travel time to a location is determined based on the exact location and the travel time per distance of an operator. A Mean Absolute Error (MAE) is used to measure the performance of the travel time determination to a location (Chai & Draxler, 2014): 

\[ \text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |e_i| \]

with \(n\) samples of model errors \(e_i\) calculated as \(e_i\) with \(i = 1,2,\ldots,n\).

**Total number of storage locations and service level**
As described in Section 4.2, the required storage capacity is a result of a determined service level. The service level is used to define the required storage locations in order to meet the service level (Rosenblatt & Roll, 1988). When assuming that all items have similar physical characteristics, the nominal capacity required in units is obtained by: 

\[ \text{NCR} = N(r + \frac{Q}{2}) \]

where \(N\) is the number of items, \(r\) is the reorder point, \(Q\) is the order quantity. Different combinations of these factors render different required capacity when using the same service level. Although, a reorder point and a fixed order quantity are not available in this study, the NCR of Rosenblatt and Roll (1988) is still used as an indication to determine the total number of storage locations given a determined service level.

**5.1.3 Output of the model**
The output of the model is described in this section. Firstly, it should give the value of the objective function for every strategy. Based on the values, the created storage allocation strategies are compared. The output of the model consists of the key performance indicators with its standard deviation to prevent extremely worse outcomes.

**Table 5: Output values of the model**

<table>
<thead>
<tr>
<th>Output values</th>
<th>Value of the objective function</th>
<th>Key Performance Indicators:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average utilization of storage locations</td>
<td>Standard deviation of utilization of storage locations</td>
</tr>
<tr>
<td></td>
<td>Average travel distance</td>
<td>Standard deviation of travel distance</td>
</tr>
</tbody>
</table>

It is expected that one strategy optimizes the overall performance in different situations. Besides, it is expected that this optimal strategy is not dependent of the size of the storage locations. All the expectations of the output of the model are translated into hypotheses in Figure 14. As observed from hypothesis 3, it is expected that the BFb-FF strategy results in a decrease in travel distance and an increase of the utilization of storage locations. In Appendix H, a diagram is created to support this expectation.
5.2 Design principles

After discussing the objective of the model, the input and output, the principles are listed that are required to design the formal model.

1. Operators always cross all aisles and it is not possible to turn around (traversal routing strategy) (Figure 15, green line);
2. Operators do not travel through the entire aisle. Traveling through the entire aisle will lead to decisions based on only the height of a location instead of the distance and height of a location (Figure 15, green dotted line);
3. Each location holds only one SKU;
4. Arrivals and departures are transferred to the same I/O point;
5. Within-aisle storage is used;
6. On each side of the aisle are the same storage locations;
7. There are no differences in priorities of SKUs within a class;
8. The priority of a SKU is constant and known;

H1. A Best Fit put away strategy with a Worst Fit pick strategy results in the best performance in terms of the utilization of locations.

H2. A Closest Fit put away strategy with a farthest pick strategy results in the best performance in terms of total traveled distance.

H3. A Best Fit with boundary put away strategy with a farthest pick strategy results in the best performance with respect to both traveled distance and utilization of storage locations.

H4. A Best Fit put away strategy with a LIFO pick strategy results in the best performance with respect to utilization of locations in comparison with a Best Fit put away strategy with a FIFO pick strategy.

H5. The strategy with the best performance is not dependent on the ratio between the arrival rate and the departure rate of SKUs.

H6. The strategy with the best performance is not dependent on the ratio between the arrival and departure quantities of SKUs.

H7. The strategy with the best overall performance is not dependent on the size of the locations.

H8. The strategy with the best overall performance is dependent of the ratio between the sizes of the locations.

H9. A warehouse that only uses storage locations of one size for a SKU results in a higher total traveled distance than a warehouse that uses storage locations of two different sizes for a SKU.

H10. A warehouse that only uses storage locations of one size for a SKU has higher total costs than a warehouse that uses storage locations of two different sizes for a SKU.

H11. A warehouse that uses large storage locations for a SKU has lower total costs than a warehouse that uses small storage locations for a SKU.

Figure 14: Formulated hypotheses
9. An order line always fits in an empty storage location;
10. Inventory levels of locations are known;
11. Interleaving is ignored;
12. A recommended ‘best practice’ strategy for one aisle is also
    the best practice strategy for the entire warehouse;
13. There is always sufficient inventory to meet the customer
    need for spare parts.
14. Current storage capacity remains the same;
15. The stairs are always stored in the middle of the corridor of the shelving area;
16. The stairs are on average two aisles away from every aisle;
17. Operators use the stairs for level 7 and higher in the shelving area;
18. An operator walks on average 5 km/h without stairs;
19. The time it takes to travel to a location is the same as the time it takes to go away from a location;
20. The time to scan a location is the same for every location.

5.3 Formal model

In this section the formal mathematical model is given. Section 5.1 discusses the objective and
components used in the model. Section 5.2 lists the design principles of the model. The mathematical
model is created based on this information and is used for the class rescheduling and for determining
the strategy of a single-aisle.

The objective is to maximize the average performance while satisfying the service level constraint. As
described in Section 1.2, a process that maximizes the storage space and handling efficiency leads to
cost savings since the expected costs are lower and the TPL provider still gets the pre-arranged price.
Therefore, the objective of the formal model is expressed as minimizing the location costs and
handling costs while satisfying the service level constraint.
5.3.1 Parameters

In Table 6 the defined parameters used in the formal model are displayed.

Table 6: Parameters of the formal model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Cycle length (days) ( t = 1, 2, \ldots, T )</td>
</tr>
<tr>
<td>( W_t )</td>
<td>Travel time on day ( t )</td>
</tr>
<tr>
<td>( N_{jt} )</td>
<td>Number of occupied storage locations of storage type ( j ) on day ( t )</td>
</tr>
<tr>
<td>( E_t )</td>
<td>Number of arrivals that cannot be stored on day ( t )</td>
</tr>
<tr>
<td>( PU_t )</td>
<td>Number of put away order lines on day ( t )</td>
</tr>
<tr>
<td>( PI_t )</td>
<td>Number of pick order lines on day ( t )</td>
</tr>
<tr>
<td>( I_{j,kt} )</td>
<td>Inventory of storage location ( k ) of storage type ( j ) on day ( t )</td>
</tr>
<tr>
<td>( C_{j,k} )</td>
<td>Maximum capacity of storage location ( k ) of storage location type ( j )</td>
</tr>
<tr>
<td>( SP_{pu} )</td>
<td>Storage of put away line</td>
</tr>
<tr>
<td>( D_{o,a,k} )</td>
<td>Travel time of order line ( o ) in area ( a ) and storage location ( k )</td>
</tr>
<tr>
<td>( a_k )</td>
<td>Area of location ( k )</td>
</tr>
<tr>
<td>( b_k )</td>
<td>Bays to cross within the aisle to storage location ( k )</td>
</tr>
<tr>
<td>( t_{a,b} )</td>
<td>Time to cross one bay in area ( a )</td>
</tr>
<tr>
<td>( g_k )</td>
<td>Gangway to cross to location ( k )</td>
</tr>
<tr>
<td>( t_{a,g} )</td>
<td>Time to cross one corridor in area ( a )</td>
</tr>
<tr>
<td>( L_k )</td>
<td>Levels to cross within the bay to storage location ( k )</td>
</tr>
<tr>
<td>( t_{a,l} )</td>
<td>Time to cross one level in area ( a )</td>
</tr>
<tr>
<td>( t_a )</td>
<td>Time to turnaround in area ( a )</td>
</tr>
<tr>
<td>( s_k )</td>
<td>Using stairs to storage location ( k )</td>
</tr>
<tr>
<td>( st_b )</td>
<td>Travel time to level ( b ) with the stairs</td>
</tr>
<tr>
<td>( w_k )</td>
<td>Using no stairs to storage location ( k )</td>
</tr>
<tr>
<td>( MEA_a )</td>
<td>Mean Absolute Error area ( a )</td>
</tr>
<tr>
<td>( x_{a,l} )</td>
<td>Average calculated travel time for level ( l ) in area ( a )</td>
</tr>
<tr>
<td>( x_{a,l}^\ast )</td>
<td>Average historical travel time for level ( l ) in area ( a )</td>
</tr>
<tr>
<td>SL</td>
<td>Determined service level</td>
</tr>
<tr>
<td>( U_{\mu} )</td>
<td>Average utilization rate of storage location</td>
</tr>
<tr>
<td>( U_{\sigma} )</td>
<td>Standard deviation of the utilization rate of storage locations</td>
</tr>
<tr>
<td>( W_{\mu} )</td>
<td>Average travel time</td>
</tr>
<tr>
<td>( W_{\sigma} )</td>
<td>Standard deviation of the travel time</td>
</tr>
<tr>
<td>( c_w )</td>
<td>Costs per travel time</td>
</tr>
<tr>
<td>( c_i )</td>
<td>Costs per occupied location of storage type ( i )</td>
</tr>
<tr>
<td>( Z )</td>
<td>Average total costs</td>
</tr>
</tbody>
</table>

Table 7: Sets of the formal model

<table>
<thead>
<tr>
<th>Set</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>Set of location types</td>
</tr>
<tr>
<td>K</td>
<td>Set of locations</td>
</tr>
</tbody>
</table>
5.3.2 Mathematical model

**Objective**

\[
Z = \min_{\text{lim } t \to \infty} \frac{1}{T} \sum_{t=1}^{T} (c_w W_t + \sum_{j=1}^{J} N_{j,t} c_i)
\]

(subject to)

\[
1 - \frac{E_t}{P_{U_t}} \geq SL
\]

\[
w_k + s_k = 1
\]

\[
0 \geq b_k \geq 22
\]

\[
0 \geq l_k \geq 13
\]

\[
g_k, s_{pu}, s_k, s_{pu}, w_k, \in \{0,1\}
\]

\[
c_w, c_i, D_{o,a,k}, E_t, P_{U_t}, N_{j,t}, SL, st_b, T, W_t \geq 0
\]

where

\[
E_t = \sum_{pu=1}^{P} P_{U_t} s_{pu}
\]

\[
W_t = \sum_{0=1}^{P} D_{o,a,k}
\]

\[
D_{o,k,a}(a) = \begin{cases} 
2(t_{a,b}b_k + t_{a,g}g_k + t_{a,l}l_k) + t_a + MEA_a & \text{if } a = \text{reach or HOPT} \\
2(t_{a,b}b_k + w_k + s_t b \cdot s_k) + t_a + MAE_a & \text{if } a = \text{shelving} 
\end{cases}
\]

\[
MAE_a = \frac{1}{I} \sum_{i=1}^{I} |x_{a,i} - \bar{x}_{a,i}|
\]

The objective (1) is to minimize the average costs where the costs are the sum of the handling costs and the storage locations costs. The percentages of the put away order lines that were stored have to be equal to or larger than the service level (2). In addition, constraint 3 includes the restriction that an operator in the shelving area can either use the stairs \(s_k\) or use no stairs \(w_k\) to location k. An order line is always in a location \(k\) that requires an operator to cross 22 or less bays (4) and 13 or fewer levels (5). When executing an order line, the operator has to cross a gangway or has to cross no gangway. In addition, a put away order line is either stored or not stored. Moreover, an operator uses the stairs or uses no stairs (6). Constraint 7 ensures that the values of the parameters are equal to or above zero. The travel time model (8) is formulated to determine the travel time to location k in area a. Finally, formula 9 is inserted to reduce the effects of the model error based on a known error (parameterization error) and an unknown error.

5.3.3 Key Performance Indicators

In addition to the value of the objective function, the values of the key performance indicators with their standard deviations are examined to prevent extremely worse outcomes.
Utilization of storage locations

\[ U_\mu = \frac{1}{T} \sum_{t=1}^{T} \left( \sum_{j=1}^{J} \sum_{k=1}^{K} I_{jk} \right) \]

\[ U_\sigma = \frac{1}{T} \sum_{t=1}^{T} \left( \sum_{j=1}^{J} \sum_{k=1}^{K} I_{jk} - U_\mu \right)^2 \] (10)

Travel time

\[ W_\mu = \frac{1}{T} \sum_{t=1}^{T} \sum_{o=1}^{O} D_{o,a} \]

\[ W_\sigma = \frac{1}{T} \sum_{t=1}^{T} \left( \sum_{o=1}^{O} D_{o,a} - W_\mu \right)^2 \] (11)

C_{j,n}, D_{o,a,k}, I_{j,n,t}, P_{I,t}, P_{U,t}, N_{t,t}, T, U_\mu, U_\sigma, W_\mu, W_\sigma \geq 0

5.4 Solution method

The first step (class rescheduling) of the decomposition is addressed by using the travel time model. With this model, the favorability of every location is determined. As a result, the classes are assigned to locations based on their favorability. The second step, the single aisle strategy determination, is addressed by a simulation study in MS Excel with using Visual Basic for Applications. In this way, the performance of the strategies is examined in a stochastic environment. Before the simulation, all strategies are validated and verified in Appendix I. It can be concluded from the results of the tests that all strategies are valid and verified.
6. Results and discussion
Chapter 6 includes the results of the model that is formulated in Section 5.3. The results of the case study are divided into the two steps of the objective: results class rescheduling (Section 6.1) and results single aisle (Section 6.2). The last section of this chapter includes a discussion of the results.

6.1 Results of class rescheduling
In this section, the results of the rescheduling of the classes are provided. The classes are rescheduled based on the favorability of the storage locations. The favorability of the storage locations is determined by comparing historical data and the travel time function (formula 8 in Section 5.3.2). In Appendix J (Table 25), the favorability of every location in a certain bay and level based on historical data of travel time from August till October 2015 is shown. The results of this analysis can be supported by both qualitative and quantitative reasons. Qualitative reasons are obtained from observing the picking process. It can be observed that pick operators do not travel via a traversal routing in the HOPT and reach area. Therefore, the aisle of the location is also relevant in order to determine the favorability. This finding can be used to explain the reach picking figure where no trend can be observed. This is supported by the fact that these numbers do not take the aisles of the travel route into account. In addition, initially only in the HOPT and shelving area operators pick more than one order line per route. However, it is observed that sometimes operators pick more than one order line per route in the reach area. The historical data is compared with the calculated travel time by using the travel time function to check whether the conclusions are consistent (Figure 16-18). By comparing and evaluating these results, the validated formulas with the model error are expressed and these are used for determining the favorability of storage locations (Appendix J).

![Figure 16: Validation of the travel time function of the reach area](image-url)
From historical data (Appendix J, Table 25) and the calculated travel time by using the travel time function (formula 8 in Section 5.3.2), it results that:

**R1.** Storage locations in the HOPT area from level 1-4 are about equal favorable as shelving storage locations from level 7 – 10.

**R2.** There is no significant difference in picking times between bays for both the HOPT and reach area.

**R3.** A storage location with a high aisle number, low bay number and low level number is more favorable than a storage location with a low aisle number, high bay number and low level number.

**R4.** A storage location with a high aisle number, low bay number and high level number is more favorable than a storage location with a low aisle number, high bay number and high level number.
From the results, the storage locations are assigned to classes. It was suggested to use a class-based storage policy in Section 4.2. However, the travel times to the locations in one aisle vary significantly. For example, the travel time to a shelving storage location on level 8 (around 22 seconds) is almost two times higher than a shelving storage location on level 3 (around 12 seconds). The variations have resulted into a rescheduling of three classes where no more than two classes are assigned to an aisle (Figure 19-21).

**Figure 19**: Classes rescheduling result HOPT area (low level ≤ 8 and high level > 8)

**R5.** A reach storage location with a low bay number and a high level number is more favorable than a reach storage location with a high bay number and a low level number when both locations are in the same aisle. In contrast, a HOPT/shelving storage location with a high bay number and a low level number is more favorable than a HOPT/shelving storage location with a low bay number and a high level number when both locations are in the same aisle.

**R6.** A HOPT storage location with a high aisle number, high bay number and low level number are about equal favorable than a low aisle number to cross, low bay number and high level number.
Figure 20: Classes rescheduling results reach area (low level ≤ 6 and high level > 6)

Figure 21: Classes rescheduling results shelving area (low level ≤ 6 and high level > 6)
The rescheduling is the result of the class-based storage policy based on the location of the input/output location (I/O). A general division of the storage locations over the classes is used with about 20% A, 30% B and 50% C storage locations. Since it is suggested to use dynamic borders, this division has to be used as a starting point. The borders of the classes can be changed if it turns out that a class requires more storage locations. Finally, the spare part environment ensures that new SKUs have to be allocated to the C class. 80 Percent of the time these new SKUs are spare parts from new machines. Therefore, it is assumed that these spare parts are not high demanding parts after they have arrived.

6.2 Results single aisle
After the discussion of the results of the class rescheduling step, the results of the storage allocation strategy that determines the exact storage location within the aisle are provided.

Different scenarios are simulated where a warming up period is used of 1,000 periods in order to provide stable predictions of performance. This warming up period starts with a large initial pool of empty locations. After this warming up period, the Nominal Capacity Required (NCR that is introduced by Rosenblatt and Roll (1988)) is determined based on the fact that the capacity must be sufficient for at least 88 percent of the put away lines at a random strategy. Statistics are recorded for the next 9,000 periods where the number of available locations is equal to the NCR. The statistics are the averages of the Key Performance Indicators that were saved after every put away transaction. The KPIs are the most interesting after a put away transaction has taken place since the occupation and utilization of the locations will be at its maximum at this moment. The factors that are taken into consideration are the size of the average pick order line, interleaving policy and the warehouse capacity. The interleaving policy refers to queues of work tasks for both inbound and outbound. All scenarios assume no interleaving of tasks. The size of the pick order line is assumed to be Poisson distributed. The put away order line is assumed to be a Uniform distribution (put away quantity = ((λ_{pu}/λ_{pu}) * pick quantity) ± (λ_{pu}/λ_{pu})). All other used functions and input values are given in Appendix K.

Independent t-tests and ANOVA tests are used in IBM SPSS Statistics to derive conclusions out of the results of the simulations. The method of interpreting the results is given and the formulated hypotheses are evaluated in Appendix L. The results based on the acceptance or rejection of the hypotheses in Section 5.1.3 is as follows:

- **R7.** The strategy with the best performance is dependent on the ratio between the arrival and departure rate of SKUs.

- **R8.** The strategy with the best performance is dependent on the ratio between the arrival and departure quantities of SKUs.

- **R9.** The strategy with the best overall performance is dependent on the size of the locations.

- **R10.** The strategy with the best overall performance is dependent on the ratio between the size of the location and the put away size.

- **R11.** A warehouse that uses large storage locations for a SKU has lower total costs than a warehouse that uses small storage locations for a SKU.
From the results, allocating put away order lines to storage locations that are larger than the size of the order line result in lower total costs. In addition, it is concluded that the strategy with the best performance is dependent on the input parameters. The future input parameters of the order lines are unknown. For this reason, the results of each situation are used with a certain probability of occurrence (Table 8). This certain probability is based on the number of historical pick requests. Situations 2, 4 and 9 are the same situations as respectively situations 1, 3 and 9. However, different location sizes are used for these situations to check whether different location sizes give different outcomes.

Table 8: Simulation input values with probability of occurrence

<table>
<thead>
<tr>
<th>Situation</th>
<th>Pick size</th>
<th>Put size</th>
<th>Storage capacity</th>
<th>NCR (SL = 88%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Poisson (λ)</td>
<td>Uniform (min,max)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3, 5</td>
<td>12,18</td>
<td>82%</td>
<td>61%</td>
</tr>
<tr>
<td>2</td>
<td>3, 5</td>
<td>12,18</td>
<td>61%</td>
<td>18%</td>
</tr>
<tr>
<td>3</td>
<td>3, 25</td>
<td>72,78</td>
<td>18%</td>
<td>13%</td>
</tr>
<tr>
<td>4</td>
<td>3, 25</td>
<td>72,78</td>
<td>13%</td>
<td>156%</td>
</tr>
<tr>
<td>5</td>
<td>5, 5</td>
<td>20,30</td>
<td>82%</td>
<td>9%</td>
</tr>
<tr>
<td>6</td>
<td>5, 25</td>
<td>120,130</td>
<td>11%</td>
<td>2%</td>
</tr>
<tr>
<td>7</td>
<td>10, 5</td>
<td>40,60</td>
<td>82%</td>
<td>12%</td>
</tr>
<tr>
<td>8</td>
<td>10, 25</td>
<td>240,260</td>
<td>18%</td>
<td>3%</td>
</tr>
<tr>
<td>9</td>
<td>10, 25</td>
<td>240,260</td>
<td>18%</td>
<td>3%</td>
</tr>
</tbody>
</table>

The differences between the probabilities of occurrence have resulted into a weighted average cost per storage allocation strategy instead of the normal average cost function (Section 5.3.2). In addition, the results of the KPIs are also based on the weighted average. Formulæ 1, 10 and 11 from Section 5.3.2 are transformed and used respectively as:

- \( Z_{\bar{\mu}} = \sum_{s=1}^{S} Z \cdot p(s) \)
- \( U_{\bar{\mu}} = \sum_{s=1}^{S} U_{\mu} \cdot p(s) \) and \( U_{\bar{\sigma}} = \sqrt{\frac{\sum_{s=1}^{S} p(s)(U_{\mu} - U_{\bar{\mu}})^2}{\sum_{s=1}^{S} p(s)}} \)
- \( W_{\bar{\mu}} = \sum_{s=1}^{S} W_{\mu} \cdot p(s) \) and \( W_{\bar{\sigma}} = \sqrt{\frac{\sum_{s=1}^{S} p(s)(W_{\mu} - W_{\bar{\mu}})^2}{\sum_{s=1}^{S} p(s)}} \)

where \( S \) is the number of different situations with a probability of occurrence of \( p(s) \), \( Z_{\bar{\mu}} \) the weighted average of the objective function, \( U_{\bar{\mu}} \) and \( U_{\bar{\sigma}} \) respectively the weighted average and standard deviation of the utilization rate of storage locations and \( W_{\bar{\mu}} \) and \( W_{\bar{\sigma}} \) respectively the weighted average and standard deviation of the total travel distance.
Table 9: Simulation results of KPIs

<table>
<thead>
<tr>
<th>Strategy</th>
<th>$U_{\mu}$</th>
<th>$U_{\sigma}$</th>
<th>$W_{\mu}$</th>
<th>$W_{\sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF-WF</td>
<td>0.72</td>
<td>0.0512</td>
<td>37986</td>
<td>21.205,18</td>
</tr>
<tr>
<td>BFbb-FF (0,70)</td>
<td>0.67</td>
<td>0.0129</td>
<td>46632</td>
<td>27.596,81</td>
</tr>
<tr>
<td>BFbb-FF (0,80)</td>
<td>0.67</td>
<td>0.0129</td>
<td>46632</td>
<td>27.596,81</td>
</tr>
<tr>
<td>BF-FF</td>
<td>0.67</td>
<td>0.008</td>
<td>49128</td>
<td>28.584,58</td>
</tr>
<tr>
<td>CF-FF</td>
<td>0.67</td>
<td>0.0228</td>
<td>45879</td>
<td>25.929,86</td>
</tr>
<tr>
<td>WF-FIFO</td>
<td>0.64</td>
<td>0.0110</td>
<td>38137</td>
<td>20.581,12</td>
</tr>
<tr>
<td>BF-FIFO</td>
<td>0.63</td>
<td>0.0022</td>
<td>40123</td>
<td>30.944,98</td>
</tr>
<tr>
<td>BF-LIFO</td>
<td>0.63</td>
<td>0.0209</td>
<td>43214</td>
<td>20.555,23</td>
</tr>
</tbody>
</table>

Figure 22: Simulation results of KPIs

From Table 9, it becomes clear that there is no significant difference between the used boundary levels with the BFbb-FF strategy. In addition, immediately observed is the high standard deviation of the total travel distance. This is explained by the fact that the storage location sizes vary between the situations, because different put away order line sizes were assumed. Since the travel distance is dependent on the determined storage location sizes, the total travel distances per strategy have a high standard deviation. Therefore, decisions based on the standard deviation of the total travel distance are invalid.

When analyzing Figure 24, the components of the model are important to take into account. To repeat, the components of the model are:
- Maximize the utilization of storage locations
- Minimize the travel distance

The BF-WF strategy has the maximum utilization rate of storage locations (around 0.72), while simultaneously it has the shortest travel distance. In addition, Figure 22 supports the rejection of hypothesis 3 and hypothesis 4.

It is remarkable that the BF-WF strategy has not resulted into the minimum total costs (Figure 23). Therefore, it has been useful to introduce and to calculate the standard deviation of the KPIs. From the
standard deviations of the KPIs in Table 9, it is observed that the BF-WF strategy has a relative large standard deviation based on the utilization rate of storage locations. This means that average utilization rates are more widespread with this strategy than with the other strategies.

From Figure 23, it is noticed that the BF-FF strategy results in the lowest objective function of average costs per year while the BF-FIFO strategy results in the highest average costs per year. To support the conclusion of the preferred strategy, the average occupation rates of storage locations are displayed in Figure 24. The BF-FF pick strategy has the lowest average occupation rate and the BF-WF strategy has the highest weighted standard deviation. In this case study, the location costs are relatively high compared to the travel costs; therefore the strategy that minimizes the number of occupied locations is preferable. This is explained by the fact that the assortment exists of spare parts where the largest parts have no monthly pick request. In this case, the largest part of the total costs exists of the location costs.
The results in Figure 22 and Figure 24 seem to contradict the expectation that a high utilization rate is associated with a low occupancy rate. The BF-WF strategy has a high utilization rate and in contrast, the strategy has a high occupancy rate in comparison with the BF-FF strategy. To examine this contradiction, the service levels of the BF-WF and BF-FF strategies are analyzed. In Table 10, the weighted average ($SL_\mu$) and the weighted standard deviation ($SL_\sigma$) of the service levels are given. A low service level can be the cause of a low average occupancy rate of the BF-FF, since less inventory is put away and consequently, less inventory is in stock. Less inventory in stock resulted in a lower occupancy rate. The result is as expected; the BF-FF strategy has a lower service level which indicates the reason for the lower occupancy rate of storage locations. No extra costs for put away order lines that could not be stored directly are calculated when achieving the service level constraint. This makes the BF-FF strategy still the preferred strategy.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>$SL_\mu$</th>
<th>$SL_\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF-WF</td>
<td>0.9519</td>
<td>0.01228</td>
</tr>
<tr>
<td>BFb-FF</td>
<td>0.9438</td>
<td>0.00822</td>
</tr>
<tr>
<td>BF-FF</td>
<td>0.9444</td>
<td>0.00822</td>
</tr>
<tr>
<td>CF-FF</td>
<td>0.9435</td>
<td>0.00883</td>
</tr>
<tr>
<td>WF-FIFO</td>
<td>0.9429</td>
<td>0.00864</td>
</tr>
<tr>
<td>BF-FIFO</td>
<td>0.9430</td>
<td>0.00662</td>
</tr>
<tr>
<td>BF-LIFO</td>
<td>0.9416</td>
<td>0.00735</td>
</tr>
</tbody>
</table>

Table 10: Weighted average service levels comparison

To conclude, the total ranking of strategies is as follows from most preferable to least preferable:

Ranking of most preferable strategies

- BF-FF
- CF-FF
- WF-FIFO
- BFb-FF
- BF-WF
- BF-LIFO
- BF-FIFO

6.3 Discussion

The simulation is executed under simplified characteristics. The actual warehouse characteristics differ significantly; therefore this section includes a discussion about the effects of the results in a more realistic environment.

The assumptions of the model stated that the operator always crosses all aisles and does not turn around. In addition, they stated that operators do not travel through the entire aisle. These assumptions hold for the shelving area. However, operators do not travel via a traversal routing strategy in the HOPT and reach area. Initially, operators had to use a traversal routing strategy in these areas. A traversal routing strategy decreases the probability that dangerous situations arise. Although, this routing policy is not pursued in practice. Besides, the average picks per aisle increase when implementing a class-based storage policy. A high number of picks per aisle requires to minimize the
travel distance for a traversal routing policy (De Koster, Le-Duc, & Roodbergen, 2007). These two reasons support the requirement to use a traversal routing policy. A traversal routing policy increases the effect of the results positively.

In the current storage allocation policy, there is already a differentiation between storage locations into five different classes. However, the current differentiation of the SKUs has not resulted into a decrease in travel time in all areas. A reason for this is the fact that divisions of storage locations into classes are not maintained in the reach and HOPT area. Although, a differentiation on storage locations is already made, it still takes away a large part of the savings that result from a decrease in handling costs with using the differentiation. The effect of pursuing the rescheduling is the increase in handling costs if the current assignment of SKUs into classes is still used. The current assignment of SKUs into classes has not resulted into a proper division where SKUs from classes always have significantly different characteristics compared to SKUs in other classes (Appendix E, Table 13 – 18). This possible effect can be largely reduced if the SKUs are reassigned to three classes based on picking frequencies.

The real dimensions of SKUs are excluded from the analysis due to the unpredictable demand in the future. In addition, the extremely diverse SKU dimensions make it impossible to simulate all of them. Even more important is the fact that only 25 percent of the SKUs are measured. This makes it impossible to verify the results of a simulation with the real data. Besides, when including the real dimensions the relative effect of the result is the same. SKUs with other dimensions resulted in different required storage location sizes and consequently, in different traveled distance. Although, the effect of the results expressed in percentage savings will remain the same. Only the actual costs change when SKU dimensions change. Therefore, effects from the results are only expressed in percentage of savings.

The expectations of the BFb-FF were rejected. This is also supported by the fact that the strategy is applied into an environment with low demanding SKUs. When the location costs overrule the travel costs, there is no reason to occupy two locations with extra costs instead of having a high travel distance to only one location. The effect of the BFb-FF can be positively increased if it is only used for SKUs with a high pick frequency. It can also be increased if one considers occupying an extra location only if the extra location costs are smaller than the travel costs to the occupied location.

Moreover, a service level constraint of 88 percent is used for the simulations. It is expected that the company has a higher service level constraint. In Table 10 it is shown that the lowest weighted average service level is 0.9416, which does not directly show the need for increasing the determined service level of 88 percent. In addition, increasing the determined service level of 88 percent in the model will not result into a different preferred strategy. In this case study, the preferred strategy is still the strategy that minimizes the storage location costs. Therefore, the results remain valid in a more realistic environment with a higher service level constraint.

Finally, the results are based on a stochastic environment. As discussed in Section 5.1.2, the case study does not behave as a purely stochastic environment. Therefore, it was suggested to be aware of the worst case scenarios. The effect of the worst case scenarios is minimized by preferring a strategy that has a small standard deviation. Therefore, the BF-FF strategy is also a preferable strategy in an environment where no knowledge of future arrivals and departures is available.
7. Implementation

After analyzing the results of the design, the rescheduling results and the preferred strategy are given in respectively Section 6.1 and 6.2. The last step of the project is describing the implementation of these results. Firstly, the implementation plan is composed with respect to the rescheduling of classes and the storage allocation strategy. In Section 7.2, the feasibility of the implementation plan is discussed.

7.1 Implementation plan

The implementation plan is divided into six steps:

1. **Reassign SKUs to only three classes;**
   The reassignment in the warehouse system has to result in a division where A SKUs responsible for about 80% of the picks, B SKUs for about 15% and C SKUs for about 5% of the pick order lines. New SKUs have to assign to the C class.

2. **Reassign storage locations to classes;**
   The reassignment of storage locations in the warehouse system has to result in a division that is based on Figure 19 – 22.

3. **Redesign of assignment rules of the storage location sizes per put away order line;**
   A put away order line has to be assigned to a storage location with a larger volume than the volume of the put away order line. The assignment rules in the warehouse system have to be changed.

4. **Redesign the put away strategy and the pick storage allocation strategy;**
   The storage allocation rules in the warehouse system have to be changed into the Best Fit put away strategy with the Farthest Fit pick strategy.

5. **Periodically pick frequency check of SKUs;**
   The actual pick frequency of SKUs needs to be checked periodically in the warehouse system.

6. **Relocate the inventory of SKUs that no longer belong to the current class;**
   Operational execution of relocating the inventory of SKUs to a storage location in the correct class based on the periodically pick frequency check.

Step 1 till 4 are short term primary implementation steps, while step 5 and 6 are long term periodically steps in order to optimize the storage process in the future.

7.2 Feasibility of the implementation

The feasibility of the implementation is determined by taking the actual warehouse characteristics into account with the requirements in order to cope with these characteristics.

The most important characteristic that influence the feasibility of the implementation is the fact that the majority of the SKUs is not measured. Implementing a new strategy can only result in savings if SKUs are measured. No storage allocation strategy can make beneficial decisions when the dimensions of the SKUs are unknown.
Besides, the effect of the four implementation steps on the storage location occupation is a kind of ‘Wilderness preservation’: the occupation of the farthest storage locations will be minimized and the occupation of the closest locations will be maximized. The system can easily mark the SKUs that have a relatively low put away and pick frequency, because these are stored at the storage locations at the end of its class. In contrast, SKUs with a relatively high put away and pick frequency are always stored in the beginning of each class. When periodically determining the actual pick frequency of the SKUs at the end of the class and the SKUs in the beginning of each class, one can determine if the SKUs have to be allocated to another class. In this way, the consequences of the dynamic fluctuations in the demand pattern of SKUs can be minimized. This contributes to the feasibility of the implementation plan, since the plan takes care of the changing demands of the SKUs.

Implementing the six steps can be doubted if initially a relocation of the current inventory is required based on the first two steps. However, implementing of the first four steps does only require changes in the warehouse system. Only the last step requires operational tasks that have to be executed after the periodically checks. In this way, the relocations of SKUs that are currently not at the correct storage location are gradually executed. Besides, the travel distance of SKUs that need to be relocated is already minimized with this strategy. These SKUs are already located at the beginning or end of the class and in this way, closer to their optimal class.

In order to determine the implementation plan as feasible, it has to be investigated whether it is still important to use FIFO. While a FIFO method is currently and theoretically used, the current system cannot manage the FIFO rules exactly. Therefore, changing the pick strategy into the Farthest Fit pick strategy that does not take care of the FIFO rules seems to be a feasible solution.
8. Conclusion

The last chapter of this report includes the conclusions that can be drawn from the research. In addition to these conclusions, the contributions towards the company are explained. Thereafter the academic relevance of the project is considered in Section 8.2. The final section consists of limitations of the research and suggestions for future research.

8.1 General conclusions

This section discusses the conclusions that are drawn from the different phases of the project.

8.1.1 Problem analysis

The problem that was indicated by the company has been examined in this report. Initially, an occupancy rate was observed that was higher than the target occupancy rate of 85 percent. However, the analysis of the problem has shown that the arrival and departure rates and quantities are difficult to forecast. Furthermore, the assortment exists of extremely diverse SKU characteristics and the capacity is limited. Another important conclusion of the analysis is the fact that multiple locations are assigned to SKUs. These challenging characteristics have ensured that using a fixed target occupancy rate of storage locations as a performance measurement is impossible. After determining a diagnosis of the problem, the initiated problem has been transformed into the following research question:

*How can a storage allocation strategy be developed to maximize the utilization of storage locations, minimize the travel distance with a service level constraint?*

8.1.2 Model

To provide an answer to the research question, a model has been designed to develop the storage allocation strategy. The first component of the model is the maximization of the utilization rate of the storage locations instead of minimizing the occupancy rate of storage locations. This has been formulated as a Dynamic Storage Allocation (DSA) problem. A minimization of the travel distance has been added to the model to prevent an increase in handling costs. Moreover, the model has a service level constraint which means that a minimum determined service level has to be achieved when solving the model. In this way, the model exists of maximizing the average performance which is transformed as minimizing the average location and handling costs while satisfying the service level constraint. As input storage allocation strategies, combinations of different existing storage allocation strategies are used. It was expected that the created storage allocation strategy ‘Best Fit with boundary put away strategy with the Farthest Fit pick strategy’ (BFb-FF strategy) would result into a minimization of the average location and handling costs. This strategy tries to store each put away order line in an empty location with a smaller travel distance than the sufficient and occupied storage location. A pick order line took place at the sufficient occupied location with the largest travel distance.

8.1.3 Results

The first step of reaching the objective consisted of a class rescheduling. It has resulted into a deviation of the reach, HOPT and shelving areas into three classes A, B and C that consist respectively of 20%, 30% and 50% of the storage locations. The deviation has to be used as a starting point and the dynamic borders ensure that the percentages can change when it is required.

The second step of reaching the objective was the determination of the storage allocation strategy for a single aisle. From the simulation study, it has been concluded that the storage allocation strategy that gives the best performance is dependent on the input parameters. In addition, a storage location
with a volume that is larger than the put away order line has resulted in a decrease in the overall costs. Moreover, the storage allocation strategy that has resulted into the minimum average costs is the ‘Best Fit put away strategy with a Farthest Fit pick strategy’. For each put away order line, the system tries to store the order line in an occupied location with the lowest leftover. For each pick order line, the system tries to pick the order line from an occupied location with the largest travel distance. The created BFb-FF strategy has not resulted, as expected, into the best overall performance.

Based on these results, the answer to the research question is as follows:

*A storage allocation strategy has been developed with a Best Fit put away strategy and a Farthest Fit pick strategy that minimizes the overall costs with respect to storage locations and handling.*

The following recommendations are formulated for succeeding the development:

- Invest in measuring all SKUs;
- Investigate whether it is still important to use a FIFO pick strategy;
- Investigate whether SKUs, especially SKUs of class E in the reach area, are still in the assortment of the customer;
- Assign SKUs to storage locations that are larger than the put away order line;
- Reassign SKUs to only three classes where A SKUs are responsible for about 80%, B SKUs for about 15% and C SKUs for about 5% of the pick order lines;
- Reassign storage locations to only three classes;
- Perform pick frequency checks periodically.

After implementing these recommendations, the utilization of storage locations will increase and the travel distance will decrease. The best practice with respect to the occupancy of storage locations is the result.

### 8.2 Contributions

The contributions of this master thesis project are divided into practical contributions and theoretical contributions.

#### 8.2.1 Practical contributions

The initial aim of the research was to find a method how the company has to respond to inventory fluctuations to maintain the optimal occupancy rate. Insights should be given about the causes of the inventory fluctuations, the factors for determining the optimal occupancy rate, the determination of the rate itself and how to maintain the optimal occupancy rate. However, it has been proven that using a utilization rate of the storage location is a better performance measurement in a warehouse with diverse distinguishing characteristics. Therefore, the aim has shifted into reaching a maximum utilization of storage locations and a minimum travel distance while satisfying a certain service level. The shifted aim has resulted into contributions with respect to the occupancy rate of storage locations. As a result, a solution is still provided for the initial problem of exceeding the target occupancy rate of storage locations. The BF-FF strategy results in 4.6 percent savings in storage location costs per SKU per year. The total costs, including storage location costs and handling costs, will decrease with 3.9 percent per SKU per year. In addition to these numbers, practical contributions can also be found in the decrease of relocation costs. These costs will decrease because of the fact that SKUs that need to be relocated due to ABC classification changes are already close to their new location.

The practical usefulness of the recommended strategy depends on the easiness to change the storage allocation strategy. Only the strategy needs to be changed in the warehouse system and the order lines
will be allocated to locations based on the new strategy. The operators do not notice the change in strategy while performing their tasks.

8.2.2 Theoretical contributions
The academic relevance is discussed by identifying the complement to the existing literature. In existing literature, much information can be found about warehouse operations in a deterministic, stochastic or dynamic environment. Models that describe more specific situations are also found in literature, however, they deal mostly only with a particular environment characteristic. Therefore, research in stochastic warehouse capacity decisions based on a tactical level seems to have some limitations. Existing literature does not focus on the special combination of the environment in which the company operates, namely a logistics provider with a changing demand and demand arrivals, dedicated storage policy, limited warehouse capacity, and accommodating a large number of different items. Therefore, this report contributes to the existing literature since it deals with the special combination of environments. A solution is given to deal with these combinations. When focusing on Dynamic Storage Allocation algorithms, most algorithms have only one dependent variable: the number of storage locations. However, in this report one extra dependent variable is added to the cost function: travel distance. This gives an extra dimension to the algorithm which has resulted into extensions of existing algorithms. Where in existing storage algorithms the storage locations are utilized till they reach their maximum capacity, it is in this case checked whether it is beneficial to fully utilize storage locations as long as there is no other location available with a smaller travel distance. Although the solution is different from the expectation, the BFb-FF strategy contributes to the academic literature and provides future research opportunities.

8.3 Limitations and future research
The last section of this report shows some limitations of the executed research and as a consequence, future research directions.

- The recommended strategy is based on characteristics of the largest part of the SKUs in a particular period. Not all different characteristics are considered. Therefore, it is interesting to examine the results of the recommended strategy with the current situation.
- Only one dimension of a SKU is considered. To manage this limitation, simulations should be executed to examine whether the results are still valid for other SKU dimensions.
- One operator executes only a single demand per time. Operations with multiple demands per time should be included.
- A put away order line does not always fit in the assigned storage location. It is interesting to further examine the effect of using overflow locations, since no significant effect is observed. However, this seems to result in a decrease in costs, especially when put away order line sizes are highly fluctuating.
- It is assumed that SKUs within a class do not have different priorities;
- This report does not specify the best practice for the exact size of locations and thereby, the required storage locations of different sizes are not determined. Future research should consider different sizes of locations and use the results of this to calculate the required storage capacity.
- A Poisson and Uniform distribution are used for respectively the pick and put away order line sizes. In order to check the validation of the results, different distributions should be assessed.
- The reslotting method where SKUs will be reallocated to another location is not completely described. However, reslotting of SKUs is based on the ABC classification method. Firstly, it
is recommended for future research to elaborate on a valid ABC classification. This has to be followed by determining a valid reslotting method.

- Simulations are executed, by using VBA, to compare the results per strategy. Other methodologies have to be used to validate and extent the results.
- Only seven strategies are simulated and compared for the dynamic storage allocation problem. Future research has to consider other available and relevant strategies.
- The results are not based on the opportunities of having a look ahead of the future arrivals and departures. It is interesting to examine whether the results of this research will change if there is a look ahead.
- The potential savings are based on the comparisons with the BF-FIFO strategy. However, the company is not certain about the current storage allocation strategy. It is useful for future storage process improvements to examine the current put away strategy.
- Only two boundary levels (0.70 and 0.80) have been considered for the BFb-FF strategy. It will be valuable to study the results of using other boundary levels.
- The simulations are executed with a target service level of 88%. Simulation with higher service level requirements is recommended to verify the solutions.
- It is suggested to invest in future research in the BFb-FF strategy. The boundary option should only be considered when the travel costs to the occupied location are higher than the additional location costs for an extra location. With this addition, the expected advantages of the BFb-FF strategy will probably increase.
- The strategies are compared in an environment with, on average, low demanding items. It is interesting to compare the strategies in an environment with high demanding SKUs such that strategies based on travel distances become more beneficial.
9. References


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Appendix A: Process flow

Figure 25: Process flow
Appendix B: Trucks

Figure 26: Example of a HOPT truck

Figure 27: Example of a reach truck
### Appendix C: Storage types

#### Table 11: Storage types with the dimensions

<table>
<thead>
<tr>
<th>Shelving Type</th>
<th>Dimensions*</th>
<th>Weight**</th>
<th>HOPT Type</th>
<th>Dimensions</th>
<th>Weight</th>
<th>Reach Type</th>
<th>Dimensions</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIN 08/15</td>
<td>15 x 8 x 8</td>
<td>3.3</td>
<td>HOPT 20</td>
<td>20 x 20 x 120</td>
<td>152</td>
<td>EURO</td>
<td>80 x h x 120</td>
<td>2.000</td>
</tr>
<tr>
<td>BIN 120/51</td>
<td>120 x 18 x 51</td>
<td>45</td>
<td>HOPT 25</td>
<td>25 x 20 x 120</td>
<td>203</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIN 22/12</td>
<td>12 x 15 x 22</td>
<td>4.5</td>
<td>HOPT 40</td>
<td>40 x 20 x 120</td>
<td>304</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIN 47/12</td>
<td>12 x 15 x 47</td>
<td>9</td>
<td>HOPT 80/20</td>
<td>80 x 20 x 120</td>
<td>608</td>
<td>Blok</td>
<td>120 x h x 120</td>
<td>2.000</td>
</tr>
<tr>
<td>BIN 53/24</td>
<td>24 x 16 x 53</td>
<td>20</td>
<td>HOPT 80/40</td>
<td>80 x 40 x 120</td>
<td>608</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIN 60/51</td>
<td>60 x 18 x 51</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* $(W_j \times H_j \times D_j)$ in centimeters

** Weight in kilograms
Appendix D: Storage assignment algorithm

1. Determination of the storage type
   - Is there an existing location?
     - Yes
       - Correct storage type
         - No mixed SKUs?
           - Yes
             - Same country of origin?
               - Yes
                 - overflow
               - No
                 - Only one storage type larger
         - No
         - Only one storage type larger
     - No
       - Only one storage type larger
   - No
     - No
     - Determination of the exact location
       - Yes
         - overflow
       - No
         - overflow

2a. Replenishment location
   - Correct storage type
     - No mixed SKUs?
       - Yes
         - Same country of origin?
           - Yes
             - overflow
           - No
             - overflow
     - No
     - overflow
   - overflow

2b. New location
   - Correct storage type
     - Correct storage type and class
       - Correct storage type and zone
         - Correct zone and one storage type larger
           - Only correct storage type
             - Only one storage type larger
               - overflow
             - No
               - overflow
           - No
           - Only one storage type larger
         - No
         - Only one storage type larger
       - overflow
   - overflow

Figure 28: Current storage assignment algorithm
# Appendix E: Stock, put away and pick quantity analysis

Table 12: Descriptive statistics of stock levels of four example SKUs

<table>
<thead>
<tr>
<th>Example</th>
<th>Statistic</th>
<th>Value</th>
<th>Equal sizes?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>7,68</td>
<td></td>
</tr>
<tr>
<td>Example1</td>
<td>95% Confidence Interval for Mean</td>
<td>6,73</td>
<td>No (4 &gt;1,35*1,974)</td>
</tr>
<tr>
<td></td>
<td>Lower Bound</td>
<td>6,73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper Bound</td>
<td>8,64</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>8,00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Std. Deviation</td>
<td>1,974</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coefficient of variation</td>
<td>0,26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interquartile Range</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>220,68</td>
<td></td>
</tr>
<tr>
<td>Example2</td>
<td>95% Confidence Interval for Mean</td>
<td>196,98</td>
<td>No (80 &gt;1,35*49,175)</td>
</tr>
<tr>
<td></td>
<td>Lower Bound</td>
<td>196,98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper Bound</td>
<td>244,39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>229,00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Std. Deviation</td>
<td>49,175</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coefficient of variation</td>
<td>4,49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>111</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>268</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>157</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interquartile Range</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>81,89</td>
<td></td>
</tr>
<tr>
<td>Example3</td>
<td>95% Confidence Interval for Mean</td>
<td>66,51</td>
<td>No (67 &gt;1,35*31,92)</td>
</tr>
<tr>
<td></td>
<td>Lower Bound</td>
<td>66,51</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper Bound</td>
<td>97,28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>63,00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Std. Deviation</td>
<td>31,92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coefficient of variation</td>
<td>0,39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>45,00</td>
<td></td>
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<td></td>
<td>Maximum</td>
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<tr>
<td></td>
<td>Range</td>
<td>78,00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interquartile Range</td>
<td>67,00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>13,00</td>
<td></td>
</tr>
<tr>
<td>Example4</td>
<td>95% Confidence Interval for Mean</td>
<td>8,56</td>
<td>No (19 &gt;1,35*9,21)</td>
</tr>
<tr>
<td></td>
<td>Lower Bound</td>
<td>8,56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper Bound</td>
<td>17,44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>20,00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Std. Deviation</td>
<td>9,21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coefficient of variation</td>
<td>0,71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>1,00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>20,00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>19,00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interquartile Range</td>
<td>19,00</td>
<td></td>
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Table 13: Normality tests results of example SKUs

<table>
<thead>
<tr>
<th></th>
<th>Kolmogorov-Smirnov</th>
<th></th>
<th>Shapiro-Wilk</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistic</td>
<td>df</td>
<td>Sig.</td>
<td>Statistic</td>
</tr>
<tr>
<td>Stock1</td>
<td>.195</td>
<td>19</td>
<td>.054</td>
<td>.841</td>
</tr>
<tr>
<td>Stock2</td>
<td>.284</td>
<td>19</td>
<td>.000</td>
<td>.818</td>
</tr>
<tr>
<td>Stock3</td>
<td>.302</td>
<td>19</td>
<td>.000</td>
<td>.791</td>
</tr>
<tr>
<td>Stock4</td>
<td>.355</td>
<td>19</td>
<td>.000</td>
<td>.641</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Kolmogorov-Smirnov</th>
<th></th>
<th>Shapiro-Wilk</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistic</td>
<td>df</td>
<td>Sig.</td>
<td>Statistic</td>
</tr>
<tr>
<td>Putaway1</td>
<td>.216</td>
<td>3</td>
<td>.989</td>
<td>.989</td>
</tr>
<tr>
<td>Putaway2</td>
<td>.385</td>
<td>3</td>
<td>.750</td>
<td>.750</td>
</tr>
<tr>
<td>Putaway3</td>
<td>.385</td>
<td>3</td>
<td>.750</td>
<td>.750</td>
</tr>
<tr>
<td>Putaway4</td>
<td>.385</td>
<td>3</td>
<td>.750</td>
<td>.750</td>
</tr>
<tr>
<td>Pick1</td>
<td>.362</td>
<td>17</td>
<td>.000</td>
<td>.703</td>
</tr>
<tr>
<td>Pick3</td>
<td>.436</td>
<td>26</td>
<td>.000</td>
<td>.583</td>
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<tr>
<td>Pick4</td>
<td>.312</td>
<td>131</td>
<td>.000</td>
<td>.588</td>
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</table>

* Pick2 is constant and therefore, omitted from the table.

* = The p-value of all SKUs is smaller than 0.05 that shows that all example SKUs have a not normal distribution. The null hypothesis for each of them is rejected that states that the sample distribution is normal (Ghasemi & Zahediasl, 2012).

Figure 29: Boxplot example stock SKU 2

Figure 30: Histogram example stock example SKU 2
Table 14: Statistics pick frequencies shelving per class in January 2016

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Shelving A</th>
<th>Shelving B</th>
<th>Shelving C</th>
<th>Shelving D</th>
<th>Shelving E</th>
</tr>
</thead>
<tbody>
<tr>
<td>N Valid</td>
<td>2018</td>
<td>6537</td>
<td>7158</td>
<td>7247</td>
<td>21973</td>
</tr>
<tr>
<td>Mean</td>
<td>7.71</td>
<td>2.20</td>
<td>.84</td>
<td>.27</td>
<td>.01</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>6.427</td>
<td>1.655</td>
<td>.871</td>
<td>.514</td>
<td>.094</td>
</tr>
<tr>
<td>Minimum</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maximum</td>
<td>90</td>
<td>14</td>
<td>7</td>
<td>4</td>
<td>3</td>
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</tbody>
</table>

Table 15: Kolmogorov- Smirnov results shelving pick frequencies per ABC in January 2016

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Kolmogorov-Smirnov</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shelving A</td>
<td>Statistic</td>
</tr>
<tr>
<td></td>
<td>,173</td>
</tr>
<tr>
<td>Shelving B</td>
<td>,202</td>
</tr>
<tr>
<td>Shelving C</td>
<td>,261</td>
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<tr>
<td>Shelving D</td>
<td>,463</td>
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<tr>
<td>Shelving E</td>
<td>,528</td>
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</table>

Table 16: Statistics pick frequencies reach per class in January 2016

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Reach A</th>
<th>Reach B</th>
<th>Reach C</th>
<th>Reach D</th>
<th>Reach E</th>
</tr>
</thead>
<tbody>
<tr>
<td>N Valid</td>
<td>1400</td>
<td>2211</td>
<td>2433</td>
<td>933</td>
<td>7399</td>
</tr>
<tr>
<td>Mean</td>
<td>2.35</td>
<td>,92</td>
<td>,82</td>
<td>,04</td>
<td>,0023</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>5.062</td>
<td>1.250</td>
<td>2.711</td>
<td>,231</td>
<td>,05571</td>
</tr>
<tr>
<td>Minimum</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maximum</td>
<td>101</td>
<td>18</td>
<td>103</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 17: Kolmogorov- Smirnov results reach pick frequencies per ABC in January 2016

<table>
<thead>
<tr>
<th>Statistics</th>
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</thead>
<tbody>
<tr>
<td>Reach A</td>
<td>Statistic</td>
</tr>
<tr>
<td></td>
<td>,321</td>
</tr>
<tr>
<td>Reach B</td>
<td>,265</td>
</tr>
<tr>
<td>Reach C</td>
<td>,381</td>
</tr>
<tr>
<td>Reach D</td>
<td>,533</td>
</tr>
<tr>
<td>Reach E</td>
<td>,514</td>
</tr>
</tbody>
</table>
Table 18: Statistics pick frequencies HOPT per class in January 2016

<table>
<thead>
<tr>
<th>Statistics</th>
<th>HOPT A</th>
<th>HOPT B</th>
<th>HOPT C</th>
<th>HOPT D</th>
<th>HOPT E</th>
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</thead>
<tbody>
<tr>
<td>N Valid</td>
<td>1967</td>
<td>2962</td>
<td>1353</td>
<td>766</td>
<td>3256</td>
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<tr>
<td>Mean</td>
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<td>1,18</td>
<td>,87</td>
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<td>Std. Deviation</td>
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<tr>
<td>Minimum</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maximum</td>
<td>155</td>
<td>24</td>
<td>113</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 19: Kolmogorov-Smirnov results HOPT pick frequencies per ABC in January 2016

<table>
<thead>
<tr>
<th>Kolmogorov-Smirnov Statistic</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOPT A</td>
<td>1967</td>
<td>0,000</td>
</tr>
<tr>
<td>HOPT B</td>
<td>2962</td>
<td>0,000</td>
</tr>
<tr>
<td>HOPT C</td>
<td>1353</td>
<td>0,000</td>
</tr>
<tr>
<td>HOPT D</td>
<td>766</td>
<td>0,000</td>
</tr>
<tr>
<td>HOPT E</td>
<td>3256</td>
<td>0,000</td>
</tr>
</tbody>
</table>

Table 20: Put and pick ratio of all SKUs that are both put and picked in January 2016

<table>
<thead>
<tr>
<th>x = λpu/λpu</th>
<th>x = pavg/pavg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of SKUs</td>
<td>% of SKUs</td>
</tr>
<tr>
<td>x ≤ 1</td>
<td>2825</td>
</tr>
<tr>
<td>1 &lt; x ≤ 3</td>
<td>1926</td>
</tr>
<tr>
<td>3 &lt; x ≤ 5</td>
<td>715</td>
</tr>
<tr>
<td>5 &lt; x ≤ 10</td>
<td>656</td>
</tr>
<tr>
<td>10 &lt; x ≤ 20</td>
<td>266</td>
</tr>
<tr>
<td>20 &lt; x ≤ 40</td>
<td>84</td>
</tr>
<tr>
<td>40 &lt; x ≤ 80</td>
<td>17</td>
</tr>
<tr>
<td>80 &lt; x ≤ 160</td>
<td>5</td>
</tr>
</tbody>
</table>
Appendix F: ABC analysis

Table 21: ABC analysis ranking example

<table>
<thead>
<tr>
<th>SKU_ID</th>
<th>Storage type**</th>
<th>Total picks per year</th>
<th>Pick ranking***</th>
<th>Months picked/Months in stock Factor</th>
<th>Months since last pick</th>
<th>Month since last pick Factor****</th>
<th>Total score ****</th>
<th>Rank</th>
<th>ABC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HOPT 20</td>
<td>1591</td>
<td>985,47</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>985,47</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>BIN 60/51</td>
<td>1666</td>
<td>964,43</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>964,43</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>HOPT 20</td>
<td>1551</td>
<td>914,5</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>914,5</td>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>HOPT 20</td>
<td>1533</td>
<td>911,23</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>911,23</td>
<td>3</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>REACH</td>
<td>1470</td>
<td>867,31</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>867,31</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>6</td>
<td>HOPT 20</td>
<td>18</td>
<td>9,24</td>
<td>0,67</td>
<td>0</td>
<td>1</td>
<td>6,1908</td>
<td>4</td>
<td>B</td>
</tr>
</tbody>
</table>

*1 = Based on most used put awayed storage type over the last year
*2 = Sum of the picks per month multiplied by the month factor (Figure 20)
*3 = Rate to put recent picks higher than picks longer ago based on months since last pick (Figure 21)
*4 = Pick ranking multiplied by the months picked/months in stock factor and the month since last pick factor
*5 = SKU 6 is assigned to class B based on the fact that SKU 1, 3 and 4 reach the maximum occupied storage locations of HOPT 20 class A
Appendix G: Existing storage allocation strategies
(Balogh et al, 2014; Dósa & He, 2006; Gambosi et al., 2000; Johnson, 1974;Johnson et al., 1974; Kamali & López-Ortiz, 2015; Masmano et al., 2004; Rieck, 2010; Yao, 1980; Wilson et al., 1995)

Table 22: Existing DSA policies

<table>
<thead>
<tr>
<th>DSA policy</th>
<th>Description</th>
<th>Complexity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Sequential fits</td>
<td>Uses a single linear list of all free locations</td>
<td>O(n)</td>
<td>- Complexity depends on number of existing free locations</td>
</tr>
<tr>
<td>a1. Wilderness preservation heuristic</td>
<td>Keeps the wilderness locations out of the list of location. These locations can only be used when no other location can be selected.</td>
<td>Unknown</td>
<td>- Best fit and First Fit will always select any other location before storing it into the wilderness</td>
</tr>
<tr>
<td>b. Segregated free lists (current algorithm)</td>
<td>Uses an array of free classes where each class holds free locations of a particular size</td>
<td>Unknown</td>
<td>- Fast when locations of a given size are repeatedly freed and reallocated over short periods of time - Exclude locations with SKUs of different sizes - Complexity is not dependent on number of free locations</td>
</tr>
<tr>
<td>c. Buddy systems</td>
<td>When a location is freed, its buddy location can always be easily found by an address computation. The buddy location is always an entirely free</td>
<td>O(log₂N)</td>
<td>- Variant of Segregated free lists - Less attractive since producing large internal fragmentation - Good timing behavior - Not suitable for real time systems due to high executing time</td>
</tr>
<tr>
<td>d. Indexed fits</td>
<td>Indexes locations by exactly its characteristics and supports efficient searching according to the characteristics</td>
<td>Unknown</td>
<td>- Size based policies seems to be more easy than address-based policies - Can perform better than Segregated free lists if searching time to find a locations block does not dependent on number of free locations</td>
</tr>
<tr>
<td>e. Bitmap fits</td>
<td>Uses a bitmap to see which locations are blocked or free</td>
<td>O(n)</td>
<td>- All relevant information is stored in a small piece of memory, so improves the response time</td>
</tr>
<tr>
<td>e1. Half-fit</td>
<td>Uses free locations groups where free locations are linked. A free locations of a required size is taken that will always satisfy the request.</td>
<td>O(1)</td>
<td>- Accesses only a few location addresses - Better than binary buddy system</td>
</tr>
</tbody>
</table>

Table 23: One dimensional packing algorithms

<table>
<thead>
<tr>
<th>Any fit online bin packing algorithm</th>
<th>Description</th>
<th>Complexity</th>
<th>ARP</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Next fit</td>
<td>Checks whether the piece fits in the current bin. If not, a new bin will be selected as the current bin.</td>
<td>O(n)</td>
<td>RNF₆₆ = 2</td>
<td>- Simple algorithm - Requires many locations - Reduce calculation time - Calculation time increases when number of free locations increase</td>
</tr>
<tr>
<td>2. First fit *</td>
<td>Checks whether the piece fits in the first created bin. If not, it will check the second bin created and so on. If no bin can be selected, a new bin will be created. (A LIFO policy can also be used where</td>
<td>O(n log n)</td>
<td>R₆₆₅₈ = 127/30</td>
<td>- Simple algorithm - Calculation time increases when number of free locations increase - Not suitable for real time systems due to high execution time</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| **3. Best fit** * | Checks whether the piece fits in the bin with the smallest leftover. If not, it will check the second bin and so on. If no bin can be selected, a new bin will be created. | $O(n \log n)$ | $R_{BF} = R_{FF}$ | - Mix of small and large order lines gives a good performance  
- Good performance if large order line arrives earlier than the small order lines  
- Small empty spaces may be useless  
- Minimize the chance of not being able to stock a large order line  
- Out performs First and Next fit for sequences generated uniformly at random and more scalable implementations are possible  
- Calculation time increases when number of free locations increase  
- Produce smallest fragmentation  
- Not suitable for real time systems due to high execution time |

| **4. Worst fit** * | Checks whether the piece fits in the bin with the largest leftover. If not, a new bin will be created. | $O(n \log n)$ | $R_{WF} = R_{NF}$ | - Achieves better performance if order lines are the same size  
- Calculation time increases when number of free locations increase |

| **5. Revised first fit** | Checks whether the piece belongs and fits in one of the four determined classes in a non-empty bin. If not, it will check a new bin in the class. If no bin can be selected in the class, a non empty bin will be checked in another class. If no bin can be selected, a new bin will be selected in that class. | $O(n \log n)$ | $R_{RFF} = \frac{5}{3}$ | - Outperforms other algorithms on the average case  
- Likely to perform well in a multi-command situation |

| **6. Move To Front** | Checks the bins one by one, starting from the front of the list, until it finds a bin that has enough space. If no bin can be selected, a new bin will be selected in that class. After placing the SKU, the selected bin is moved to the front of the list. | $O(n \log n)$ | Unknown | - Outperforms other algorithms on the average case  
- Likely to perform well in a multi-command situation |

| **7. Almost Worst fit** * | Checks whether the piece fits in the non-empty bin with the second largest leftover. If not, it will check the largest leftover. If no bin can be selected, a new bin will be created. | $O(n \log n)$ | $R_{AWF} = R_{FF}$ | - Assumes that a certain number of very small SKUs in the same bin can be collected together and considered as a single unit |

| **8. Harmonic Fit Rule** – k | SKUs are divided into different classes as they arrive. Checks whether the piece fits in the current bin within the class. If not, a new bin will be selected as the current bin. | $O(n)$ | $R_{HRF} = 1,692$ | - Allow only a restricted finite number of open bins in each step  
- Maximum number of repacks |

**Other any fit online bin packing algorithm**

**Semi online bin packing algorithm***

* = An Any Fit (AF) algorithm never puts an order line into an empty storage location, only when the order line does not fit in any of the partially filled locations.  
An Almost Any Fit (AAF) algorithm never puts an order line into a partially filled location with the largest leftover, only when there is more than one location with the largest leftover or only when the partially filled location is the only location that has enough free space (Complexity AAF $\geq O(n \log n)$ and for any $R_{AAF} = R_{FF}$).  
*** = Semi online algorithms do allowed at least one of the following: repacking, look ahead or preprocessing.
Appendix H: Expectations BFb-FF strategy

- Storage size is determined based on average inventory.
- Prefers empty put locations of determined size with a smaller distance rather than occupied, sufficient put locations of determined size with high utilization rate.
- Assigns to Best Fit put location if no new put location is closer.
- Assigns to empty put location of determined size if no occupied put location is sufficient.
- Assigns pick location where travel distance is the smallest.

Figure 33: Expectations BFb-FF strategy
## Appendix I: Validation & verification of the model

### Table 24: Summary of the verification and validation of the models

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Interleaving</th>
<th>$\lambda_{pi}$ / $\lambda_{pu}$</th>
<th>Put away size</th>
<th>Pick size</th>
<th>Locations size</th>
<th>Max. used locations</th>
<th>Average utilization rate</th>
<th>Average travel distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Predicted</td>
<td>Actual</td>
<td>Predicted</td>
</tr>
<tr>
<td>BF-FF</td>
<td>Perfect interleaving</td>
<td>1</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>15/18</td>
</tr>
<tr>
<td></td>
<td>Perfect interleaving</td>
<td>1</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>15/18</td>
</tr>
<tr>
<td></td>
<td>No perfect interleaving</td>
<td>3</td>
<td>18</td>
<td>6</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>18/18</td>
</tr>
<tr>
<td>BF-FIFO</td>
<td>Perfect interleaving</td>
<td>1</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>15/18</td>
</tr>
<tr>
<td></td>
<td>No perfect interleaving</td>
<td>3</td>
<td>18</td>
<td>6</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>18/18</td>
</tr>
<tr>
<td>BF-LIFO</td>
<td>Perfect interleaving</td>
<td>1</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>15/18</td>
</tr>
<tr>
<td></td>
<td>No perfect interleaving</td>
<td>3</td>
<td>18</td>
<td>6</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>18/18</td>
</tr>
<tr>
<td>WF-FIFO</td>
<td>Perfect interleaving</td>
<td>1</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>15/18</td>
</tr>
<tr>
<td></td>
<td>No perfect interleaving</td>
<td>3</td>
<td>18</td>
<td>6</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>18/18</td>
</tr>
<tr>
<td>BF-WF</td>
<td>Perfect interleaving</td>
<td>1</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>15/18</td>
</tr>
<tr>
<td></td>
<td>No perfect interleaving</td>
<td>3</td>
<td>18</td>
<td>6</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>18/18</td>
</tr>
<tr>
<td>BFb-FF</td>
<td>Perfect interleaving</td>
<td>1</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>15/18</td>
</tr>
<tr>
<td></td>
<td>No perfect interleaving</td>
<td>3</td>
<td>18</td>
<td>6</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>18/18</td>
</tr>
<tr>
<td>CF-FF</td>
<td>Perfect interleaving</td>
<td>1</td>
<td>15</td>
<td>15</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>15/18</td>
</tr>
<tr>
<td></td>
<td>No perfect interleaving</td>
<td>3</td>
<td>18</td>
<td>6</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>18/18</td>
</tr>
</tbody>
</table>

* = One location can be utilized by four lines. After every four lines, the current location is (15/18 $\rightarrow$ 3/18 $\rightarrow$ 18/18 $\rightarrow$) 6/18 utilized. A new location has to be occupied with a put away quantity of 12. Therefore, in order to store 100 order lines 25 locations are needed.

** = On average, every location is utilized in the following order (after every put away line) 15/18; 18/18; 6/18. After this, the location will stay for 6/18 utilized and a new location will be utilized for 15/18. The average utilization for 25 locations goes to 42,4 % over 100 order lines.

***=Average travel distance to the first 25 locations.

---

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Appendix J: Rescheduling results

Figure 34: Racking design

Most favorable locations

Least favorable locations

Table 25 Favorability of locations based on historical data

<table>
<thead>
<tr>
<th>Reach area</th>
<th>Pick times (sec)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bay / Level</td>
<td>Low (0 – 6)</td>
<td>High (7 – 9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 – 17</td>
<td>48</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 – 34</td>
<td>51</td>
<td>89</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 – 52</td>
<td>43</td>
<td>99</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HOPT area</th>
<th>Pick times (sec)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bay / Level</td>
<td>Low (1-8)</td>
<td>High (9-13)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 – 15</td>
<td>30</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 – 30</td>
<td>31</td>
<td>59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31 - 44</td>
<td>30</td>
<td>61</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shelving area</th>
<th>Pick times (sec)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bay / Level</td>
<td>Low (1-4)</td>
<td>Mid (5-7)</td>
<td>High (8-10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>13</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>14</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>17</td>
<td>28</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results travel time function

\[ D_{o,k,a}(a) = \begin{cases} 
2(1,2b_k + 1,8g_k + 1,8l_k) + 4,2 + 6,6 & \text{if } a = \text{reach} \\
1,2b_k + 1,8g_k + 3,6l_k + 4,2 - 3,4 & \text{if } a = \text{HOPT} \\
1,8b_k \ast w_k + st_b \ast s_k + 3,0 + 5,7 & \text{if } a = \text{shelving} 
\end{cases} \]

where
\[ w_k + s_k = 1 \]
\[ g_k, s_k, st_b, w_k \geq 0 \]
\[ 0 \geq f_k \geq 26 \]
\[ 0 \geq b_k \geq 22 \]
\[ 0 \geq l_k \geq 13 \]

Figure 35: Travel time formula results
Appendix K: Functions and parameters simulation

Functions

- \( D_{a,k,k-1} = \frac{1}{N_C R} f_a \)

where \( D_{a,k,k-1} \) is the travel distance between \( k \) and \( k-1 \) in area \( a \) and \( f_a \) the total length of an aisle in area \( a \)

- \( \bar{O}_\mu = \sum_{s=1}^{S} O_s \cdot p(s) \) and \( O_\sigma = \sqrt{\frac{\sum_{s=1}^{S} p(s)(O_s - O_\mu)^2}{\sum_{s=1}^{S} p(s)}} \) with \( O_\mu = \sum_{t=1}^{T} \frac{\sum_{j=1}^{N} J_{j,t}}{K} \)

where \( O_\mu \) is the weighted average occupancy rate, \( O_\sigma \) the weighted standard deviation of the occupancy rate and \( O_\mu \) the average occupancy rate

- \( SL_\mu = \sum_{s=1}^{S} SL_s \cdot p(s) \) and \( SL_\sigma = \sqrt{\frac{\sum_{s=1}^{S} p(s)(SL_s - SL_\mu)^2}{\sum_{s=1}^{S} p(s)}} \) with \( SL_\mu = \sum_{t=1}^{T} \frac{P_U_t - E_t}{P_U_t} \)

where \( SL_\mu \) is the weighted average service level, \( SL_\sigma \) the weighted standard deviation of service level and \( SL_\mu \) the average service level

Table 26: Input values simulation

<table>
<thead>
<tr>
<th>Classes</th>
<th>Monthly picks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3,31</td>
</tr>
<tr>
<td>B</td>
<td>0,81</td>
</tr>
<tr>
<td>C</td>
<td>0,06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Days per year</td>
<td>360</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost components</th>
<th>Variable</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holding costs</td>
<td>( c_w )*</td>
<td>€/m²/month</td>
</tr>
<tr>
<td>Handling costs</td>
<td>( c_n )**</td>
<td>€/m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aisle length</th>
<th>Variable</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shelving</td>
<td>( f_{shelving} )</td>
<td>m</td>
<td>8,10</td>
</tr>
<tr>
<td>Reach</td>
<td>( f_{reach} )</td>
<td>m</td>
<td>29,70</td>
</tr>
</tbody>
</table>

* Based on 13% shelving m² and 87% reach m² and 10 levels per m²
** Based on 62% shelving picks with an average speed of 0,5m/s and 38% reach picks with an average speed of 2 m/s
Appendix L: Interpretation of simulation results in SPSS

1. Hypotheses related to the put away and pick strategy

1.1 Comparing strategies
When interpreting the results of the simulation, it started with analysing categorical variables in order to predict a kind of continuous outcome about the strategies. The categorical values are the frequencies a strategy is assigned as the best practice strategy for every KPI. This includes the frequency a specific strategy is appointed as the strategy that leads to the minimum KPI. By doing a Pearson’s chi-square test, it is examined whether there is a relationship between the KPIs. The assumptions of this test are (Field, 2009):
1. Observations should be independent;
2. The expected frequencies should be greater than 5.

From the simulation design it is assumed that the simulations are independent of each other since all statistics are recorded separately. However, the second assumption is not met. The frequency a strategy is appointed as a best practice strategy is expected to be lower than 5. For this reason, the Pearson’s chi-square test will give inaccurate outcomes. A Fisher’s exact test is used that can deal with small sample sizes.

Table 27: Crosstabulation of best practice frequencies per strategy per KPI

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average utilization rate</th>
<th>Total travel distance</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF-WF</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>BFb-FF</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BF-FF</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CF-FF</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>WF-FIFO</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>BF-FIFO</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>BF-LIFO</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>9</strong></td>
<td><strong>9</strong></td>
<td><strong>18</strong></td>
</tr>
</tbody>
</table>

Table 28: Chi-Square tests best practice frequencies

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>df</th>
<th>Asymp. Sig. (2-sided)</th>
<th>Exact Sig. (2-sided)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson Chi-Square</td>
<td>20.357*</td>
<td>12</td>
<td>0.061</td>
<td>0.019</td>
</tr>
<tr>
<td>Likelihood Ratio</td>
<td>22.038</td>
<td>12</td>
<td>0.037</td>
<td>0.039</td>
</tr>
<tr>
<td>Fisher's Exact Test</td>
<td>15.233</td>
<td></td>
<td>0.048</td>
<td></td>
</tr>
<tr>
<td>N of Valid Cases</td>
<td>18</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From the output of SPSS, it can be concluded that there is a significant relation between the KPIs (p<0.05). This conclusion can be supported by the fact that having a high utilization results in a small number of storage locations that result in higher travel costs. Therefore, this conclusion can be validated. Furthermore, observable is that for almost 45% of the situations the BF-WF strategy results in the best practice strategy with respect to both KPIs.

1.2 Comparing means
After comparing only the results of the strategies, an ANOVA test is executed to compare the means of the strategies. Firstly, the assumptions of this test are checked in order to be able to use an ANOVA test. The assumptions are (Field, 2009):
1. The distribution within the results of the strategies needs to be normally distributed;
2. Observations should be independent;
3. The variances in each experimental condition need to be fairly similar.
Table 29: Descriptives per strategy of the KPIs

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
<th>95% Confidence Interval for Mean</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average utilization rate</td>
<td>BF-WF</td>
<td>6.5801</td>
<td>.150639</td>
<td>.061498</td>
<td>.49993</td>
<td>8.10610</td>
<td>4.69</td>
<td>8.79</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BFb0.7-FF</td>
<td>6.62037</td>
<td>.117838</td>
<td>.048107</td>
<td>.49671</td>
<td>7.4403</td>
<td>4.70</td>
<td>7.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BFb0.8-FF</td>
<td>6.62037</td>
<td>.117838</td>
<td>.048107</td>
<td>.49671</td>
<td>7.4403</td>
<td>4.70</td>
<td>7.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BF-FF</td>
<td>6.63581</td>
<td>.093328</td>
<td>.038101</td>
<td>.53787</td>
<td>7.3376</td>
<td>5.30</td>
<td>7.66</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CF-FF</td>
<td>6.61388</td>
<td>.118745</td>
<td>.048477</td>
<td>.48927</td>
<td>7.3850</td>
<td>4.70</td>
<td>7.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WF-FIFO</td>
<td>6.63839</td>
<td>.058823</td>
<td>.024014</td>
<td>.57666</td>
<td>7.0012</td>
<td>5.70</td>
<td>7.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BF-FIFO</td>
<td>6.61074</td>
<td>.094483</td>
<td>.038573</td>
<td>.51159</td>
<td>7.0990</td>
<td>4.90</td>
<td>7.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BF-LIFO</td>
<td>6.58339</td>
<td>.112014</td>
<td>.045729</td>
<td>.46584</td>
<td>7.0094</td>
<td>4.40</td>
<td>7.27</td>
<td></td>
</tr>
<tr>
<td>Total travel distanceBF-WF</td>
<td>6</td>
<td>53107.328</td>
<td>47567.4131</td>
<td>19419.3150</td>
<td>3188.3851</td>
<td>103026.2624</td>
<td>25539.30</td>
<td>149747.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BFb0.7-FF</td>
<td>6</td>
<td>67063.5718</td>
<td>61744.1981</td>
<td>25206.9633</td>
<td>2267.0997</td>
<td>131860.1339</td>
<td>32020.46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BFb0.8-FF</td>
<td>6</td>
<td>67063.5718</td>
<td>61744.1981</td>
<td>25206.9633</td>
<td>2267.0997</td>
<td>131860.1339</td>
<td>32020.46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BF-FF</td>
<td>6</td>
<td>69740.4477</td>
<td>64181.8520</td>
<td>26202.1337</td>
<td>2385.7247</td>
<td>137095.1706</td>
<td>32742.51</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CF-FF</td>
<td>6</td>
<td>64845.7173</td>
<td>58399.0043</td>
<td>23841.2930</td>
<td>3199.7208</td>
<td>125771.7139</td>
<td>32264.61</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WF-FIFO</td>
<td>6</td>
<td>53312.0491</td>
<td>45910.4892</td>
<td>18742.8787</td>
<td>101492.1528</td>
<td>26984.57</td>
<td>146609.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BF-FIFO</td>
<td>6</td>
<td>63044.2547</td>
<td>58819.4653</td>
<td>20095.4290</td>
<td>19177.3539</td>
<td>35265.8453</td>
<td>26610.81</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BF-LIFO</td>
<td>6</td>
<td>57901.5809</td>
<td>46358.5755</td>
<td>18925.8092</td>
<td>9251.2395</td>
<td>10655.9223</td>
<td>151549.20</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td>61964.8135</td>
<td>53353.3850</td>
<td>7700.8978</td>
<td>46472.6054</td>
<td>74457.0216</td>
<td>25539.30</td>
<td>203217.30</td>
<td></td>
</tr>
</tbody>
</table>

Table 30: Normality check KPIs

<table>
<thead>
<tr>
<th>KPI</th>
<th>Kolmogorov-Smirnov*</th>
<th>Shapiro-Wilk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average utilization rate</td>
<td>.096</td>
<td>.200</td>
</tr>
<tr>
<td>Total travel distance</td>
<td>.378</td>
<td>.000</td>
</tr>
</tbody>
</table>

Table 31: Test for homogeneity of variances KPIs

<table>
<thead>
<tr>
<th>KPI</th>
<th>Levene Statistic</th>
<th>df1</th>
<th>df2</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average utilization rate</td>
<td>1.379</td>
<td>7</td>
<td>40</td>
<td>.241</td>
</tr>
<tr>
<td>Total travel distance</td>
<td>1.149</td>
<td>7</td>
<td>40</td>
<td>.993</td>
</tr>
</tbody>
</table>

It can be observed that the results of the BF boundary – FF for both boundaries are equal. Therefore, only BF boundary – FF is displayed instead of two different strategies. The SPSS output in Table 30 shows that the results of the average utilization rate of storage locations is normality distributed (p>0.05) and the total travel distances deviates from normality. However, the number of results of all strategies is equal which suggests that ANOVA can still be executed. The variances for each strategy are about equal for every KPI (p>0.05). Finally, it can be assumed that the simulations are independent of each other since.

1.2.1 Comparing means strategies

The results of ANOVA are displayed in Table 32. There were no statistically significant differences between strategy means as determined by one-way ANOVA. This could be explained by the fact that the results of the strategies differ and are dependent of the input parameters. Therefore, the standard deviations per KPI per strategy are relatively high as can be observed in Table 29.
Table 32: ANOVA results comparing strategy means of strategies

<table>
<thead>
<tr>
<th></th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average utilization rate</td>
<td>1021</td>
<td>7</td>
<td>.003</td>
<td>240</td>
<td>.972</td>
</tr>
<tr>
<td>Between Groups</td>
<td>.491</td>
<td>40</td>
<td>.012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Within Groups</td>
<td>.512</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1738863626,932</td>
<td>7</td>
<td>248409089,562</td>
<td>.075</td>
<td>.999</td>
</tr>
<tr>
<td>Between Groups</td>
<td>13205056983,065</td>
<td>40</td>
<td>3301264249,577</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Within Groups</td>
<td>133789433609,997</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>133789433609,997</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For checking hypothesis 4, the means of BF-LIFO and BF-FIFO results are compared based on their utilization rate.

Table 33: Comparison of FIFO and LIFO

<table>
<thead>
<tr>
<th>Strategy</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average utilization rate</td>
<td>BF-FIFO</td>
<td>6</td>
<td>.61074</td>
<td>.094483</td>
</tr>
<tr>
<td></td>
<td>BF-LIFO</td>
<td>6</td>
<td>.58339</td>
<td>.112014</td>
</tr>
</tbody>
</table>

Table 34: Independent t-test FIFO versus LIFO

<table>
<thead>
<tr>
<th>Levene’s Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Sig.</td>
</tr>
<tr>
<td>Average utilization rate</td>
<td>835</td>
</tr>
<tr>
<td>Equal variances assumed</td>
<td>.457</td>
</tr>
<tr>
<td>Equal variances not assumed</td>
<td></td>
</tr>
</tbody>
</table>

In order to reject or accept the hypothesis that stated that the BF-LIFO strategy results in the best performance in terms of utilization of storage locations in comparison with a BF-FIFO strategy an independent t-test is executed. It can be observed that there is no difference in variances between the strategies (p>0.05). Besides, there is no significant difference between the means of both strategies (p>0.05). From these statements, it can be concluded that hypothesis 4 can be rejected.

2. Hypotheses related to the size of a location

2.1 Total travel distance

2.1.1 Size of location

Table 35: Descriptives size of a location based on travel distance

<table>
<thead>
<tr>
<th>Size of a location</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travel distance</td>
<td>8</td>
<td>38626,875</td>
<td>3575,13680</td>
<td>1264,00174</td>
</tr>
<tr>
<td>2*max put away order line</td>
<td>8</td>
<td>32923,9312</td>
<td>5861,93895</td>
<td>2072,50839</td>
</tr>
</tbody>
</table>
Table 36: Independent t-test size size of a location based on travel distance

<table>
<thead>
<tr>
<th>Situation</th>
<th>KPI</th>
<th>Levene's Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
<th>Std. Error Difference</th>
<th>95% Confidence Interval of the Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>Sig.</td>
<td>df</td>
<td>Mean Difference</td>
</tr>
<tr>
<td>Total travel distance</td>
<td>Equal variances assumed</td>
<td>4.865</td>
<td>.045</td>
<td>2.349</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Equal variances not assumed</td>
<td>2.349</td>
<td>11.575</td>
<td>0.37</td>
<td>5702.94375</td>
</tr>
</tbody>
</table>

An independent t-test is executed to check what size of a location minimizes the total travel distance. The location size is expressed in the maximum units that can be stored at a location. The variances between the means seems to be significant (p<0.05). It is concluded from the independent t-test that there is a significant difference in means between the sizes of the locations (p<0.05). A warehouse that uses locations with a maximum capacity equal to the put away line size has a smaller travel distance than a warehouse that uses locations with a maximum capacity that is equal to twice the put away line size.

2.1.2 Different storage sizes

Table 37: Descriptives different storage sizes based on travel distance

<table>
<thead>
<tr>
<th>Situation</th>
<th>KPI</th>
<th>Different storage sizes</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Total travel distance</td>
<td>1</td>
<td>8</td>
<td>40965.8938</td>
<td>3432.17827</td>
<td>1213.45826</td>
<td></td>
</tr>
<tr>
<td>2 Total travel distance</td>
<td>2</td>
<td>8</td>
<td>37878.8588</td>
<td>3812.10405</td>
<td>1347.78231</td>
<td></td>
</tr>
<tr>
<td>6 Total travel distance</td>
<td>1</td>
<td>8</td>
<td>177200.7188</td>
<td>23921.30953</td>
<td>8457.46009</td>
<td></td>
</tr>
<tr>
<td>6 Total travel distance</td>
<td>2</td>
<td>8</td>
<td>172495.1963</td>
<td>18119.7259</td>
<td>6406.29053</td>
<td></td>
</tr>
</tbody>
</table>

Table 38: Independent t-test different storage sizes based on travel distance

<table>
<thead>
<tr>
<th>Situation</th>
<th>KPI</th>
<th>Levene's Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
<th>Std. Error Difference</th>
<th>95% Confidence Interval of the Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Total travel distance</td>
<td>Equal variances assumed</td>
<td>.012</td>
<td>.915</td>
<td>1.702</td>
<td>14</td>
</tr>
<tr>
<td>2 Total travel distance</td>
<td>Equal variances not assumed</td>
<td>.790</td>
<td>202</td>
<td>14</td>
<td>.664</td>
</tr>
<tr>
<td>6 Total travel distance</td>
<td>Equal variances assumed</td>
<td>1.790</td>
<td>202</td>
<td>14</td>
<td>.664</td>
</tr>
<tr>
<td>6 Total travel distance</td>
<td>Equal variances not assumed</td>
<td>1.790</td>
<td>202</td>
<td>14</td>
<td>.664</td>
</tr>
</tbody>
</table>

The independent t-test shows that there are no significant differences in variances between having one or two locations per SKU. However, in both situations there is no significant difference in means (p > 0.05).
2.2 Overall performance

2.2.1 Size of a location

Table 39: Descriptives size of a location based on overall performance

<table>
<thead>
<tr>
<th>Capacity of a location</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall performance</td>
<td></td>
<td>2.3548</td>
<td>.03366</td>
<td>.01190</td>
</tr>
<tr>
<td>2*max put away order line</td>
<td>8</td>
<td>2.5052</td>
<td>.12454</td>
<td>.04403</td>
</tr>
<tr>
<td>1*max put away order line</td>
<td>8</td>
<td>2.5052</td>
<td>.12454</td>
<td>.04403</td>
</tr>
</tbody>
</table>

Table 40: Independent t-test size of a location based on overall performance

<table>
<thead>
<tr>
<th></th>
<th>Levene's Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
<th>95% Confidence Interval of the Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>Sig.</td>
<td>t</td>
</tr>
<tr>
<td>Overall</td>
<td>5.890</td>
<td>.029</td>
<td>-3.296</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In order to give a recommendation about the size of a location and the different storage types, independent t-tests are executed with the results of simulation 1 versus 2 to see if there is a difference in overall performance between sizes of a location. There is no significance between the variances (p<0.05) and it is clear to see that there is a significance in means (p<0.05). As a result, a locations that has a size twice as large as the maximum put away order line results in significant lower total costs over one year than a location that store only one times the maximum put away order line.

2.2.2 Different storage sizes

Table 41: Descriptives different sizes of locations based on overall performance

<table>
<thead>
<tr>
<th>Situation</th>
<th>Different storage types</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Overall 1</td>
<td>8</td>
<td>2.9448</td>
<td>.11746</td>
<td>.04153</td>
</tr>
<tr>
<td></td>
<td>performance 2</td>
<td>8</td>
<td>4.0972</td>
<td>.16674</td>
<td>.05895</td>
</tr>
<tr>
<td>6</td>
<td>Overall 1</td>
<td>8</td>
<td>2.1935</td>
<td>.09329</td>
<td>.03298</td>
</tr>
<tr>
<td></td>
<td>performance 2</td>
<td>8</td>
<td>2.1742</td>
<td>.03596</td>
<td>.01271</td>
</tr>
</tbody>
</table>
Table 42: Independent t-test different sizes of locations based on overall performance

<table>
<thead>
<tr>
<th>Situation</th>
<th>Levene’s Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
<th>95% Confidence Interval of the Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>Sig.</td>
<td>t</td>
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<tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Overall</td>
<td>.355</td>
<td>.561</td>
<td>-15.982</td>
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<tr>
<td>Equal variances not assumed</td>
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<td></td>
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</tr>
<tr>
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<td>5.089</td>
<td>.041</td>
<td>.548</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
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</tr>
<tr>
<td>Equal variances assumed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal variances not assumed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For situation 2, there is no significance difference between the variances (p>0.05) and it is also clear to see that there is a significant difference in means (p<0.05). A SKU that has an overflow location type that is half the size of a normal location does not result in significant lower total yearly costs than a SKU that has only normal locations.

When observing situation 6, there is a significant difference in variances between the two situations. Therefore, using this output for giving recommendations about the storage types per SKU will result in unreliable recommendations. From this result, it cannot be concluded that different sizes of storage locations result in better overall performance.