Improving warehouse layout design

A study to optimize the warehouse of the hospital of Aruba

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Preface

This thesis before you is my final step in finishing my master Industrial Engineering and Management at the University of Twente. In the last year I have worked really hard on this project, in order to design the layout of the new warehouse of the hospital of Aruba. Part of the project I performed on Aruba, and the final part was executed in the Netherlands. Doing such a project in another country was at sometimes hard, because of some cultural differences. And later on also time difference turned out to be an obstacle. But it was also a very interesting project and an amazing experience.

I would express my gratitude towards a couple of people who helped me during this project. First, I would like to thank my supervisors from the Dr. Horacio E. Oduber Hospitaal: Stefan Lucas, for his practical point of view and for helping me reach various people on Aruba when I was back in the Netherlands, and Nikky Kortbeek, who always had a critical view and valuable feedback. I furthermore like to thank the management of the warehouse: Anthony, Randolf, and Maurice, for their help, feedback and insights. And I like to thank the order pickers from the warehouse, Sergio, Jeffrey, and Jeffrey, for showing me around and answering my many questions.

I furthermore want to express my gratitude towards my supervisors from the University of Twente, Erwin Hans and Peter Schuur, for their guidance, suggestions and valuable feedback.

Last but not least, I want to thank my roommates for reading through my paper and motivating me to keep working, and my parents, and sisters for their moral support. I could not have done it without you.

Sylvia Wentzel

Management summary

The Horacio E. Oduber Hospitaal is the only hospital of Aruba. Currently the hospital is building a new building, including a new warehouse. This gives the opportunity to improve the logistic processes of the hospital. The building and racks are already planned, but it has not been decided how this space should be used. This study focusses on this new warehouse.

Research goal

This study aims to find the optimal layout for this new warehouse. For a layout to be optimal, its processes should be efficient, with a low probability of mistakes. It also should support growth, since the warehouse department plans to expand its assortment in the future. Besides the layout, also the way of supplying the hospital departments is important. Since the hospital building changes, the routes that are used to deliver the departments will no longer be optimal, and new ones should be found. The goal of this research is therefore as follows:

To design a warehouse layout and order delivery routes in order to make processes efficient and non-sensitive to mistakes, while it remains suitable for growth

Approach

To design warehouse layouts, we construct a framework, based on the literature, which consist of all the steps that are required to design a warehouse layout. This framework consist of seven steps: investigate the situation, determine operating policies, select equipment, form a general layout, allocate aisles, determine space usage, and evaluate the resulting options.

By following the steps of this framework, we compose several alternative layouts. Those alternative layouts contain all the techniques that can be implemented within the scope of this research, this mainly

concerns space allocation and policies of the main warehouse. Out of scope are for example additional purchases, or altering the inventory levels.

To select the best alternative, we score them on a list of criteria, which we composed in collaboration with the management and employees of the warehouse. These criteria can be divided over three categories: quantitative, time based and numerical criteria, which are all measured in a different way.

- Qualitative criteria, for example the clarity of the present inventory level, are scored by the warehouse department via the AHP method.
- Time based criteria, for example the average picking time per order, are scored with a discrete event simulation model that simulates the picking process.
- Numerical criteria, for example the percentage of occupied storage areas, are scored through simple calculations. In this case we for example counted the occupied and empty storage slots.

To make the scores comparable, we weighted the criteria, and rescaled the results to a scale from 0 to 1.

Results

Based on this comparison, we recommend a warehouse layout that contains the aspects in Table 1. This solution results in the lowest average picking time, the lowest percentage of late deliveries, and the most equal workload division. Compared to the current situation, the average picking time would drop with 10%, from 15.7 to 14.1 minutes. The amount of late deliveries would drop even more: from 5.2 % to 0.5%. This drop in late deliveries is mainly the effect of the more equal workload division.

Our research shows the importance of variation reduction. The demand of the HOH fluctuates to a great extent. An unequal workload division would cause even more variation. An equal workload division is therefore important. Our research shows its strong influence on the percentage of on time deliveries. It has more effect than, for example, the product allocation, which only affects the average picking time.

Decision	Options
Flow rack	This is a rack that stores the perishable products, and assures that the oldest product is picked first
Corridor	This is an opening at the end of the aisle, so trespassing becomes possible at both ends of the racks.
Dedicated storage	All products are assigned a fixed storage location
Wave picking	1 wave per day This means that all orders that arrive on a day, become available for picking at the same moment, 12:00 AM, and they should be delivered before 12:00 AM the next day.
Routes	We proposed a new workload division, called a 'Route', which assures that neighboring hospital departments are delivered by the same order picker.
Forward and reserve area	When products require more than one storage location, the additional products are stored on the highest rack
Slotting strategy	The exact storage location is determined by the Route based heuristic. It assigns the end of an aisle to route specific products, so only one order picker has to visit that route specific area.

Table 1: The recommended configuration for the warehouse

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Definitions

External delivery

The delivery of products from the supplier to the warehouse

Internal delivery or Delivery

The delivery of products from the warehouse to the departments

Department

A part of the hospital with the autonomy to place an order at the warehouse, and all its orders are delivered to the same local storage.

Order

A set of products that is requested by a department on one day

SKU

An SKU (Stock Keeping Unit) is a product in the size that it is ordered by the departments, for example a pen, or a box of 12 milk cartons. It is also referred to as an item or a product. A part of an SKU, for example 1 milk carton which are picked per 12, is referred to as a single product.

Risk pooling effect

The risk pooling effect is that the sum of variations is larger than the variance of the group. It occurs if similar, but independent risks are grouped. A high demand from one source can be leveled out by a small demand from another source, resulting in smaller total fluctuations than the sum of all individual demand variations (Yang & Schrage, 2009).

NP-Hard

NP stands for Nondeterministic-polynomial time. It is a complexity class for certain types of decision problems and means that the problems are only solvable in polynomial time using a theoretical non-deterministic Turing machine. NP-hard means that this problem is at least as hard as an NP problem. In practice this means that large problem instances cannot be solved optimally in reasonable time.

Decisions

A 'decision' is an aspect of the warehouse layout that contains several options, of which we aim to find the best one in this research. A decision is for example how to divide the workload over the employees.

Options

An option is a possible alternative for a decision. We can for example use the current workload division: option 1, or create a new one: option 2.

Scenario

In a scenario, for every decision one option is selected. We give an example. Decision I has 2 options: A and B. Decision II has also two options: C and D. Then we can form 4 scenarios: AC, AD, BC, and BD.

1 Introduction

This research is conducted at the Horacio E. Oduber Hospital on Aruba as part of the master Industrial Engineering and Management, Production and Logistics track. In this research we design a lay-out for the new warehouse of the Dr. Horacio E. Oduber hospital (HOH). In this chapter we describe the context of this research (Section 1.1), the problem (section 1.2), research objective and scope (section 1.3) and the research questions (section 1.4), which are the base of this research.

1.1 Context: The Dr. Horacio E. Oduber Hospitaal

This research is conducted at the HOH, the only hospital on Aruba. Aruba is an island in the Caribbean Sea, 29 kilometers north of the coast of Venezuela. It is part of the kingdom of the Netherlands and its official languages are Papiamento and Dutch. Aruba has over 112.000 citizens and a surface of 180 square kilometers (Cia, 2016).

Figure 1: The Dr. Horacio E. Oduber Hospitaal source: (Aruba Tourism Authority, 2016)

Since the HOH is the only hospital on the island, it has all major medical specialties, like Pediatrics, Gynecology, General Surgery, Neurology, Psychiatry, and Cardiology. Furthermore, it has a Wound Care Clinic, Dialysis Clinic, Oncology department and Rehabilitation Center. Most specialties are located inside the hospital building but due to space constraints, some departments are situated in a building nearby. It has 288 beds, and over 10 000 inpatients and 32 000 emergency patients per year (Dr. Horacio E. Oduber Hospitaal, 2016).

The hospital of Aruba wants to become one of the best hospitals of the Caribbean, Venezuela and Columbia. They expect this will also lead to growth because of the many tourists on the island, who nowadays often prefer to go home for their healthcare. To facilitate this growth and improvements, a new building is being built. This new building will also facilitate departments that are currently located in a building near the hospital, and a laboratory that recently became part of the hospital.

The new building will also contain a warehouse. The purpose of this warehouse is to lower ordering costs by storing all products that are ordered often, by several departments, or both. The remaining products are directly delivered from the supplier to the department. In the future the hospital wants to store more products in the warehouse, so fewer products will directly be ordered by the departments. The current warehouse of the hospital stores 1982 kinds of products, of which 545 are sterile. The warehouse processes consist of ordering, storage, picking, internal deliveries, and urgent deliveries.

1.2 Problem description and research objective

In this section we describe the problem and elaborate on the research objective. The HOH is building a new warehouse. Figure 2 shows the plan for the warehouse. The dimensions of the warehouse, and the racks are predetermined, and it will contain a regular storage area and a sterile area. How this space will be used exactly and the storage locations of the products still have to be determined.

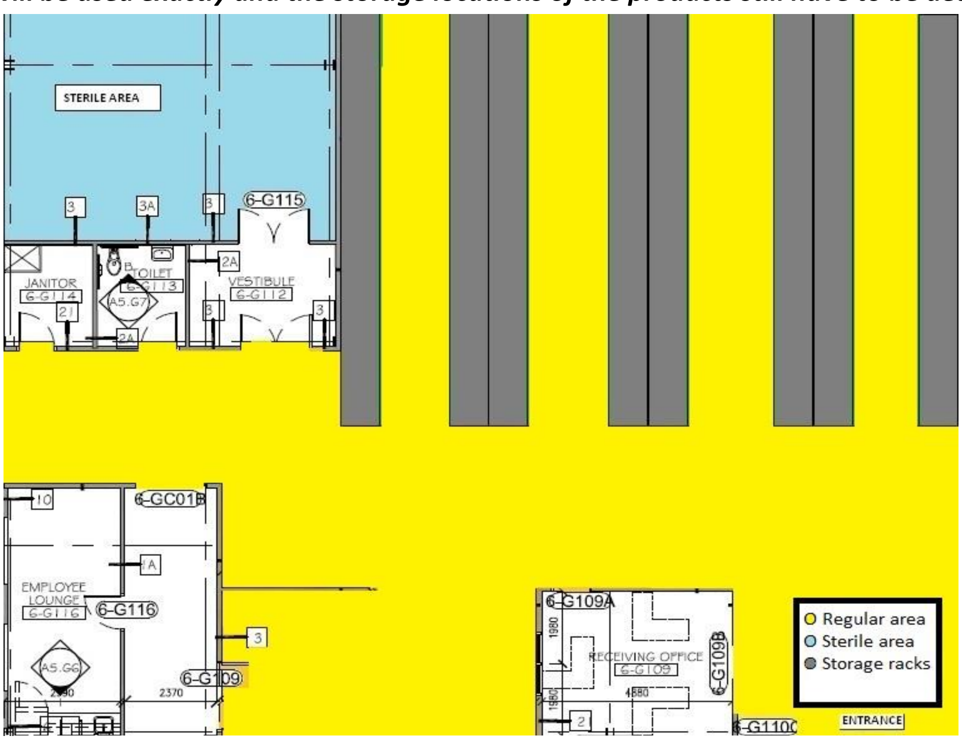

Figure 2: Warehouse areas

Since the hospital is building a new building, the mapping of the departments changes as well. This means that the current order delivery routes from the warehouse to the departments will no longer be optimal, and new routes should be designed. The main focus of this research lies with the warehouse lay-out, but the order delivery routes will be taken into account at the relevant moments.

The goal of this research is to design the lay-out of the new warehouse and determine the order delivery routes. This gives an opportunity to optimize its logistics performance.

The future should also be taken into account in the warehouse layout. This means that there should be room for growth in the variety and amount of products. The current assortment of the warehouse will grow in the future. In the near future, for example, more products of the cafeteria will be stored in the warehouse. Furthermore, the HOH has taken over the Lands laboratories, so the products they use also need a storage location in the warehouse. The warehouse lay-out should facilitate this growth, so there has to be space available for those new products. Also, the reasoning behind the allocation of the storage area has to be clear and reproducible so new products can be added.

To assess those problems described in this section, we formulated the following research goal:

To design a warehouse layout and order delivery routes in order to make processes efficient and non-sensitive to mistakes, while it remains suitable for growth

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1.3 Research scope

This research aims to design a layout for the new warehouse and new order delivery routes. In this section we explain what we take into account in this research and what we consider to be out of scope.

Recall that the new warehouse will contain two areas: a main area and a sterile area. For time purposes we decided to focus only on one of those areas: the main area. The sterile area is considered out of scope because the situation of the main area is more difficult, whilst the results are likely to be translatable to the sterile area. The situation of the main area is considered more difficult for a couple of reasons. First, all departments use products from the main area, while only some use sterile products. Second, the products in the sterile area are all more or less the same size while the products in the main area differ significantly in size. Third, the sterile area is smaller and contains less products, and thus improvements will have a smaller effect.

The focus of this research is on the internal warehouse processes. Factors that do not interfere with those processes are therefore considered out of scope. This contains for example the appearance of the products, most equipment and the features of the local storage. For the order delivery routes this means that we only consider its effect on the internal processes. The time required to walk to the departments is not an internal process and is, also because of time constraints, considered out of scope.

There are also some factors that have an influence on the internal processes but nevertheless are considered out of scope because its cause lies somewhere else in the process. Classified as such is the fact that some products can expire, and the sizes of the internal orders.

The ordering policies at the supplier is also considered out of scope due to time constraints and because this is not considered to be an internal warehouse process. It does, however, strongly determine what is on stock, so it is taken into account that the minimum and maximum inventories are not constant and that the inventory levels are likely to change.

Finally, the rack sizes, the kind and amount of racks, and the available storage area are given because they are already bought. Furthermore, the acquisition of equipment is not considered. This means for example that the acquisition of new pick and delivery carts, or sorting equipment, is out of our scope.

1.4 Research questions

In order to achieve the research goal we formulate the following five research questions.

Research question 1:

What processes are conducted in the warehouse, what is its current performance, and what should be taken into account for the new lay-out?

Before a warehouse can be designed, it should be known what processes will be conducted in it and what the situation looks like. Its performance is also important to get insight in what to change for the new situation. We answer this first sub question in chapter 2 by observing the current situation and conducting interviews with several employees.

Research question 2:

What steps and options should be taken into account when designing a warehouse lay-out and how can they be assessed?

Designing a warehouse consists of many steps and options. Before those can be executed, it should be clear what they are. We use the literature to constitute a list of the common steps in warehouse design, and the corresponding options. Furthermore, to investigate those options, performance indicators are required. We investigate what indicators are commonly used in the literature to evaluate the warehouse performance. Chapter 3 lists the steps, options and performance indicators found in the literature.

Research question 3:

What alternative lay-outs are possible?

Not all options found in chapter 3 are relevant for the HOH. In chapter 4 we evaluate the relevance of the options we found in chapter 3 by comparing the theory with the situation of the HOH. At the end of this chapter we give all the relevant options for the lay-out of the warehouse.

Research question 4:

How should those alternatives be analyzed?

From the alternatives presented in chapter 4 only one can be implemented, so a way of comparing them is required. In chapter 5 we present our model to compare the existing alternatives. The model consist of qualitative measures, calculations and a simulation study.

Research question 5:

What is the expected performance of the alternative layouts?

The results of the model presented in chapter 5 are described in chapter 6. These results also indicate the best alternative.

We conclude this thesis with chapter 7, in which we give a conclusion on the research goal, recommendations to the HOH and recommendations on future research.

2 Current situation

In this chapter we describe the situation of the current warehouse, its processes and performance. This chapter starts with a description of the warehouse activities and its challenges (2.1). Section 2.2 shows the performance of the current warehouse, and section 2.3 describes the features of the new warehouse that are already determined. We conclude with section 2.4, which describes the resulting flaws, desires and constraints for the new warehouse layout design

2.1 Warehouse processes and control

For the design of a warehouse layout it is important to first investigate what processes will be conducted there and the content of those processes. We observed the current situation and conducted interviews to get an insight on those processes. In this section, we describe the current situation, the processes and the challenges for the warehouse design.

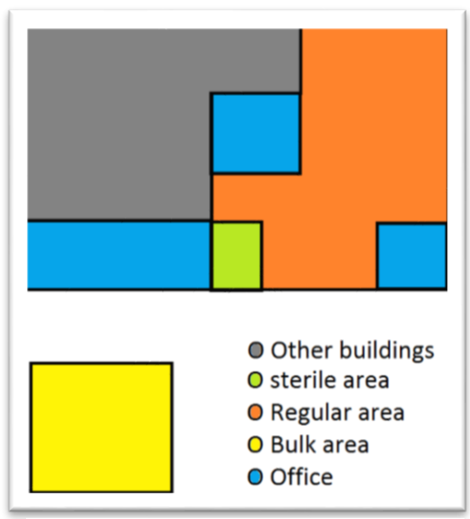

Figure 3: Sketch of the current situation

The current warehouse of the HOH consists of two buildings: the bulk and regular storage area. A sketch is given in Figure 3. The bulk area stores the big products and large amounts. The regular storage area stores the smaller and more frequently ordered products. Products inside the regular area have a fixed location, whilst in the bulk area the locations are randomly determined at the moment of arrival. The assigned space for a product in the regular area is however not always sufficient, so there is also a small random storage area inside the regular building for temporary bulk storage. This area is quite full, so rearranging this area to store additional products, and finding the right product in this area can be time consuming. Furthermore, the corridors are small, so order pickers cannot pass each other. This results in lots of waiting.

The warehouse has four order pickers responsible for the warehouse activities. The warehouse activities consists of storing the ordered products in the warehouse, picking the products ordered by the departments, delivering those products to the departments and processing rush orders. In the next section we describe those activities in further detail.

During this research the situation of the warehouse changed. Before we go into further detail on the current situation, we briefly explain those changes. At the beginning of this research the hospital was already rebuilding. This means that for example the old sterile area was no longer in use, and a temporary location was set up for those sterile products. This is the situation as described in section 2.1. After a couple of months those rebuilding resulted in a construction error of the main warehouse building. There was a danger the building would collapse, so it was partly evacuated. It remained evacuated until, at the end of this research, the new warehouse building was taken into practice.

2.1.1 *Storage*

In this section, we elaborate on the storage process at the moment a delivery from the supplier arrives. For local suppliers this is in the week after ordering, on Monday, Tuesday or, occasionally, Wednesday. For overseas suppliers the arrival date is less predictable, but around a month after ordering. When goods arrive they should be checked and stored on its assigned location as soon as possible.

Often, especially for the larger intercontinental deliveries, there is a lack of time at the moment a delivery arrives. In that case, checking and storing is postponed and those products are stored on a temporary storage location.

The aisles inside the storage area are relative small. They are often blocked by empty boxes, pick carts, and delivery carts. Therefore the shipment package has to be split before products can be brought to its storage location. This also means that a pallet stacker and a hand trolley are required in the storage area.

Important for the warehouse design is that both random and dedicated storage are used in the current situation. Furthermore, little time is reserved for the storage process.

2.1.2 *Picking*

This section explains how the departments can request products and how those orders are picked.

Inside the warehouse, there are four order pickers. Three of them are responsible for the orders placed by the departments. The fourth order picker is responsible for supplier deliveries and urgent orders. But when needed, for example when many urgent order arrive, another order picker will assist him.

The ordering of the departments is regulated through the ABC- system, also referred to as the ABC-route system. In this system all departments are assigned to a group, called a ‘route’, and between one and three delivery days per week. The route a department is assigned to, indicates what order picker is responsible for picking its products. Preferably the departments are evenly spread over the routes. Furthermore, all departments are assigned one to three days in which it can place orders. For example, the kitchen is assigned to route A and can request orders two times a week, on Monday and Thursday. Figure 4 shows how the departments are currently divided over the routes. The names are the abbreviations used by the hospital. SU4 (Snijdend Unit 4) is for example the fourth department that performs surgery.

The goal of the ABC-system is to spread the workload evenly over the days and the order pickers, and to make it clear who is responsible for what order. Because of this responsibility, the department knows who to contact in case of a problem or adjustment, and the order picker can check if all orders arrived yet. The order pickers rotate over the routes, so the order picker of route A will pick the departments of route B the next month.

Route A				
Monday	Tuesday	Wednesday	Thursday	Friday
CAFE-D	COMM-D	RADI-D	CAFE-D	PAAZ-D
CATE-D	ARBO-D	VOED-D	CATE-D	AUTO-D
KEUK-D	DIET-D	KWVE-D	KEUK-D	BLBK-D
AFWAS-D	HYGE-D	DIRE-D	AFWAS-D	
INTER-D	OPLE-D	EAD-D	INTER-D	
VAS5-D	PERS-D	PAST-D	KIND-D	
Route B				
Monday	Tuesday	Wednesday	Thursday	Friday
ONCO-D	UROL-D	OKCH-D	ONCO-D	OKCH-D
OKCH-D	GYNA-D	ANAE-D	CSA-D	ANAE-D
ANAE-D	PEDI-D	RECO-D	MICU-D	RECO-D
RECO-D	PBEG-D	CMSN-D	SU4-D	PSYC-D
CSA-D	PINT-D	CMNS-D	NSU4-D	
MICU-D	PSYC-D	CMVK-D	VERL-D	
SU4-D	PIJN-D	CMMO-D	VAS1-D	
NSU4-D	DAGV-D	WOND-D S/N	VAS4-D	
HUIS-D	EAD - BUITEN			
	NEUP-D			
Route C				
Monday	Tuesday	Wednesday	Thursday	Friday
SEH-D	TECH-D	SEH-D	HART-D	SEH-D
ENDO-D	LINN-D	ENDO-D	SU2-D	ENDO-D
GIPS-D	BEVE-D	APOT-D	NSU2-D	LINN-D
SU2-D	CIVI-D	FUNK-D	SU3-D	MAMMA-D
NSU3-D	LOGO-D	FYTH-D	NSU3-D	REVA-D
HART-D	LONG-D	MDSR-D	GIPS-D	
NEUF-D		ERGO-D	VAS2-D	
NEUR-D		WOND-D	VAS3-D	

Figure 4: Current route division

The order has to arrive before 12:00 AM and be delivered before 12:00 AM the next day. Every order has its own pick list. To prevent that orders mix up, they are picked separately. The current warehouse is ordered by product kind, so an order usually contains products from all aisles and both buildings. The pick list is ordered in picking sequence. Order pickers sometimes deviate from this when aisles are blocked, for example by other order pickers, or pick carts. Furthermore, if the picklist is long, some pickers pick large and heavy items first. Because all pickers visit all the areas for all departments, corridors are often crowded, what results in congestions.

The location of products in the regular warehouse is indicated by a row and shelf number. Small products often share a shelf. Because products often look alike, the codes on the assigned part of the shelf should be read to assure that the right product is picked. The product itself usually lacks such a code, unless it is written by hand, so erroneous stored products have a high probability to become wrong picked.

The amount to be picked and the pick unit should be read carefully from the list since the pick unit is not always obvious or visible. Pens, for example, are picked per piece and stored in boxes, envelops are picked per 25 pieces and stored without boxes. Counting the amount to pick is time consuming and prone to errors, while its added value is questionable since this often concerns small and low value products.

When the amount on the shelf is insufficient, reserves are located somewhere in the pallet area nearby. This happens for many products, because products have no predetermined maximum inventory level. Preferably a whole box is picked; otherwise an opened box remains. Remaining products should be stored in the shelves, but this does not always happen. Empty boxes are often left behind until someone takes the time to remove them. The corridor and bulk area contain many empty and opened boxes.

In short, currently the following things happen that should be prevented in the future:

- Large amounts of products are ordered per piece
- Several products share the same location index
- Visual similar products are abreast, making incorrect picks likely
- Not all products have a fixed location
- Product codes are only on the shelf, not on the product unless handwritten
- The pick cart is unsuitable for picking several departments concurrent
- Long travel distances for picking an order
- Large products are located in middle of the route, so the standard pick route is altered
- Empty boxes lie in the hallway

2.1.3 *Delivery to the departments*

In this section, we elaborate on the process of bringing the products to the departments. For this purpose usually a delivery cart is used, which is bigger than the picking cart. This means that the items have to be displaced on this delivery cart. Small items have no safe location on that cart, so they are put in boxed to make sure they will not be lost. Those boxes are picked from the empty boxes that lie in the hallway. The cart sometimes has enough capacity for several deliveries. But orders are mostly delivered separately because they easily mix up.

Some departments lie far from the warehouse, so they are supplied with a minivan. The dialysis department requires heavy products and is therefore delivered by forklift.

The order pickers do not only deliver the products, but they also put it on the shelfs in the decentral storage locations. Because many departments determined the locations by themselves, and often consist of several storage areas, searching for the storage location can take a lot of time.

For the design of the warehouse lay-out it is notable that the delivery cart is different from the picking cart, unsuitable for several deliveries, and has no logical space for small items.

2.1.4 *Urgent deliveries*

The last process we discuss is the process of urgent deliveries. When a department is in need of a product it has not on stock, it can request a rush order. Every day around 4 rush orders arrive at the warehouse. A rush order is requested by filling in a form and sending an employee, with the form, to the warehouse. Rush orders have priority, what means that an order picker has to stop its current activities to handle this rush order. Those 'Rush orders' are often office supplies or food.

Although the process takes a lot of time from several people, and it is perceived quite distracting by the order pickers, our focus lies on preventing them instead of making the process more efficient. For the warehouse layout this means that it should reduce the probability of rush orders, by preventing picking a wrong or expired product.

2.2 Performance

In the design of a warehouse, several goals can be pursued. In chapter 3.3 we elaborate on the performance indicators found in the literature. We determined the key performance indicators (KPIs) in collaboration with the management of the warehouse and used the literature from chapter 3.3 as a basis. Those KPIs are listed in Table 2.

What?	How measured?
Operational costs	Required amount of employees
Volume flexibility	The amount of free storage locations.
Quality of delivery	Amount of on time deliveries Percentage of expired products

Table 2: Relevant performance indicators

The operational costs are measured through the required amount of employees for picking, storing and delivering, which is currently equal to 4 employees.

The volume flexibility is important because the warehouse should be able to store more products in the future. The current performance is however irrelevant since this warehouse will no longer be used.

The most important factor according to the management of the warehouse is the quality of deliveries. Some aspects of this, for example the probability of mistakes, are hard to measure. Those aspects are taken into account later on but cannot be translated into realistic measurable KPIs. Therefore, to measure this, we only use two indicators: the amount of on time deliveries, and the percentage of expired products.

The percentage of on time deliveries is not available for the current situation. No historical data is available and it could not be measured due to a problem with the current hospital building. As mentioned in section 2.1, the warehouse was partly evacuated during this research because it had a high probability to collapse. This caused major disruptions in the picking process, so the current percentage of on time deliveries became unrepresentative.

The current performance of quality can therefore, only be measured by the probability to pick an expired product measured as the percentage of expired products in the system.

To measure the percentage of expired products, we did a sample test of almost 600 products. It appeared that around 4.9% of the products inside the warehouse with an expiring date are expired. This was 2.5% of the sterile products and 8.8% of non-sterile products. See Figure 5 and Appendix A: Percentage of expired products. The non-sterile products costs around 560 000 florin, which is around 300 000 euro. Since 8.8 % of those products is expired, this has a value of around 49 000 florin (€ 26 000,-) per year. See appendix B for the calculations.

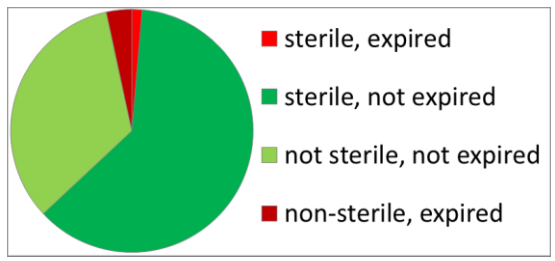

Figure 5: percentage of expired products

2.3 The new warehouse

The previous sections discussed the current warehouse. The processes discussed in that section have to be transferred to the new warehouse. In this section, we elaborate on the new warehouse, and the aspects of it that are already fixed. Those aspects are the total floor area, the racks and equipment. The warehouse area and the location of the racks are depicted in Figure 6.

The regular warehouse area is around 500 square meters and three meters high. Inside this area around 150 square meter is left for non-storage purposes. The sterile area is around 100 square meters. The regular area contains 8 pallet racks, forming 4 aisles of around 17 meters long.

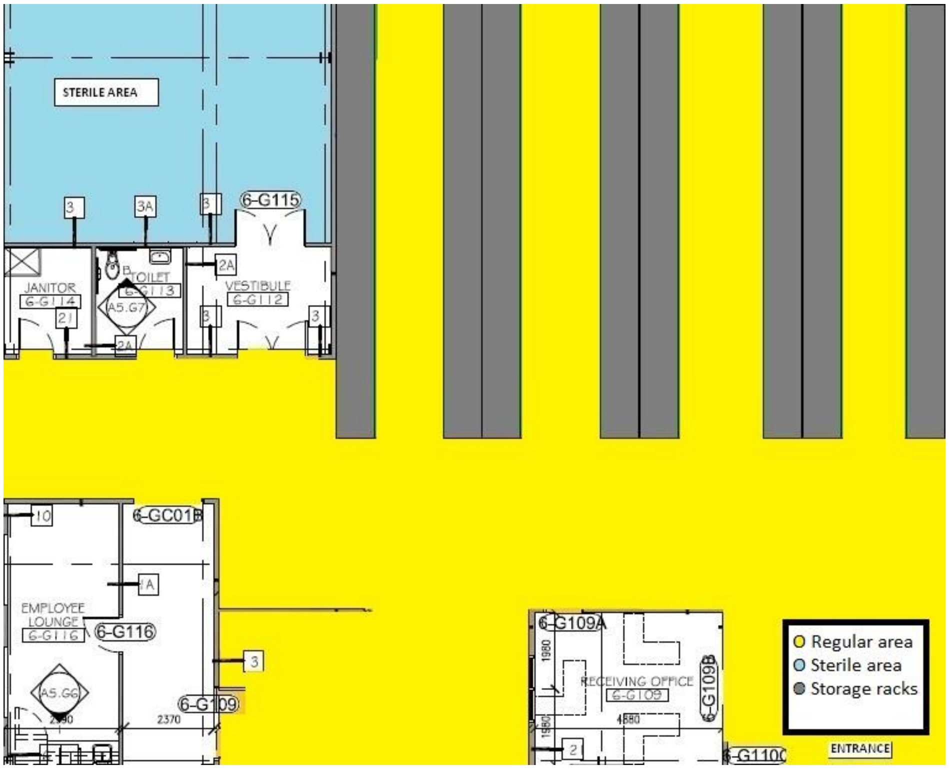

Figure 6: Map of the new warehouse

As Figure 6 shows, trespassing at the end of the aisle is impossible, but the option of removing the last rack can be examined. The racks contain 114 pallets at floor level. Since the area is three meters high, the total storage capacity will be around 400 m^2.

Inside the part for non-storage purposes the equipment has to be assigned a location, consisting of:

- 3 picking carts – those are used for order picking
- 3 delivery carts – those are used to bring products to the departments
- A Box disposal – this is a large container to drop of the empty boxes
- A pallet stacker – this is a machine that can lift full loaded pallets to any height

In short, the racks inside the regular warehouse area are fixed, and have a storage capacity of around 400 square meters. The regular area should furthermore store the carts, pallet stacker and box disposal.

2.4 Conclusion: Problem analysis and scope

This section lists the points that should be taken into account for the warehouse layout design. Those flaws, desired and constraints result from the current situation (described in section 2.1) and the performance of the current warehouse (described in 2.2). Furthermore, there are some preferences that do not result from the current situation but from expected changes in the future. We list those here too. Points that are considered out of scope, as indicated in 1.3, are not mentioned in this section. We divided this part into two categories. In the first part we discuss what should be taken into account with respect to the storage locations. In the second part we discuss the preferences of the overall layout.

2.4.1 *Storage locations*

Recall that section 2.1 described the picking and storing process. We also described what problems arise from the way the products are stored. Those problems and challenges can be translated into preferences with respect to the storage locations. In this section, we list the preferences and constraints associated with this processes.

- *Similar products should not be located abreast:* In the current situation some similar products are located abreast on the same shelf. This makes incorrect picks more likely.
- *Large products should be placed in the beginning of the route:* When orders are big, large items are preferable picked first to create a logical positioning on the cart. In the current situation sometimes illogical routes are followed, so the large products can be picked first.
- *Product locations should be easy to find:* Part of the warehouse uses random storage, what means that the order pickers require more time to search for the right product.

- *Product locations should be unambiguous*: Currently location indexes refer to a shelf. But some products share a shelf, so a location index can refer to several products. This leads to searching, and a higher chance of wrong picks.

- *It should be clear what product on the shelf should be picked first*: some products have an expiration date, which are small displayed on the package. To make sure the products do not expire, the oldest product should be picked first. The way of storing those products should facilitate this.

- *The storage locations should facilitate fluctuating inventory levels:* The amount of units per product differs. Recall from chapter 1 that altering the ordering policy is out of scope. Therefore the storage locations should suffice to store the largest amount that is likely to occur.

Besides the preferences, there is also a constraint about the product locations:

- For safety reason, heavy products cannot be located on the top of the shelf.

2.4.2 *The overall layout*

Besides the storage locations, we also discussed the overall process and the expected changes in the future. This results in preferences about the overall layout, which are listed in this section.

- *Minimize the travel distances:* If the travel distances become smaller, the time required for an order will too. Furthermore, it decreases the waiting times because corridors will be less crowded.

- *There should be an easy accessible location for the empty boxes.* Currently empty boxes lie in the hallway. This is probably because it takes too much time to bring them to the disposal location outside. Furthermore, some empty boxes are required to safely transport small products. To facilitate easy disposal and reuse of those boxes, the disposal location should be easy accessible.

There are also some preferences about the overall layout resulting from the expected changes in the future. It is expected that the warehouse will store more products in the future and the warehouse should be able to facilitate this. This results in the preferences listed below.

- *Enough room for growth.* Space available and suitable for future products, including small or heavy products.
- *Reproducible allocation logic:* To be able to store more products in the future, the logic of assigning locations to products should be simple and reproducible.

3 Theory about the design of the a warehouse lay-out

This section elaborates on the literature on warehouse layout design. It consists of three sections. The first section (3.1), elaborates on the steps that are required for warehouse layout design. The literature discusses extensive what should be considered and done in warehouse layout design. From this literature we constructed a framework that contains all the steps that are usually taken in warehouse layout design. The next section (3.2) discusses the important decisions and possible techniques. The last section (3.3) discusses the criteria that are regularly used to evaluate the possible layouts.

All statements made in this section are based on literature. Most articles are found via search engine Scopus, with search terms like: warehouse, layout, and performance. We also used search terms of specific methods like 'wave picking' or 'forward area'. Additionally, interesting references where checked.

3.1 Framework for warehouse layout design

The design of a warehouse layout contains many steps and decisions. According to the literature, the consecution of those steps is important. We constructed a framework that contains the most common steps and decisions. This framework is depicted in Figure 7 and is mainly based on the theory of Baker & Canessa (2009). *We use this framework in the next chapter to form alternative layouts. This section explains the content of the framework and how we constructed it.*

Figure 7: Steps in warehouse design, based on (Baker & Canessa, 2009)

The goal of warehouse layout design is to determine and allocate the warehouse area according to a couple of strategic and tactical decisions. The decisions influence each other strongly (De Koster, Le-Duc, & Roodbergen, 2006; Rouwenhorst, et al., 2000) and draw the boundaries for the short term operational decisions (Strack & Pochet, 2010). Since the decisions are interdependent, the consecution in which decisions are made is important. Many theories exist about the best consecution of those decisions. Those theories can be divided into two categories: hierarchical and step-by-step approaches (Baker & Canessa, 2009).

In hierarchical approaches the decisions are divided according to the time horizon (see Figure 8). Strategic decisions have to be made first since they concern the long term and high investments. Those decisions are strongly interdependent. Tactical decisions are moderate interdependent and made afterwards. They concern the medium term and medium investments. Finally the short term operational decisions remain (Accorsi, Manzini, & Maranesi, 2014; Rouwenhorst, et al., 2000).

Figure 8: Visualization Hierarchical approach (Rouwenhorst, et al., 2000)

Baker & Canessa (2009) do not distinguish between those decision levels but designed a step-by-step method based on the most common steps found in literature. This theory contains all the steps from the hierarchical approach and some additional steps. We used this second method as the basis of our framework since it is more extensive and our research does not specifically focus on one decision level.

The framework consists of a couple of steps, which are more broadly discussed in the following sections. Most steps follow directly from Baker & Canessa (2009). Steps about obtaining and analyzing data are combined into one step. Furthermore, we added step 5 and 6 according to Hassan (2002). The steps are:

1. Analyze the situation (section 3.1.1)
2. Determine what operating policies to use (3.1.2)
3. Select the equipment (3.1.3)
4. Form a general layout (3.1.3)
5. Determine the aisles and space requirements (3.1.5)

6. Determine the locations of the facilities: the docks, entrances, exits, products, and zones (3.1.6).
7. Evaluate the alternatives (3.1.7)
8. Short term operational decisions (3.1.8)

In the next sections we discuss those steps more elaborate. It should be noted that the design process is an iterative process. Previous steps could need adjustments in later phases (Baker & Canessa, 2009) .

3.1.1 Situation

The first step in warehouse layout design is to assess the situation, so well founded decisions can be made. This also determines the focus, requirements and boundaries of the research. Factors about the situation that should be assessed are the warehouse type, its process flow, demand properties, order characteristics (Hassan, 2002) *and the requirements and constraints corresponding to the business strategy* (Baker & Canessa, 2009).

Three types of warehouses can be distinguished: distribution, production and contract warehouses (Van den Berg & Zijm, 1999). Every type has its own main focus. Distribution warehouses have multiple suppliers and multiple internal customers, and focus mainly on cost-efficient order picking. Production warehouses supply a production facility, so fast supply and storage capacity are important (Rouwenhorst, et al., 2000). Contract warehouses store on behalf of external customers so they have no influence on the stored amounts (Gu, Goetschalckx, & McGinnis, 2010), and often focus on space utilization (Hassan, 2002).

The process flow and its steps determine the required equipment and space. A basic process flow consists of receiving, storing, picking and delivering goods. In some cases other processes, like sorting two orders that were picked together, can be needed too (Rouwenhorst, et al., 2000).

To get a complete overview, some data should be analyzed. Demand information consists of the volume, fluctuations, trends and (seasonal) patterns of the demand of items. Order information is about who orders what, the volumes, and whether full or partial loads are ordered (Hassan, 2002). Also data about the goods arrival patterns should be analyzed (Baker & Canessa, 2009).

Summarizing, step one:

- Determines the warehouse type
- Determines the process flow
- Analyses demand and delivery data

3.1.2 Operating policies

The second step of warehouse layout design is to establish the inventory levels and operating policies. For the inventory levels, it is important to take several scenarios into account (Hassan, 2002)*. The operation policies determine how products are stored* (Hassan, 2002)*, picked, and delivered to the customers* (Baker & Canessa, 2009)*. For the operation policies many strategies and techniques can be used. Those are more elaborately discussed in section 3.2. In this section, we will shortly enumerate what decisions should be made in this phase and what section elaborates on the corresponding techniques.*

An important operating policy is the storage strategy (De Koster, Le-Duc, & Roodbergen, 2006). The storage strategy states in what way the storage location of a product is determined. In this step it should be decided what strategy will be used and how it will be implemented. Section 3.2.1 elaborates on the possible storage strategies.

Another operating policy is whether orders will be picked separately or in batches (Accorsi, Manzini, & Maranesi, 2014). Batching is discussed in section 3.2.3. Furthermore, picks can be assigned to employees in several ways. Often this is based on the order content, but it can also be based on the location of the products (Gu, Goetschalckx, & McGinnis, 2010). The latter is called zoning and is discussed in 3.2.4. Another option is to use waves (Accorsi, Manzini, & Maranesi, 2014). In that case orders do not become available instantly but at a certain moment in time. Section 3.2.5 elaborates on this technique.

Finally it should be noted that parts of the storage area can be treated as separate small warehouses, where different policies can be applied to different situations and parts of the warehouse (Hassan, 2002; Rouwenhorst, et al., 2000). So for example batching can be used only for the small orders.

Step two determines:

- The inventory levels
- The storage strategy (see section 3.2.1)
- Batching strategy (see section 3.2.3)
- If and how to implement zoning (see section 3.2.4)
- If and how to implement waves (see section 3.2.5)

3.1.3 Equipment

When the unit loads and operating policies are determined, the equipment should be selected (Baker & Canessa, 2009) *and assigned to a particular warehouse area. The equipment has a lot of impact, since it determines the level of automation* (Gu, Goetschalckx, & McGinnis, 2010) *and the required space* (Hassan, 2002)*. An important part of the equipment is the type, amount and capacity handling equipment. Sometimes additional equipment is required, for example a sorting machine. That equipment has to be selected in this stage as well. Furthermore, the storage method should be determined. This also includes the amounts and dimensions of the racks and bins* (Hassan, 2002).

To ease the decision process, it is best to choose the most economic option between the technical feasible options (Rouwenhorst, et al., 2000).

Step three selects and assigns:

- The amount, type, and dimensions of racks and bins
- The handling equipment
- The optional machinery

3.1.4 General layout

Step 4 determines the general warehouse layout (Baker & Canessa, 2009)*. In this step, warehouse departments are formed and the required space is determined* (Gu, Goetschalckx, & McGinnis, 2010)*. A warehouse department is an area in the warehouse in which one or several steps form the process flow are performed. The general layout is formed by arranging them. A straight line is preferred, like a flow shop, since almost all products follow the same route* (Hassan, 2002).

Systematic layout planning of Richard Muther is a method that can be used to form this general layout. According to that method, first the situation has to be analyzed. Then it should be analyzed how the materials flow and how the warehouse activities relate to each other, to from a relationship diagram. Then the available space should be determined and assigned to the activities in the relationship diagram. Finally the constraints and limitations should be taken into account and a layout can be generated (Yang T. S., 2000).

When the general layout is formed, the storage area can be designed in more detail. To speed up the picking process the storage area can be divided into a forward and a reserve area (De Koster, Le-Duc, & Roodbergen, 2006). This method is more broadly explained in 3.2.6 and if this method is implemented, also the dimensions of the areas are determined in this step (Rouwenhorst, et al., 2000). Furthermore, a slotting strategy should be selected. This is the logic that determines the exact storage location of a product. The storage location of an item can for example depend on its size, or pick frequency (Onut, Tuzkaya, & Dogac, 2008). Section 3.2.2 elaborates on the slotting strategies found in literature.

Step four determines:

- The division of warehouse activities into several functional departments
- If and how the storage area is divided into a separate forward and reserve area
- The slotting strategy for the products

3.1.5 Aisles and space

Step 5 determines the total space and the racks. For the racks this determines its amount, orientation, length, width and aisle locations. The most common goal is to minimize travel distance (De Koster, Le-Duc, & Roodbergen, 2006)*, but it also determines the probability of congestion and required space.*

According to Hassan (2002), the required warehouse area should be based on all previous steps. Other theories determine the space in the beginning, treating it as a constraint later on (Gu, Goetschalckx, & McGinnis, 2010; Onut, Tuzkaya, & Dogac, 2008). We do not discuss which consecution is better since the warehouse area is already fixed in our situation.

Step 5 determines the aisles and total warehouse area.

3.1.6 Facility locations

In step 6 the layout is finalized by locating the required facilities. First the amount and location of the docks need to be determined (Hassan, 2002)*. A dock is the location where transportation modes are loaded or unloaded. The amount of docks is a tradeoff, since every additional dock requires space but reduces the congestions, and increases routing flexibility and throughput* (Onut, Tuzkaya, & Dogac, 2008)*. Furthermore, it can accommodate various transportation modes and frequent shipping.*

Second, the amount and location of the I/O points should be determined. I/O point stands for Input / Output point, and it is the location where products arrive or leave the warehouse. They influence the average picking time and distance, throughput, and the probability of congestion.

Finally, the specific locations should be assigned to the products and equipment. Also the required amount of employees should be determined. This influences the throughput, probability of congestions, productivity and movement time (Hassan, 2002).

Step 6 determines:

- ❖ The amount and locations of the docks

- The amount and locations of the I/O-points
- The location of the equipment
- The required amount of employees

3.1.7 Evaluation

After step 6, several alternative solutions can be drafted. To determine the best option, the effects on the important criteria should be estimated (Baker & Canessa, 2009). In section 3.3 we discuss what criteria and performance indicators are used in literature. The AHP- method is a good way to weight the alternatives and compare the scores (Yang T. S., 2000). The AHP method will be further explained in section 5.1. After the best option is determined and implemented, only short term decisions remain (Rouwenhorst, et al., 2000). When demand characteristics change, a couple of decisions can be revised, especially the decisions about the inventory levels, zoning, and storage arrangement (Hassan, 2002).

Step 7 evaluates all alternatives and chooses the best alternative.

3.1.8 Operational decisions

According to Gu, Goetschalckx, & McGinnis (2010): "One should not ignore operational performance measures in the design phase since operational efficiency is strongly affected by the design decisions, but it can be very expensive or impossible to change the design decisions once the warehouse is actually built" (p. 1). So, although those decisions have to be made in a later state, assumptions about those assignment tasks can be necessary. It is furthermore, required to measure performance. Therefore, we also clarify what decisions have to be made at the operational level.

On the operational level the strategic and tactic decisions are translated into daily business, based on the incoming orders. Workload has to be divided over the employees, defining who will do what and what picks should be performed simultaneously. Movable objects should be assigned a space: unused equipment should be assigned to dwell points, and arriving and departing trucks to docks. In the case of sort-and-pick, products have to be assigned to sorting equipment (Rouwenhorst, et al., 2000).

Step 8 is about the way the warehouse is managed on a daily basis, including:

- Assign workload to employees
- Allocate movable objects
- Assign products to sorting equipment

3.2 Decisions in warehouse design

Paragraph 3.1 discussed what steps should be performed for designing a warehouse layout. Those steps are summarized in Figure 9. In some of those steps, policies and techniques were mentioned that can be used to improve the performance of the warehouse. In this section, we explain those policies and its options more elaborate.

The first policy we discuss is the storage strategy. As explained in section 3.1.2, this is part of step 2, operating policies. Many storage strategies exist, those options are explained in section 3.2.1. The storage strategy provides the basis for the product locations. After the storage strategy is determined, the product location is more precise determined by the slotting strategy. The slotting strategy is part of step 4 and it is discussed in 3.2.2.

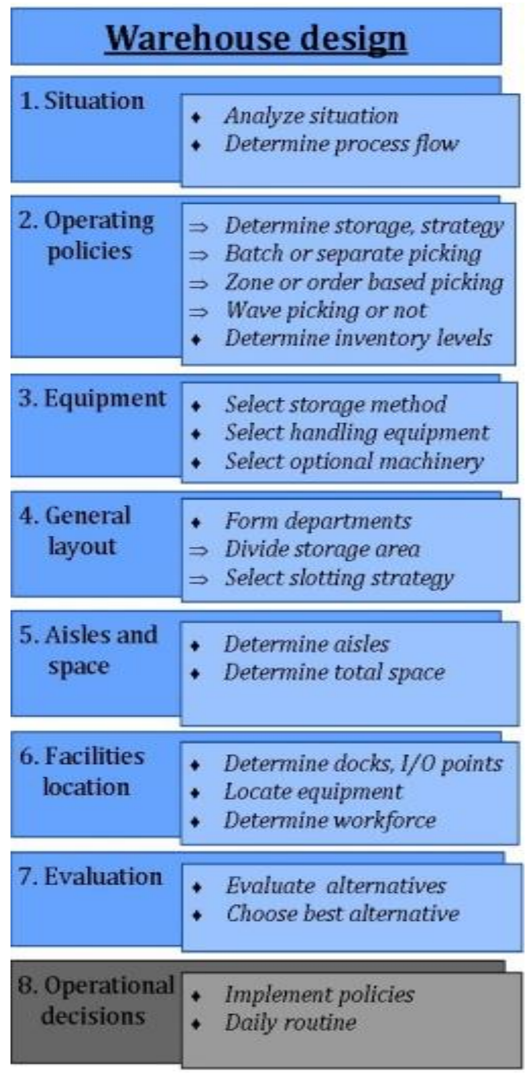

Figure 9: Activities in warehouse design

In step 2 (section 3.1.2) we also mentioned some techniques that can be used to improve the efficiency of the warehouse. In section 3.2.3 we explain batching in further detail, section33 3.2.4 addresses zone picking, and section 3.2.5 elaborates on wave picking in.

In section 3.1.4 we discuss step 4. We mentioned that the storage area can be divided into a separate forward and reserve area. We explain this method in further detail in section 3.2.6.

It should be noted that we only mention techniques in this part that are possible relevant for this research. This means that we only discuss options in which the picker has to go to the products (picker-to-part), since this is implied by the pre-determined racks and equipment. Furthermore, we do not discuss techniques about determining inventory levels, since this is beyond the scope of our research.

3.2.1 Storage strategy

This section explains what a storage strategy is and the existing options. The storage strategy is the logic that determines the storage location of a Stock Keeping Unit (SKU) (Pan, Shih, & Wu, 2012). *It determines to a large extent the space utilization and order picking efficiency* (Chiang, Lin, & Chen, 2011). *The storage strategies can be divided into three main categories: random, dedicated and class based storage. In this section, we explain those categories in further detail. The differences between dedicated and random storage are summarized in Table 3.*

	Random	**Dedicated**
Required area	Smaller	Larger
Traceability	System required	Can be known by heart
Travel distance	Can be minimal because less space is required	Can be minimized through algorithm

Table 3: Comparing dedicated and random storage

The idea of random storage is to determine the storage location of an SKU randomly at the moment the products arrive (Fumi, Scarabotti, & Schiraldi, 2013). In theory the probability that a product is assigned to a certain location is equal for all locations (Chiang, Lin, & Chen, 2011), but in practice the product is often stored in the available space closest to the entrance (Hausman, Schwarz, & Graves, 1976). Random storage minimizes the required storage space, since as soon as a slot becomes available, a new, different product can be stored there (Petersen & Aase, 2004). A disadvantage of random storage is that it requires an information system to track the storage locations of products (Fumi, Scarabotti, & Schiraldi, 2013).

In dedicated storage the storage locations are fixed (Fumi, Scarabotti, & Schiraldi, 2013). This means that the storage locations can be optimized and known by heart by the order pickers (Fumi, Scarabotti, & Schiraldi, 2013). But since the locations are reserved for a certain product, locations can stay vacant for quite some time (Malmberg, 1996). Even more space is wasted when the amount of products to store fluctuates, for example due to seasonal effects (Fumi, Scarabotti, & Schiraldi, 2013). Note however, that if all products are delivered simultaneously, and with constant maximal inventories over the year, random and dedicated storage require the same amount of spaces.

Often in dedicated storage, the storage locations are optimized though a slotting algorithm. This is a heuristic that determines the exact storage location of a product. Most of them minimize the average travel time (Malmberg, 1996), which can be significant, compared to random storage (Gu, Goetschalckx, & McGinnis, 2010). There are however some exceptions, since the total required storage space is often larger compared to random storage (Malmberg, 1996), as explained in the next section (3.2.2).

Class based storage is a combination between random and dedicated storage (Chan & Chan, 2011). In this method, SKUs are divided over a couple of classes. This is often based on the turnover (Hausman, Schwarz, & Graves, 1976). A fixed area is assigned to every class, but the storage locations of all individual items inside a class are random (Pan, Shih, & Wu, 2012). Even when only three classes are formed in one aisle, it decreases the required storage area, whilst providing almost the same travel time savings as dedicated storage (Petersen & Aase, 2004). Class based storage can behave more like dedicated or random storage, depending on the amount of classes. Random storage is comparable to assigning all SKUs to the same class, and when all items have its own class it becomes a dedicated storage policy (Chan & Chan, 2011).

In short, three storage strategies exist: random, dedicated or class based, and the decision between those is mainly a trade of between storage capacity and efficiency.

3.2.2 Slotting methodology

The previous section discussed the options for storage strategies. When dedicated or class based storage is used, a specific location can be determined with a slotting heuristic. Those are discussed in this section.

The problem of allocating the products optimal, with minimal total travel distance, is proven to be NP-hard. This means that heuristics are required to approach the optimal solution (Wutthisirisart, Noble, & Chang, 2015). In this section, we discuss 4 assignment heuristics: Duration of Stay (DoS), Cube per Order Index (COI), Order Oriented Slotting (OOS) and the Minimal Delay Algorithm (MDA)

For the slotting of items to storage locations, the most popular products is often located to the locations closest to I/O point (Brynzer & Johansson, 1996). This is based on the idea that this distance has to be walked most often, so minimizing it has the most effect. The DoS method approaches this by allocating the product that will be stored in the warehouse for the shortest amount of time to the best accessible location (Kim & Park, 2003).

A more common method is the Cube-per-order index (COI) rule, which bases the products popularity on the order frequency and also considers the product size. In COI the item that requires the least storage space (cube) per order frequency is located closest to the I/O point (Malmborg, Balachandran, & Kyle, 1986). Its optimality is proven when only one or two products are picked at a time (Malmborg & Bhaskaran, 1990), though this is not necessarily true for larger orders (Schuur, 2015) because it neglects what products are ordered together.

Correlated storage also takes into account what products are often ordered together (Garfinkel, 2004) and is therefore often preferred for larger orders. The correlation between products should be taken into account when several products are picked simultaneously and its correlation is predictable (Brynzer & Johansson, 1996). Mantel, Schuur and Heragu (2007) developed OOS, a heuristic that assigns products based on its popularity and its interaction frequencies with other products. The interaction frequency is between two products, and states the percentage of orders that contain both. When a product has no interaction with other products, it is assigned according to the COI rule. The highest interaction frequency is considered first, and both products are allocated as close to each other as possible, unless both are already assigned (Mantel, Schuur, & Heragu, 2007).

The minimum delay algorithm (MDA) takes, besides the correlation, also the size of the orders into account. Wutthisirisart et al. (2015) developed MDA, because they recognized that it is sometimes better to place a smaller order close to the I/O point instead of a more frequently occurring order. They state that the travel distance is determined by the product that is the furthest from the I/O point. If a smaller order is placed in the beginning, the distances for the other orders change less. So this can be desirable even when that smaller order is less popular. On the other hand, the least important product is the product that is part of the orders that require the most space for the fewest picks. If they have a distant location, it is likely to influence the total travel time the least. Therefore, MDA assigns the least important product first, to the most remote location. Then the next least important product is determined, but orders that contain already assigned products are not taken into account since the distance for that order is already determined by the most distant located product.

In short, slotting methods vary from simple methods that focus on single products, to more advanced methods that also take interaction frequencies and order sizes into account.

3.2.3 Batching

Batching is the activity of grouping orders to be picked simultaneously (Hsu, Chen, & Chen, 2005)*. It reduces travel time significant when performed properly* (De Koster, Van der Poort, & Wolters, 1999)*. It is* *especially useful for orders with few items* (Gademann, Van den Berg, & Van der Hoff, 2001)*, located in close proximity to each other* (Pan & Liu, 1995)*. Two categories of batching exist, sort-while-pick and sort-and-pick. Those will be explained first. Then we elaborate on several heuristics for batch forming.*

When orders are picked simultaneously, it is important to keep track to what order a product belongs. This division can be made during picking, called sort-while-pick, or afterwards, called sort-and-pick (Parikh & Meller, 2008). In sort-while-pick, the picking cart should have separate compartments and enough space to keep the division between the orders clear. When it is not possible to maintain the individual order integrity, sorting is needed afterwards. But then the benefits from batching may quickly disappear (Petersen & Aase, 2004). It is furthermore, important to balance workload between order pickers, to assure that all orders are fulfilled in time (Parikh & Meller, 2008).

The batching problem is NP-hard if batches contain more than 2 orders (Le-Duc & De Koster, 2007), so finding an optimal solution can take an enormous amount of time. Therefore, heuristics are used (Pan & Liu, 1995). Heuristics can be divided into three categories: Straightforward methods, seed algorithms and savings algorithms (De Koster, Van der Poort, & Wolters, 1999) but also hybrids exist (Pan & Liu, 1995).

Straightforward methods are simple, often not numerical methods like First-come First-served (FCFS) (Gibson & Sharp, 1992) or First-Fit-decreasing (FFD) (Parikh & Meller, 2008). In FCFS the arrival sequence determines the batches (Petersen & Aase, 2004). In FFD the largest order that fits is added to the batch. For small order sizes this gives an optimal or near-optimal solution (Parikh & Meller, 2008).

Seed heuristics consist of two rules: the seed and order addition rule (Pan & Liu, 1995). The seed rule selects the first order of a batch. It is often an order that is hard to add to an existing route. Its items are for example the most spread over the total area (Ho, Su, & Shi, 2008).The order addition rule determines what orders should be added to that seed. If the vehicle capacity allows it, the batch is enlarged with an extra order that have proximity to the seed order (Chen & Wu, 2005). Seed heuristics are preferred over savings algorithms when batches contain many orders (De Koster, Van der Poort, & Wolters, 1999).

In savings algorithms all orders are initially considered to be a separate route. The largest possible saving of combining two routes is executed until no more savings are possible. This means that the amount of batches is not predetermined. Calculations can take a lot of time, especially for a large amount of orders. But when batches are small, and the picking route follows the largest gap routing strategy, its performance is superior (De Koster, Van der Poort, & Wolters, 1999).

More advanced methods can result in substantial gains, especially when batches contain small amounts of orders (De Koster, Van der Poort, & Wolters, 1999). But they are difficult to implement because they are hard to convey to employees (Petersen & Aase, 2004). Straightforward methods, however, are more practical since batch forming takes less time (De Koster, Van der Poort, & Wolters, 1999).

In short, batching is the process of picking of several orders simultaneous. The orders can be sorted during picking, sort-while-pick, or after picking, sort-and-pick. There are several techniques for batch forming, from simple, straightforward techniques to more advanced techniques like seed heuristics and saving algorithms.

3.2.4 Picking zones

Zoning is "the problem of dividing the whole picking area into a number of smaller areas (zones) and assigning order pickers to pick requested items within the zone" (Yu & De Koster, 2009)*. In other words, in zoning the order picker only has to pick orders in a partial warehouse. In this section, we elaborate on zoning. We describe the advantages and disadvantages of zoning, and the variants.*

Zoning has several advantages. Since the order picker picks from a smaller area, the order picker becomes more familiar with its zone, travel time is reduced (Jane & Laih, 2005), and the response time drops

(Rouwenhorst, et al., 2000). Furthermore, only one or a few people pick from a zone. This minimizes or even eliminates traffic congestion (Van Nieuwenhuyse & De Koster, 2008). And when only one person is assigned to a zone, it facilitates clear zone responsibility, for example in the case of a messy workplace or inventory discrepancies. A disadvantage of zoning is that order pickers can only pick partial orders and have to wait until other parts of an order are picked. This creates a workload imbalance, what increases the amount of unfulfilled orders. Even when the workload is spread optimally, a small workload imbalance is inevitable due to fluctuating demand and a diminished risk pooling effect. (Parikh & Meller, 2008).

Since in zoning orders are spread over several zones, two variations exist for conjoining the several parts: parallel and sequential zoning (Rouwenhorst, et al., 2000). In parallel zoning, several parts of several orders are picked simultaneously in different zones, gathered centrally and sorted per order (Gu, Goetschalckx, & McGinnis, 2010). Because several partial orders are picked simultaneously, the pick rate of the order picker rises (Parikh & Meller, 2008). The response time is often smaller, but at the cost of order integrity (Jane & Laih, 2005). Extra operations are required to consolidate the parts from different zones (Petersen & Aase, 2004) and order pickers have to wait until all the zone pickers finish the current order (Parikh & Meller, 2008).

In sequential zoning, also referred to as pick-and-pass order picking or progressive zoning (Yu & De Koster, 2009), an order picker passes the order through to the next zone after picking al products inside its zone (Parikh & Meller, 2008; Yu & De Koster, 2009). No sorting is needed afterwards but the pick rate per picker is lower than in parallel zoning (Parikh & Meller, 2008).

Besides the decision between parallel and sequential zoning (Gu, Goetschalckx, & McGinnis, 2010) also the amount of locations and dimensions of the zones have to be determined (Rouwenhorst, et al., 2000). This has to be done carefully in order to avoid that movement and picking time increases. It is however possible to change the composition of zones when conditions change (Hassan, 2002).

In short, zoning has several advantages in efficiency and responsibility. Two kinds of zoning exist, called parallel and sequential zoning.

3.2.5 Wave picking

Although wave picking is often mentioned as an important decisions in warehouse design, research about this subject is limited (Gu J. , 2005; Nieuwenhuyse & De Koster, 2009). *A wave is a group of orders that becomes available for the order pickers at the same time. Two categories can be identified, a wave can be order or time based. In an order based wave the next wave becomes available when all orders in that wave are picked* (Van den Berg & Zijm, 1999). *In a time based wave the next wave becomes available at a predetermined moment in time, the amount of orders in such a wave is variable* (Gu, Goetschalckx, & McGinnis, 2010). *In this section, we elaborate on this subject.*

Wave picking can be practical when several orders should be picked at the same time, for example because they will be shipped in the same truck (Gademann, Van den Berg, & Van der Hoff, 2001) or share the same due date (Gu, Goetschalckx, & McGinnis, 2010). Wave picking is often implemented when both batching and zoning are applied (De Koster, Le-Duc, & Roodbergen, 2006). Waves can be formed to assure the due dates are obeyed in batch picking, since all orders inside the wave must be picked before a next wave becomes available (Van den Berg J. P., 1999). Furthermore, waves minimize the maximum lead time (Gademann, Van den Berg, & Van der Hoff, 2001; De Koster, Le-Duc, & Roodbergen, 2006).

The disadvantage of waves is that order pickers have to wait when they are finished early (Jane & Laih, 2005). So it is important to determine the right amount of waves, but an optimal solution requires extensive statistical calculations (Nieuwenhuyse & De Koster, 2009). The number and size of picking waves per day should be determined at the tactical level, based on expected operations volume (Hassan, 2002).

In short, waves determine when orders become available to control the due dates. Waves can be time and order based, and are often used in combination with batch and zone picking.

3.2.6 Reserve and forward area

In order to make the order picking process more efficient, the warehouse area is often divided into a forward area and a reserve area (Van den Berg, Sharp, Gademann, & Pochet, 1998)*. In this section, we describe the functions of both areas and the advantage of this division.*

The main function of the forward area is order picking (Gu J. , 2005). It stores fast movers that require little space and is often used to ease the picking process (Heragu, Du, Mantel, & Schuur, 2005). Typically a forward area is small, to have the most advantage in reduced travel times and lower cost (Van den Berg, Sharp, Gademann, & Pochet, 1998). Products in this area are stored in easy accessible racks to ease the picking process (Walter & Scholl, 2013).

The main function of the reserve area is storage (Gu J. , 2005). The reserve area stores the bigger, less demanded products and the reserve of some products that are also located in the forward area (Heragu, Du, Mantel, & Schuur, 2005). Because most products are picked from the forward area, the storage in the reserve area can focus on capacity (Walter & Scholl, 2013) and an inexpensive storage method usually suffices (Van den Berg, Sharp, Gademann, & Pochet, 1998).

When the storage space is divided into a forward and reserve area this improves the efficiency of the picking process. The required total space is more or less equal since bulk can be stored more efficiently (Gu J. , 2005). However, when some products are stored in both areas, additional replenishments will be necessary (Walter & Scholl, 2013). When this technique in implemented it is therefore, important to make sure advantages outweigh the disadvantages. To assure this, the size of the forward area and the products that will be stored there should be selected carefully (Van den Berg J. P., 1999). Heragu, Du, Mantel, & Schuur (2005) describe a method for determining what products should be assigned to what area and in what amount.

Besides the standard method also several variants of this method exist. The reserve area can for example be divided into a picking area and a replenishment area. Another method is to have a forward and reserve area in the same pallet rack. In that case the lower levels function as a forward area, and the higher levels represent the reserve area (Van den Berg, Sharp, Gademann, & Pochet, 1998).

In short, dividing the area into a forward and reserve area can improve the efficiency because the frequently picked products are more accessible.

3.3 Criteria for evaluating warehouse designs

In section 2.2 we mentioned the criteria that will be used to evaluate the performance of the warehouse. Those criteria will also be used to evaluate the alternatives later in this research. The set of criteria is determined together with the management of the warehouse. We based those set of criteria on the criteria that are regularly mentioned in the literature. In this section, we elaborate on this literature and the most common criteria.

The set of criteria should be selected carefully because they influence to a large extend what constitutes the best solution. What makes a solution optimal is however not obvious since the decisions are strongly coupled (Gu, Goetschalckx, & McGinnis, 2010), a lot of factors are involved, and improving one factor could have a negative effect on other factors. Batching, for example, makes the picking process more efficient but, because of sorting, can lower the order integrity. The best option therefore, depends on the most suitable combination of factors. The factors that can be influenced can be divided into four categories (Gu, Goetschalckx, & McGinnis, 2010):

1. Costs
2. Service quality, which is determined by:
    a. Order picking time (De Koster, Le-Duc, & Roodbergen, 2006)
    b. Picking accuracy (Gu, Goetschalckx, & McGinnis, 2010; Rouwenhorst, et al., 2000)

3. Space utilization
4. Throughput

Note however, that performance criteria can be treated both, as a design objective or as a constraint (Rouwenhorst, et al., 2000). Factors should be selected carefully, and unimportant factors are better left out, since this can improve the performance on more relevant factors (Hassan, 2002). For every factor several Key Performance Indicators (KPIs) can be used to measure the performance of the warehouse.

In the next sections we discuss the KPIs for costs (3.3.1), order picking time (3.3.2), accuracy (3.3.3), space utilization (3.3.4), and throughput (3.3.5). We conclude in section 3.3.6 with a list of the possible performance criteria.

3.3.1 Costs

The costs of a warehouse design can be divided into investment and operating costs. Investment costs are often high, but occur only once. This mostly concerns the costs of purchasing the building and the required equipment (Rouwenhorst, et al., 2000). Operating costs are often low, but have to be paid during the lifetime of the warehouse. Operating costs are mostly determined by the required amount of operational employees (Onut, Tuzkaya, & Dogac, 2008). To compare those, the net present value can be calculated (Rouwenhorst, et al., 2000). This results in the following KPIs for costs:

- ❖ Average operational cost per day (minimize)
- ❖ The net present value of all (estimated) cost (minimize)
- ❖ Required amount of employee hours needed for storage and picking (minimize)

3.3.2 Order picking time

Order picking time strongly influences the service quality (De Koster, Le-Duc, & Roodbergen, 2006), and it is the most important, laborious and time-consuming process of all warehouse processes (Onut, Tuzkaya,

& Dogac, 2008). It is the cause of around 65% of the total operating cost of a warehouse, and for distribution warehouses this is even more (Strack & Pochet, 2010). The warehouse of the HOH can be classified as such, because it has multiple suppliers and multiple (internal) customers. This means that order picking time is important here. A lower order picking time has several advantages. Fulfilling all orders takes less time, so more orders will be delivered on time. Also, late changes in orders can be handled, since the process becomes more flexible, so the service quality rises. An efficient and flexible order picking system is especially important when many and small amounts are ordered with a short due date (Yu & De Koster, 2009).

Minimizing travel distance is one of the most widely used performance criteria. See for example Accorsi, Manzini & Maranesi (2014), De Koster, Le-Duc & Roodbergen (2006) or Gu, Goetchsalckx & McGinnis (2010). This is probably because it is easy to quantify, and provides an accurate indication of the performance of an order picking system (Chew & Tang, 1999) whilst it does not add value, (De Koster, Le-Duc, & Roodbergen, 2006). Furthermore, for almost all warehouses, the dominant part of the order picking process is travel time. This results in the KPIs listed below.

- The total traveled distance (minimize)
- The average lateness* per order (minimize)
- The average travel time or picking an order (minimize)
- The percentage of on time deliveries (maximize)

*With average lateness we mean the average time an order is delivered at the department after its due date. If for example an order is delivered one hour too early, its lateness is zero. If another order is delivered one hour too late, its lateness is one. The resulting average lateness is half an hour.

3.3.3 Accuracy

An important measure for the quality of the warehouse service is the accuracy (De Koster, Le-Duc, & Roodbergen, 2006). We define accuracy as the delivery of the right product in the right amount. Delivering unexpired products is also part of the accuracy since an expired product is useless, and thus more or less equal to no product at all. The same holds for damaged products (Baker & Canessa, 2009). The probability of picking an expired product can be measured as the percentage of expired products, if the product is picked random. A few KPIs are stated below.

- ❖ Percentage of correctly fulfilled orders (maximize)
- ❖ Percentage of correctly fulfilled order lines (maximize)
- ❖ Percentage of expired products in the system (minimize)

3.3.4 Space utilization

Storage capacity is mostly determined by the type and dimensions of the storage system (Rouwenhorst, et al., 2000), and, to a lesser degree, by the space utilization. The space utilization is to a large extent determined by the storage policy (De Koster, Le-Duc, & Roodbergen, 2006).

In the context of our research, the racks and available storage space are already fixed. Therefore, only the usage of the available storage space can be influenced to enhance the available storage capacity. A more efficient space usage is preferable since it gives room for new products. This increases the ability to growth without having the need to alter the overall layout. Additionally, a dispersion of the available storage area is preferred, to make sure different kinds of products can be added. This results in the KPIs stated below.

- ❖ The amount of free storage area (maximize)
- ❖ The percentage of free storage space per storage type (maximize)

3.3.5 Throughput

The throughput capacity can be defined as "the material flow processed through the warehouse per time unit" (Accorsi, Manzini, & Maranesi, 2014, p. 176). In other words, the throughput capacity is the amount of orders that can be fulfilled per time unit, for example per hour. With a higher throughput capacity, the picking process of an order can start faster after its arrival and takes less time (Tang & Chew, 1997). The throughput is determined by several factors: the amount and type of the resources (Rouwenhorst, et al., 2000), the location and amount of I/O points, the assignment of products to storage locations and in a lesser degree by some other factors like the demand and physical characteristics (Hassan, 2002).

Throughput is an important factor for the time it takes to fulfill an order (Rouwenhorst, et al., 2000). It is different from the travel distance since it also depends on all other factors that could take time, like the time to count and pick the products. It furthermore, depends on the distribution of the workload between order picking; the most balanced division will result in the highest throughput (De Koster, Le-Duc, & Roodbergen, 2006). Possible KPIs of throughput can be found below.

- ❖ The maximal amount of products that can be picked per hour (maximize)
- ❖ The average order fulfillment time (minimize)

3.3.6 Conclusion – performance indicators

In this paragraph we determined what is important for the performance of a warehouse and composed a couple of performance indicators for cost, travel time, accuracy, space utilization, and throughput. This results in the following list of performance indicators:

1. The net present value of all (estimated) cost
2. Average operational cost per day
3. Required amount of employees needed for storage and picking
4. The total traveled distance

5. The average travel time per order
6. The average lateness per order
7. The percentage of on time deliveries
8. Percentage of correctly fulfilled order lines
9. Percentage of expired products in the system
10. The amount of free storage area
11. The percentage of free storage space per area
12. The maximal amount of products that can be picked per hour
13. The average order fulfillment time

3.4 Conclusion

In this chapter we proposed a framework for designing a warehouse layout. This framework consist of a couple of steps, as depicted in Figure 10. In this framework some decisions have to be made with respect to some techniques and policies. Those were discussed in the second section of this chapter. In the next chapter we follow the steps that constitute this framework, to form alternative layouts.

Figure 10: Steps in warehouse design, based on (Baker & Canessa, 2009)

We made a list of the most commonly used criteria. This list was used as a concept for the criteria used in this research, and together with the management of the warehouse a definitive list was formed. Recall that this list is used in section 2.2, to evaluate the performance of the current warehouse. In chapter 5 we will use this list again to evaluate the alternative layouts.

4 Alternative lay-outs

Chapter 3 presented a framework with the steps and decision for designing a warehouse. In this chapter we use this framework to design alternative layouts for the warehouse of HOH. Recall from section 1.3 that inventory levels, equipment, aisles, and spaces are considered out of scope. This means that some steps, or parts of steps, are beyond the scope of this research. They are indicated by a checkmark in Figure 11, and are not discussed in this chapter. All other steps will be discussed, and at the end of this chapter a couple of alternative solutions will be formed. In the next chapters, chapter 5*Fout! Verwijzingsbron niet gevonden.* ***and 6, they will be evaluated.***

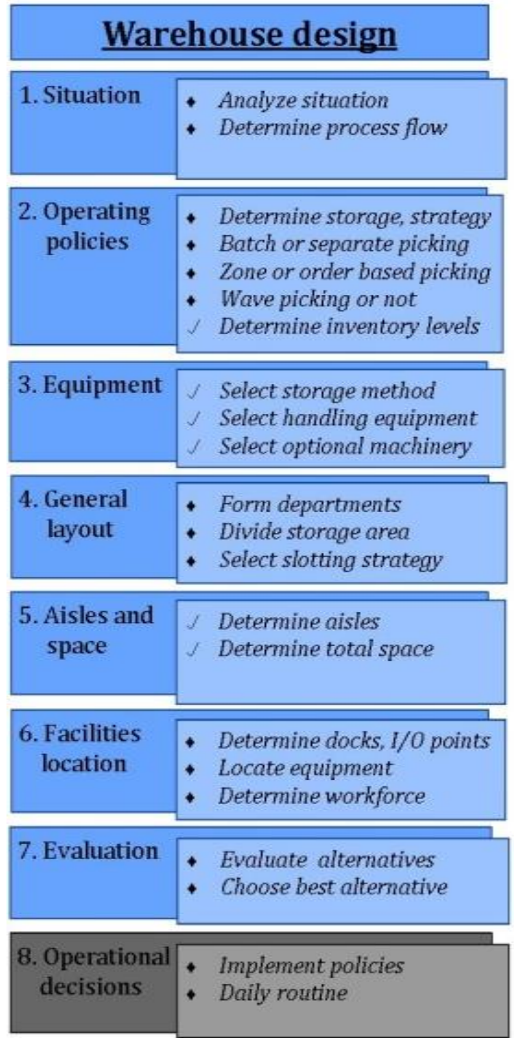

Figure 11: Steps to perform in warehouse design (✓ means predetermined, ● means to be done)

This chapter starts with step one of the framework; analyze the situation and determine the process flow (4.1). The inventory levels, equipment, aisles and space are also considered part of the situation because changing them is out of scope. In section 4.2 we discusses the applicability of operating policies. Step 4 is discussed in section 4.3, and step 6 in 4.4.

4.1 Situation

The first step is to describe the current situation. This is already discussed in chapter 2, but in this part we give additional information. In section 4.1.1 we discuss the warehouse type and process flow. Recall from chapter 2 that, even though the racks are already fixed, some small adjustments to them are possible. Those will be explained more elaborate in section 4.1.2. Section 4.1.3 summarizes this part.

4.1.1 *Type and scope of the warehouse*

This section discusses the warehouse type, process flow, inventory, and equipment of the HOH.

Recall that the HOH has multiple internal customers and multiple suppliers, this means that it can be classified as a distribution warehouse. The hospital has around 80 internal customers, called departments. Figure 12 lists those departments, with the abbreviations used by the hospital. BEVE-D stands for example for the security (in Dutch 'beveiliging') and WOND-D is the Wound Care Clinic.

Once a week				2 days / week	3 days / week
APOT-D	GYNA-D	PERS-D	ERGO-D	AFWAS-D	ANAE-D
ARBO-D	HUIS-D	PIJN-D	KWVE-D	CAFE-D	ENDO-D
AUTO-D	HYGE-D	PINT-D	MEDA-D	CATE-D	OKCH-D
BEVE-D	KIND-D	RECE-D	PAST-D	CSA-D	RECO-D
BLBK-D	KRAAM-D	REVA-D	RADI-D	GIPS-D	SEH-D
CIVI-D	LOGO-D	SU3-D	VAS4-D	HART-D	
CMMO-D	LONG-D	TECH-D	VOED-D	INTER-D	
CMNS-D	MAMMA-D	UROL-D		KEUK-D	
CMSN-D	MDSR-D	VAS1-D		LINN-D	
CMVK-D	NEUF-D	VAS2-D		MICU-D	
COMM-D	NEUP-D	VAS3-D		NSU3-D	
DAGV-D	NEUR-D	VERL-D		NSU4-D	
DIET-D	NSU2-D	WOND-D		ONCO-D	
EAD - BUITEN	OPLE-D	WOND-D S/N		PSYC-D	
ERGO-D	PAAZ-D	CZLO-D		SU2-D	
FUNK-D	PBEG-D	DIAL-D		SU4-D	
FYTH-D	PEDI-D	DIRE-D		VAS5-D	

Figure 12: Delivery days per department

This figure also shows how often per week the departments can place an order. The pharmacy (APOT-D), for example, can place an order once a week on Wednesday. Recall from section 2.1.2 hat the orders are divided over the employees through the ABC-route system. This route division can however change once in a while. For example because a better solution is found, or departments are added or altered. In the last months for example, 9 new departments where added, because the hospital had taken over a laboratory.

Inside the warehouse products are received, stored, picked, and delivered. This is called the process flow. Sorting is optional but currently not necessary. The products inside the warehouse vary significant in size, varying from one square meter to one square centimeter. Its inventory levels are already determined so the supply characteristics are not of interest here.

4.1.2 *Options to alter the situation*

In this section, we discuss the parts of the situation that can be altered. This concerns two alternations possible in the racks: a corridor can be formed at the end of every aisle, and a Flow rack can be placed. Initially those parts were fixed, but after some discussions, the management of the warehouse agreed that those changes are possible and could be considered in our research.

Recall from section 2.3 that the new warehouse will contain 8 pallet racks, forming 4 aisles of around 17 meters long. The end of the aisle is blocked, so the order picker has to walk back, before he can enter the next aisle. It is however possible to form a corridor by removing the lower racks at the end of the aisle, as shown in Figure 13. This makes it possible to go to the next hallway at the end of the aisle. This probably improves the pick efficiency to a large extent. But it costs some storage space. However, those racks can easily be replaced when they become necessary.

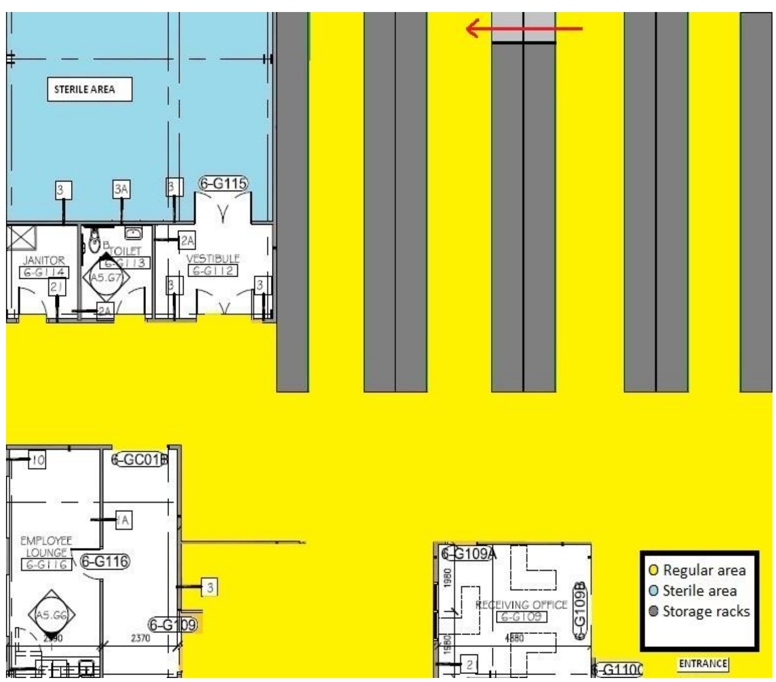

Figure 13: warehouse area

Another option is to place a Flow rack to store the perishable goods. Recall from section 2.2 that around 8.8% of the perishable goods inside the warehouse are expired. To prevent products from expiring, they are manually rearranged, to assure that the oldest product will be picked first. This does however take a lot of time and is thus often omitted, as indicated by the 8.8 % of expired products. To prevent that products will expire, a Flow rack can be placed. In a Flow rack, storage is performed at the back side of the rack, and picked at the front side. This forces a First-in, First-out (FIFO) priority without extra handling. A disadvantage of this method is that such a rack should be accessible at two sides, so the rack at the back side has to be removed. Therefore, this method results in less storage space.

4.1.3 *Conclusion: the resulting options*

The first step of warehouse layout design is to assess the situation. The current situation was already discussed in chapter 2. In this section we made some additions, based in theory. We also considered the racks, aisles, equipment, and total space part of the situation, since they are already fixed. There are however two small changes possible for the racks, as depicted in Table 4. The lower racks at the end of the aisles can be removed to facilitate trespassing there. This is called a corridor. Furthermore, a Flow rack can be placed, replacing two normal racks, to make the FIFO priority rule easier maintainable.

Decision	Options
Flow rack	❖ Yes ❖ No
Corridor	❖ Yes ❖ No

Table 4: options from step 1

4.2 Operating policies

As described in 3.2, step 2 selects the operating policies. This section discusses the options for the HOH and what decisions can be made. We explain why, in the remaining of this research, we only consider dedicated storage as storage strategy (4.2.1), do not consider batch picking (4.2.2) nor zone picking (4.2.3), and only consider one wave per day (4.2.4). Furthermore, we elaborate on the options for dividing the departments over the routes (4.2.5). We summarize the resulting options in section 4.2.6.

4.2.1 ***Storage strategy***

As explained in section 3.2.1, the storage strategy is the way storage locations are assigned to products. Three options are available: Random, Dedicated, and a combination of both, called Class based storage. In this section, we explain why random and class based storage are not advisable, and we only consider dedicated storage in the remaining of this research.

In random storage the storage locations are not fixed. In theory, a computer system can be used to track the storage locations of the products. But the warehouse does not have such a system and purchases are out of scope. Therefore, the locations have to be searched for. But since many products look really similar, random storage is likely to cause many pick errors. We therefore will not examine this option further.

In Class based storage, product are assigned to groups, and products in a groups are stored random in a joint space. In the HOH only the appearances of a small group of products is different enough for random storage. But for this group, the space advantages are negligible, since they are all delivered by the same supplier, on the same dates, with constant inventory over the year. So, class based storage will have limited space advantages. And because it still requires more searching time, with a higher probability of pick errors, only dedicated storage is considered in the remaining of this research.

4.2.2 ***Batch picking and batch deliveries***

Recall from section 3.2.3 that batching reduces the picking time, by picking multiple orders simultaneous. For the HOH, batching can be applied in two ways: deliveries and picking. This section discusses both. We conclude that some, small orders are already delivered in batches, but this can be improved by altering the ABC-routes. We also conclude that batch picking is not possible under the limitations of this research.

4.2.2.1 Batch deliveries

Some orders are already delivered simultaneously to save time. This amount is however limited due to a couple of reasons:

1. On a day, every route contains only a limited amount of orders that are suitable for batch delivery.
2. The delivery cart is unsuitable for several deliveries. So to prevent orders from mixing up, only small orders can be delivered in batches.
3. Batches are formed manually. This is based on logic sense, so only a limited amount of options is noticed. Software for forming batches can improve this, but the warehouse lacks such software. And the sizes of the orders and products differ too much for simple heuristics to perform well.

Problem 2 and 3 require additional purchases, which is beyond the research scope. The amount of orders that can be batched, as mentioned in problem 1, can however increase, through changing the ABC routes. If neighboring locations are allocated to the same route, more batches can be formed. This altering of the routes is discussed more elaborate in section 4.2.5.

4.2.2.2 Batch picking

Currently, orders are never picked in batches. And even though it can have large positive results, it is not taken into account in the rest of this research for the following reasons:

1. Just like batch deliveries, the batches have to be formed manually since the information system cannot form batches. It is however hard to estimate what orders can be picked together, due to the different product and order sizes. Furthermore, the system cannot print a joint picklist, so the order picker has to use several pick lists simultaneously. This is confusing and thus prone to errors.
2. On the current carts it is hard to keep track of to what order a product belongs. This means that a different cart is required, or the orders have to be sorted afterwards. Sorting is prone to errors, thus undesirable, and purchases are beyond the scope of this research.
3. The warehouse employees are really skeptical about batching. It will probably call resistance, especially when it is implemented at both, picking and delivering. If batching is implemented, it is

better to start with batch deliveries because the gains are larger, due to larger distances. In a later phase, when batching has proven its benefits, picking in batches can be considered again.

In short, batch picking and batch delivering will not be taken into account in the remaining of this research. In section 4.2.5 we discuss altering the routes. We expect that this will increase the amount of potential batches.

4.2.3 *Zone picking*

Recall from section 3.2.4 that zoning has the potential to reduce the picking and congestion time. In this section, we explain however that it is not a suitable solution for the HOH, because the warehouse is too small. It provides however, the basis of one of the slotting strategies in section 4.3.3.

If in zoning, all 4 order pickers of the HOH are assigned a zone, they get on average ¼th of the total warehouse area. But those order pickers also have to bring the products to the departments, so every zone is idle half the time. This forces the other zones to wait. Another option is to split the pick and delivery process, then a picking employee will be assigned half a warehouse. This results in a small scale advantage and the zone is never idle. A small scale advantage and area clear area responsibility, do however not outweigh the importance of the order responsibility.

4.2.4 *Wave picking*

Section 3.2.5 described waves, and that its length can be time or order based. In this section, we explain that the HOH currently uses time based waves, and that one wave per day is desirable here. For the remaining of this research, we assume that orders become available in one time based wave per day.

Currently, time based wave picking is already implemented, so its feasibility is proven. It is furthermore, useful, since all orders that arrive on a certain day, share a due date. Currently, a wave consists of all orders that arrived that day, with a duration of 24 hours: from 12 O'clock, to 12 O'clock the next day.

The next step is to determine the amount of waves. The best amount is the smallest amount that assures that all products are delivered on time. Because all orders on a day have the same deadline, 1 wave per day is very logical. If waves become shorter, the chance on an imbalanced workload will rise, and order pickers will have to wait for the next wave. Recall from section 3.2.5 that this causes unfulfilled orders. One wave per day is therefore desirable, since all orders that arrive on a day have the same due date.

4.2.5 *Routes*

In the HOH, the workload of all orders is divided over the employees through the ABC-routes system. This system divides the workload over the order pickers, as explained in section 2.1.2. So even though the division of the departments into routes is an uncommon decision in warehouse design, it is important for the performance of this warehouse. Therefore it is discussed in this section. We discuss the advantages of this ABC system, and how we created a different division of the departments over the routes. In the remaining of this research, we evaluate both, the old and new routes, as part of the alternative solutions.

The ABC system works well for the HOH. It assures a clear division of responsibility. Every order picker is responsible for a group of departments. This makes it is easy to track the performance of the employees, and the department knows who to contact in case of a problem. In the future, the order pickers will also become responsible for checking the local inventory. This is currently the responsibility of the departments. Then, the division of responsibility becomes even more important, since the order picker becomes responsible for the whole supplying process.

But the situation of the hospital changes, so new routes should be formed. The hospital is building a new building, so the locations of the departments will change. As discussed in section 4.2.2, the proximity of the departments in a route has a large impact on the amount of batches that can be formed. Furthermore, the order picker will become responsible for checking the local inventory. This means that he has to visit all departments at the beginning of the day. So, for a route to be optimal, the proximity of departments in the same route is important. Furthermore, the workload of all routes should be more or less equal, since that maximizes throughput, as explained in section 3.3.5.

We investigated how those routes should change for the new situation. The amount of options is however extremely large. The hospital has 80 different departments, and all should be assigned to one of the three routes, with the correct amount of delivery days. This results, for example, for all the 58 departments with one delivery day per week, in 3*5= 15 options. It is impossible to investigate them all individually.

Simulated annealing is a method that considers a limited amount of options in a structured way, to get a good solution in a considerable amount of time. We wrote a simulated annealing program to optimize the route division. The program minimizes the amount of hospital areas that are visited, while the expected amount of orders that arrive on a day has to be smaller than 4. An explanation of this value, and a more elaborate explanation of this program, is given in Appendix C: Program for optimizing the routes.

Route A				
Monday	Tuesday	Wednesday	Thursday	Friday
OKCH-D	CSA-D	OKCH-D	SU4-D	OKCH-D
ANAE-D	KRAAM-D	ANAE-D	NSU4-D	ANAE-D
SU4-D	VAS1-D	VAS3-D	VERL-D	CSA-D
NSU4-D	DAGV-D	RECO-D	RADI-D	APOT-D
RECO-D				RECO-D
				RECE-D

Route B				
Monday	Tuesday	Wednesday	Thursday	Friday
KEUK-D	MICU-D	WOND-D	CATE-D	MICU-D
CATE-D	VAS4-D	VOED-D	AFWAS-D	KEUK-D
AFWAS-D	GIPS-D	KIND-D	INTER-D	VAS2-D
INTER-D	BLBK-D	REVA-D	CAFE-D	GIPS-D
CAFE-D	ONCO-D	UROL-D	BEVE-D	ONCO-D
INTER-D	LINN-D		GYNA-D	LINN-D
PAST-D	TECH-D		NEUP-D	
	MDLP-D		NEUR-D	

Route C				
Monday	Tuesday	Wednesday	Thursday	Friday

NSU3-D	VAS5-D	DIAL-D	NSU3-D	SU3-D
ENDO-D	NSU2-D	ENDO-D	SU2-D	ENDO-D
SU2-D	PEDI-D	SEH-D	EAD-D	VAS5-D
SEH-D	FUNK-D	HYGE-D	PAAZ-D	SEH-D
HART-D	AUTO-D	COMM-D	HART-D	PERS-D
MEEL-D	LONG-D	HUIS-D	MEDA-D	DIRE-D
PBEG-D	MAMMA-D	FYTH-D	LABO-D	PSYC-D
PSYC-D	CMMO-D	CIVI-D	MDSR-D	PINT-D
CMVK-D	KWVE-D	WOSN-D		ARBO-D
	CZLO-D	CMNS-D		ENDO-S
	DIET-D	EAD - BUITEN		LOGO-D
	NEUF-D			PIJN-D
	CMSN-D			
	ERGO-D			
	OPLE-D			

Figure 14: New routes A, B, and C

Figure 14 shows the resulting route division. This new route division redistributes the departments, with nearby departments in the same route, and a different workload balance. Table 5 lists the expected amount of orders per day, for both options. This shows that the workload division is more equal in the new route division. In the new route division we expect around 3 to 4 orders per route, per day. In the old routes this differs much more, from 1.24 to 6.91 orders per route, per day.

New route division				
Route A				
Monday	Tuesday	Wednesday	Thursday	Friday
3.99	3.62	3.08	3.91	3.93
Route B				
Monday	Tuesday	Wednesday	Thursday	Friday
4.00	3.86	4.00	3.91	3.82
Route C				
Monday	Tuesday	Wednesday	Thursday	Friday
3.94	4.00	3.94	3.89	3.97

Old route division				
Route A				
Monday	Tuesday	Wednesday	Thursday	Friday
4.71	1.24	3.21	4.76	1.59
Route B				
Monday	Tuesday	Wednesday	Thursday	Friday
6.23	3.03	2.37	6.91	2.23
Route C				
Monday	Tuesday	Wednesday	Thursday	Friday
3.47	1.38	3.06	6.53	1.91

Table 5: Comparison between the old and the new routes (average amount of orders per day)

4.2.6 *Conclusion: The resulting options*

Section 4.2 discussed the results of step 2 of the framework. We discussed which operating policies are suitable for the HOH warehouse. The results are listed in Table 6, and summarized in this section.

Decision	Options
Storage strategy	Dedicated storage
Batches	No
Zone picking	No zones
Wave picking	1 wave
Routes	❖ Current ❖ Optimized for the locations

Table 6: Options from step 2

First a decision has to be made about the storage strategy. There are three options: random, dedicated or class based storage. Random and class based storage will probably cause many pick errors, since many products look are really similar. Therefore, dedicated storage is assumed in the remaining of this research.

The second operating policy is batching. For the HOH picking and deliveries can both theoretically be performed in batches. Picking in batches can however not properly be introduced within the scope of this research, because it requires additional purchases. Batch deliveries are already performed for some, small orders. This amount can grow by altering the ABC-delivery routes.

We evaluated how the ABC-delivery routes should change in the new situation, and made an alternative division of the departments over the routes. This new division aims to place neighboring departments into the same routes, so more batches can be formed. It furthermore spreads the expected amount of orders more evenly over the days and routes. In the remainder of this research we take both, the old and new routes, into account.

We also discussed zone picking. We conclude that the warehouse of the HOH is too small to have significant advantage of zoning. We did however, based one of the slotting strategies on this principle. This is further discussed in section 4.3.3.

The last operating policy we discussed is wave picking. Wave picking is currently performed with one time based wave per day. Because all orders arrive before 12:00 AM and have to be delivered before 12:00 the next day, one wave per day is very suitable here, and assumed in the remaining of this research.

4.3 General layout

Recall from section 3.1.4 that in step 4 a general layout is formed. This section describes how the theory about forming a general layout can be applied to the HOH. We explain how the warehouse areas are formed (4.3.1), how the storage area is divided (4.3.2) and how a slotting strategy is selected (4.3.3).

4.3.1 *Form warehouse areas*

Recall from section 3.1.4 that a warehouse area is a part of the warehouse in which one or several steps of the process flow are performed. This section explains the warehouse division depicted in Figure 15.

As explained in section 4.1.1, the process flow of the HOH hospital consists of receiving, storage, picking, and delivery. Storage and picking both happen at the storage location of a product. Therefore, we distinguish the following 3 areas:

1. **The receiving area:** between arrival and storage, goods are checked and temporarily stored here.
2. **The storage/picking area:** the goods are stored in this area.
3. **The shipping area:** this area contains the parts that are already picked, but still have to be delivered to the departments.

These three areas have to be allocated to a part of the warehouse. Every area should be large enough for the processes that will be performed there, and to store the required equipment. As stated in 3.1.4, the areas are preferably ordered in a straight line. But this is not possible in the current situation, so it is approached as much as possible. Therefore they are ordered in a U-shape, as depicted in Figure 15.

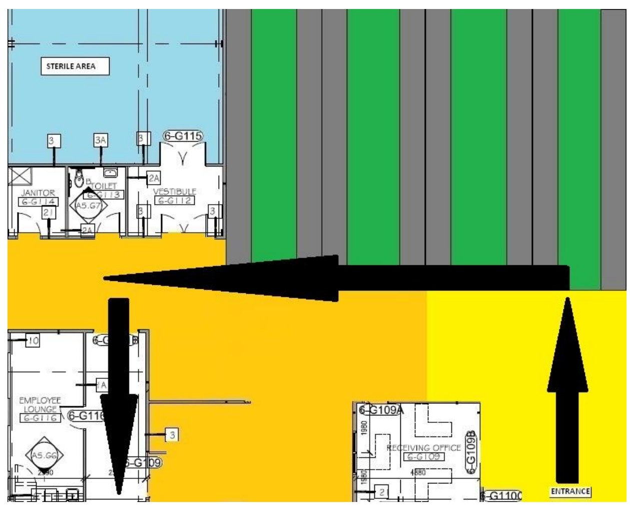

Figure 15: The division of the warehouse into departments

4.3.2 *Divide storage area: Forward and reserve area*

As explained in section 3.2.6, the storage can become more efficient if it is divided into a forward and a reserve area. Recall that the racks in the HOH are already determined. Since they are all the same, it is not possible to get full advantage of this principle. In this section, we will explain that a division in a forward *and reserve area is only useful for products that already require several storage locations. In the remaining of this research we will consider two options for those products: Upper Rack Reserve and Reserve aisle.*

Since storage locations are the same, the storage requirements and picking efficiency will be equal for both, the forward and reserve area. Splitting the storage area will thus have limited advantage. Products that require several storage locations are an exception, since its locations are already split. Those products are often big, and stored in large amounts. The first storage location of those products can be seen as forward area, and the other storage locations can be seen as reserve area. There are two ways to allocate the reserve stock. We call them Upper Rack Reserve and Reserve Aisle.

The Upper Rack Reserve (URR) method stores the reserve stock on the highest rack. This is based on the idea that the less frequently accessed reserve stock should be stored on less accessible locations. The highest rack is considered less accessible than the other racks and therefore, used for the reserve stock.

The Reserve Aisle (RA) method, one aisle is classified as reserve area and stores the reserve products. The other aisles will store the other, more frequently picked products. In that way more picks will be performed close to each other, to minimize the average route length.

4.3.3 *Select slotting strategy*

Recall, from section 3.2.2, that the slotting strategy is the heuristic that allocates the products to specific storage locations. The most frequently picked products are preferably allocated close to the entrance, and products that are ordered together are best allocated close to each other. Whether it is more important to focus on ordering frequency or the order composition, depends in the order structure. We therefore start this section with a short analysis of the order structure. Then we propose four slotting strategies: COI, route based, department based and expert opinion. In the next chapters we evaluate them further.

To determine whether the focus should lie on the pick frequency or the order structure, we investigated the average order size. The order frequency is the most important if orders consist of only one product. The composition of the orders becomes more important when orders are large, and often contain the same products. As shown in Figure 16, the order sizes differ to a large extent, from 1 product to more than 100, with an average of 30 products. So larger orders are more frequent, but small orders are no exception. Therefore, both focusses could be suitable.

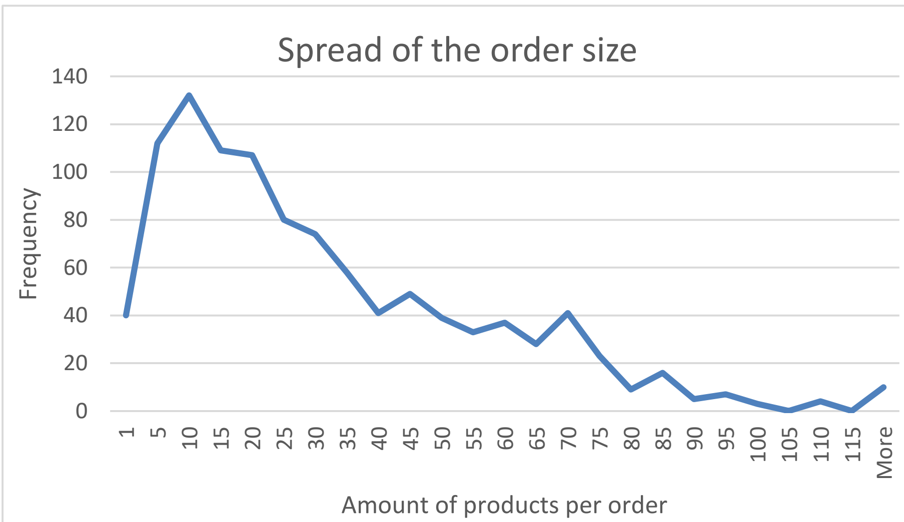

Figure 16: Spread of the order sizes from last year

It is furthermore, important to get an insight in the interaction frequency. Recall from section 3.2.2 that the interaction frequency is between two products, and measures the amount of orders that contain both. It is however hard to calculate reliable interaction frequencies, since the orders differ to a great extent. The assortment of the departments can however serve as an indication of this interaction frequency, because every department has its own subset of products it orders from. Around 37% of all products is ordered by one department only. This method is not exact, since it neglects it if two products are always ordered together. But we expect such combinations to be rare, so this is likely to be a good indicator.

In short, the order sizes differ to a great extent, so it is hard to estimate whether it is better to focus on the pick frequency of the interaction frequency. We therefore examine three options, one focusing on the individual products, one on the orders, and a method that focusses a little bit on both.

There is also a fourth option, which is created by the employees of the warehouse. This product allocation does not use a heuristic but is based on the intuition of the order pickers. Therefore, the options are:

1. COI based - main focus on the single product
2. Route based - mix of the single product and order composition
3. Department based - main focus on order composition
4. Expert opinion - based on the intuition of the order pickers

COI based.

As described in section 3.2.2, COI assigns products according to the order frequency per required space. This method is widely used, and focusses on the individual product. Additionally, we allocate large products in the first aisle, and smaller products in the latter ones, to provide a logical pick sequence.

Route based

The Route based slotting heuristic is based on two principles. The first principle is the ABC-route system, as described in section 2.1.2. The second principle is zoning. Recall that in zoning, every order picker is assigned to a certain area. But we concluded that the warehouse of the HOH is too small to get an advantage of this principle. The route system does however divide the departments, and thus a large part of the products, into three categories. Those products can easily be assigned to a zone.

These two principles can therefore, be combined, by assigning the end of the aisle to the products specific to a certain route. In other words, the end of the aisle is a zone, assigned to an order picker. The rest of the aisle is a regular area, which contains products for all routes. Products inside the aisle will be assigned according to the COI rule, as visualized in Figure 17.

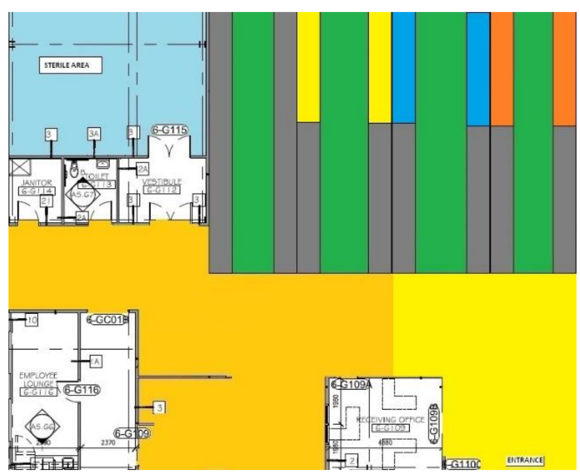

Figure 17: Route based heuristic (Orange represents route A, blue: B, yellow: C)

Because an order picker will be assigned to an aisle as much as possible, congestion is reduced and the responsibility becomes more clear.

This heuristic is however much more suitable for the new route division, since that division has more route specific products. In the old division this was around 30%, and for the new division it is around 50%.

Department based

The department based heuristic is a simplification of the Minimum Delay Algorithm (MDA). Recall from section 3.2.2, that MDA first assigns the infrequently ordered product that belongs to a large order. But instead of actual orders, we base it on what a department can order. And all the department specific products are considered as one product. So we treat, for example, all products that are only ordered by the gypsum department as one item. When a department is already assigned, it is not considered in the remaining of this heuristic. This idea is visualized in Figure 18. The colored blocks represent the department specific products, and the grey blocks are the general products.

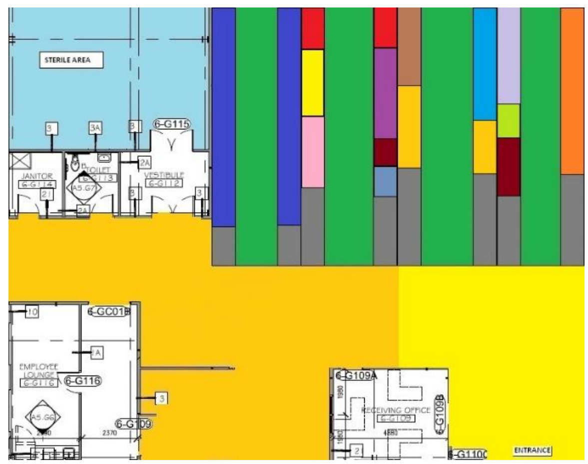

Figure 18: Department based product allocation (every color represents a different department)

This method is likely to perform well, because every department has its own subset of products it can order. Some products are even department specific, so a reliable correlation between products can be taken into account.

Expert opinion

The forth product allocation is created by the employees of the warehouse. It is based on their intuition of what products are often ordered, and often part of the same order.

In short, 4 slotting strategies are available: COI based, ABC-based, department based, and expert opinion.

4.3.4 *Conclusion: The resulting options*

This section elaborated on the general layout, which is step 4 of the framework.

We formed functional warehouse areas, and selected options for the logic behind the storage locations. In this step, we divided the warehouse into functional areas. We formed three functional areas: a receiving area, a storage area, and a shipping area, as depicted in Figure 20.

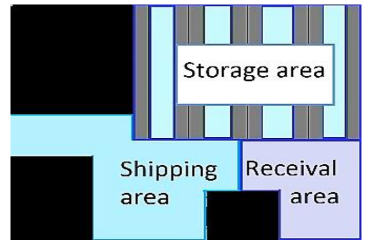

Figure 19: Warehouse areas

We furthermore discussed the option to divide the storage area into a forward and a reserve area. A strict implementation of this principle is not investigated any further. All racks are the same, so we expect limited effect. There are however, some products that require multiple storage locations. Its main picking location can be referred to as the forward area, and the other locations as the reserve. For those products, the location of the reserve stock should be determined. The reserve can be placed on the highest rack, called Upper Rack Reserve (URR), or in a different aisle, called Forward Aisle (FA). In the next chapters, chapter 5 and 6, we investigate them both.

Decision	Options
Warehouse areas	1 option
Forward and reserve area	❖ Forward Aisle (FA) ❖ Upper Rack Reserve (URR)
Slotting strategy	❖ COI ❖ Route based ❖ Department based ❖ Expert opinion

Table 7 *lists the results.*

Table 7: results of step 4

We also divided the warehouse into functional areas. We formed three functional areas: a receiving area, a storage area, and a shipping area, as depicted in Figure 19.

Finally, a slotting strategy should be selected. The slotting strategy is the logic that determines the exact storage location of a product. We propose four slotting strategies for the HOH. The first, COI, focusses on the pick frequency of the individual product. The second is based on picking zones, and is called Route based. The third, department based, focusses on order content. And the fourth, expert opinion, is created by the order pickers.

4.4 Location of facilities

This section elaborates on step 6 of the framework. Recall from section 3.1.6 that in this step, the layout is finalized by assigning a location to the required facilities. Facilities are all the things, and equipment that are required inside the warehouse, except for the storage racks and SKUs. In this part we explain how we came to the allocation of the facilities depicted in Figure 20.

This part is structured according to the warehouse areas from section 4.3.1, because the equipment should be assigned to the area where they are used. Those areas are depicted in Figure 20. We discuss the location assignment in the receiving area (yellow) in section 4.4.1, the storage area (green) in section 4.4.2, and the shipping area (Orange) 4.4.3. But before we go into further detail, we

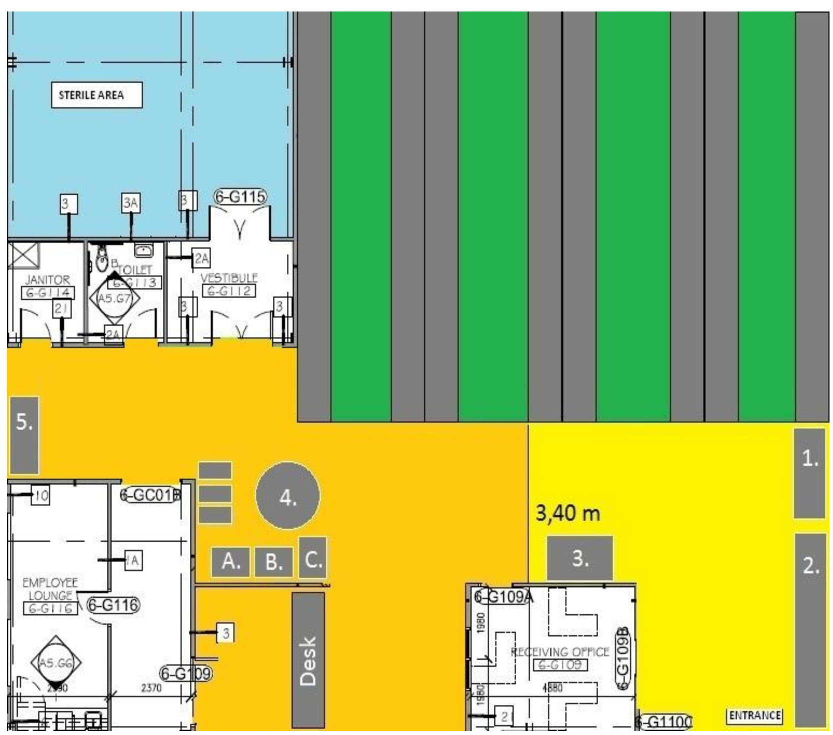

Figure 20 : Location of facilities

list below all the equipment that should be assigned a location inside the warehouse.

1. <u>Pallet stacker</u>

   This is a machine that can lift full loaded pallets to any height

2. <u>Short storage</u>

   A temporarily storage location for products that just arrived

3. <u>Box disposal</u>

   This is a large container to drop of the empty boxes

4. <u>Carts</u>

   - 3 carts for picking
   - 3 carts for deliveries

5. <u>Direct orders</u>

   A temporarily location for the products that the departments order themselves from the supplier.

4.4.1 ***Receiving area***

In the receiving area, the deliveries from suppliers to the hospital are received, checked and sometimes temporarily stored. This area therefore, requires the pallet stacker and a temporarily storage space. The forklift is also used here occasionally, but it is more often used outside. And since there is plenty of room outside, it is located there.

Location 1: Pallet stacker

The pallet stacker requires a space of 1.25 meter by 2 meters, and is stored on location 1 in Figure 20. Besides receiving, it is also used for storage and retrieval. We assigned it to location 1, since it is located inside the receiving area but as close to the storage and retrieval area as possible.

Location 2: Short / temporary storage

The short storage space is assigned to location 2 in Figure 20. The area is used when products cannot be stored on its assigned location immediately, for example because they need to be checked first. Location 2 is assigned for those products because it is on the line between the entrance and the storage location, what means that the extra travel time is minimized. Furthermore, this location is good accessible, but does not block other processes.

4.4.2 ***Storage and retrieval area***

Inside the storage and retrieval area, the products are stored and picked later on. Those processes require the pallet stacker, which is already allocated, a box disposal, and the pick carts. This area has however little space to store facilities, since it is filled with racks. This means that equipment that is used in this area, should be allocated nearby, instead of inside this area.

Location 3: Box disposal

The box disposal is assigned to location 3 in Figure 20 and has a size of 2 meters by 1.45 meters. Recall from 2.1.1, that empty boxes remain after products are stored. The process of getting rid of those boxes should be as easy as possible, otherwise it is likely to be omitted. Location 3 is assigned to the box disposal because it relatively close to all storage locations, whilst it does not hinder other processes.

Location 4: Pick and delivery carts

The Pick carts share a location with the delivery carts, and are assigned to location 3 in Figure 20. This area stores 3 pick cart, with a size of 0.65 by 1 meter, and 3 delivery carts, of 0.82 by 1.27 meter. The pick- and delivery carts can have a joint location, since an order picker always uses one of them. First, the pick cart is used to walk to the storage locations. Then picked products are transferred to the delivery cart, which is used to bring the products to the departments. This means two things:

1. The location of the delivery cart should be good accessible, but only when the pick cart is in use.

2. The order picker only visits the location of the cart at the beginning or end of the picking process.

Since the pick cart is in use when products are transferred to the delivery cart, the location of the pick cart can block the access of the delivery cart. Since the storage location of the carts is only visited at the start or end of a picking route, it will minimize the travel distance if it is located on the line between the exit and the storage locations. We selected location 4, since it is large enough, and located on this line.

4.4.3 Shipping

Picked product are gathered in the storage area, before they are shipped to the departments. This requires the delivery carts of location 4. There are furthermore, products that the department order directly at the supplier. Those products also arrive at the warehouse, but are not assigned a location in the racks. They require a temporary storage location between arrival and shipment.

Location 5: products directly ordered by the departments

Location 5 is assigned to the products that are directly ordered by the departments. It is located close to the exit, to minimize handling cost. The products are assigned a joint location to minimize the required storage area. A joint location minimizes the required space because of the risk pooling effect, since the amount and size of those goods differ significant. The risk pooling effect is explained in Definitions.

4.5 Conclusion: alternative layouts

In this chapter we applied the framework, as proposed in chapter 3. We limited ourselves to the steps that are within the scope of this research, for example step 3: purchasing equipment. From the performed steps, many options arose. We selected the options that can be implemented within the scope of this research, and are likely to improve the warehouse performance.

In this section, we briefly summarize the existing options, and why we selected the options listed in

Decision	Options
Flow rack	❖ Yes / No
Corridor	❖ Yes / No
Storage strategy	Dedicated storage
Batches	No
Zone picking	No zones
Wave picking	1 wave
Routes	❖ Current ❖ New - Optimized for the locations
Departments	1 option
Forward and reserve area	❖ Forward Aisle (FA) ❖ Upper Rack Reserve (URR)
Slotting strategy	❖ COI ❖ Route based ❖ Department based ❖ Expert opinion
Location of facilities	1 option

Table 8. A combination of one option per decision forms the alternative layouts, this result in 64 alternative layouts. Those are evaluated in the next chapters.

Decision	Options
Flow rack	❖ Yes / No
Corridor	❖ Yes / No
Storage strategy	Dedicated storage
Batches	No
Zone picking	No zones
Wave picking	1 wave
Routes	❖ Current ❖ New - Optimized for the locations
Departments	1 option
Forward and reserve area	❖ Forward Aisle (FA) ❖ Upper Rack Reserve (URR)
Slotting strategy	❖ COI ❖ Route based ❖ Department based ❖ Expert opinion
Location of facilities	1 option

Table 8: Options for forming alternative layouts

In section 4.1 we discussed the situation, this also includes the racks, since they are already determined.

There are however two changes possible for the racks:

- A corridor can be formed at the end of the aisle, to minimize the average travel distance per order.
- A Flow rack can be placed, to make the FIFO priority rule more maintainable.

Section 4.2 discussed the operating policies:

- We selected dedicated storage as the storage strategy. Many products look really similar, so storing them random or class based will probably raise the probability on incorrect picks.

- We conclude that both batch picking and batch delivering cannot be properly introduced with the current equipment and will thus not be considered any further. Batch deliveries are however possible to a small extend and already performed for small orders. To make more batch deliveries possible, we constructed a different division for the ABC routes.
- We concluded that the warehouse is too small to introduce strict zone picking, and based a slotting strategy on this principle.
- We introduced a new way of dividing the departments over the routes to maximize the potential amount of batch deliveries.

In section 4.3 we discussed the general layout:

- We divided the warehouse into three functional areas: the arrival, the storage, and shipping area.
- We also proposed two options for the products that require several storage areas. The products that do not fit in the first storage location can be placed on the highest rack (URR) or in another aisle (FA).
- We proposed four slotting strategies. COI, which focusses on the pick frequency of the individual product. Route based, which is based on picking zones. Department based, which focusses on order content. And expert opinion, which is created by the order pickers.

In section 4.4 we assigned a location to the equipment. The resulting assignment is depicted in Figure 21. In this figure, the numbers refer to the following:

1. Pallet stacker
2. Temporary storage
3. Box disposal
4. Pick and delivery carts
5. Directly ordered products

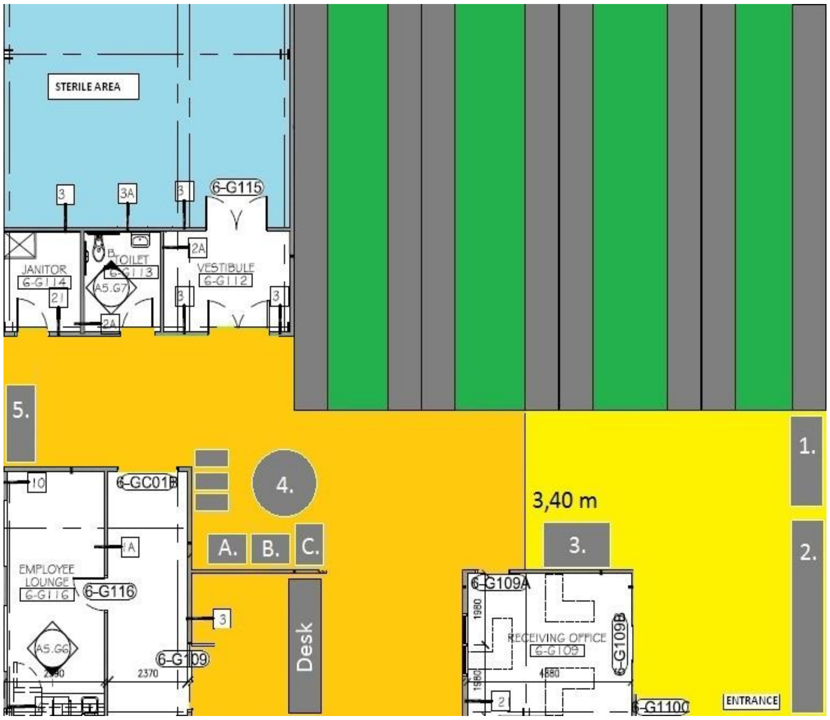

Figure 21 : Location of facilities

5 Method for selecting the best alternative

This chapter describes our computational approach for assessing different warehouse layouts and strategies. We refer to such a layout-strategy combination as a scenario. The buildup of this chapter is as follows. Section 5.1 describes the qualitative and quantitative criteria we use to assess the scenarios. Section 5.2 describes the scenarios and section 5.3 describes the simulation model used to score the scenarios on the quantitative criteria.

5.1 Criteria

To be able to choose the best scenario, all scenarios have to be compared. In this section, we describe what criteria are used to assess the scenarios, and how we measure them.

5.1.1 *The selection of the criteria*

This section explains the criteria we selected for evaluating the scenarios. Section 3.3 discussed what criteria are often used in literature. And as explained in section 2.2, we cooperated with employees and management of the warehouse, to form a list of KPIs, based on this list from 3.3 . Those KPIs are listed in Table 9. Its purpose is however to measure the performance of an existing warehouse. But for the performance of the alternative lay-outs, different and extra criteria can be used. For the evaluation of the scenarios we therefore add some criteria and adjust some of those KPIs. Table 10 lists the resulting criteria.

What?	**How measured?**
Operational costs	Required amount of employees
Volume flexibility	The amount of free storage locations.
Quality of delivery	Amount of on time deliveries Percentage of expired products

Table 9: list of criteria for the current warehouse

Table 10 lists the criteria we selected for evaluating the scenarios. They are ordered according to the importance. This importance is determined in cooperation with the management and employees of the warehouse, using the AHP method. We explain AHP in the next section. But first we explain how we created this list of criteria, based on the KPIs.

	Criterion	weight
A.	Percentage of on time deliveries	27.93%
B.	Clarity of present inventory level	16.90%
C.	Clarity of storage locations	13.91%
D.	Ease of FIFO	10.60%
E.	Low probability of mistakes	8.61%
F.	Ability to focus on one task	7.32%
G.	Equal workload	4.99%
H.	Volume flexibility	3.09%
I.	Efficient picking process	2.65%
J.	Amount of tasks	1.63%

Table 10: Criteria for evaluating the scenarios and the weights

- Criterion A follows directly from the KPI: Quality of delivery – amount of on time deliveries.
- Criterion D is based on the KPI: Quality of delivery – percentage of expired products. But the layout can only influence this performance, by easing the FIFO process. Therefore, only that is measured.
- Criterion H follows directly from the KPI: Volume flexibility – the amount of free storage locations: the amount of free storage spaces determines the flexibility to add extra products.
- Criterion I is based on the KPI: Operational cost – required amount of employees. The warehouse layout does however not affect the time required for deliveries. We therefore only measure the time required for the picking process.

- Criteria B, C, E, and F also determine the quality of deliveries. They are not considered a KPI due to the qualitative nature. But they are perceived important by the employees and management of the warehouse. Therefore, we consider them as criteria, to score the scenarios, and base its performance on expert opinion.
- The employees of the warehouse furthermore, value a fair way of dividing the workload. This is measured by criteria G, and J.

5.1.2 *Measurement of the criteria*

In the previous section we selected criteria, but also a measurement method is required. We start this section with an explanation of the Analytical Hierarchical Process (AHP) method, which we used to determine the weight. At the end of this section we explain how we measured the criteria.

AHP assigns weight to the criteria, through pairwise comparison. Those pairwise comparisons all get an individual score, for example 1, when they are equally important. An example is given in Table 11. Those comparisons need to be consistent. If for example A is more important than B, and B is more important than C, than A must be more important than C. Those scores are then translated into a final score. Finally, a consistency measure is calculated to check whether the comparisons are consistent enough. In our case the consistency measure is 0.089. This is smaller than 0.1, thus consistent.

	A	**B**	**C**
A	1	3	5
B	1/3	1	3
C	1/5	1/3	1
SCORES	0,10	0,29	0,61

Table 11: example AHP scores

The next step is to determine how to measure the performance of the criteria. This is listed in Table 12. Criteria B, C, E, and K are qualitative, as they are based on expert opinion. To assign scores, we also used the AHP method. In 5.1.1 we used this method to weight the criteria, but here we use this method to indicate how the employees perceive the options. The remaining criteria are quantitative, and measured through calculations, or simulation study. To compare the scores, they are all translated to a score from 0 to 1, with 1 being the best scoring scenario, and 0 the worst.

	Criterion	Measured by	Method
A	Percentage of on time deliveries	Percentage of on time deliveries	Simulation
B	Clarity of present inventory level	Expert opinion	AHP
C	Clarity of storage locations	Expert opinion	AHP
D	Ease of FIFO	Percentage of perishable products stored in a Flow rack	Calculations
E	Low probability of mistakes	Expert opinion	AHP
F	Ability to focus on one task	Amount of tasks an employee has on a day	Calculations
G	Equal workload	The average time between the moment the first order picker has picked al orders and the last order picker	Simulation
H	Volume flexibility	Percentage of occupied storage space	Calculations
I	Efficient picking process	Average time it takes to pick all products of an order	Simulation
J	Amount of tasks	Expert opinion	AHP

Table 12: Criteria and measurement method

5.2 Scenario description

As explained in chapter 4, warehouse design consists of many decisions, and those decisions consist of many options.* Table 13 *summarizes the options that resulted from chapter 4. A combination of one option per decision is called a scenario, and the goal of this research is to find the best one. This section explains what scenarios can be formed, and for which scenarios it is relevant to run a simulation.

Through combining all *options* for all *decisions*, 64 scenarios can be created. However, some *decisions* are mostly influenced by qualitative criteria, so the best option can be selected without running a simulation. This concerns the *decisions* about the Flow rack, Corridor, and Forward and Reserve area.

Decision	Options
Flow rack	❖ Yes ❖ No
Corridor	❖ Yes ❖ No
Storage strategy	Dedicated storage
Batch picking	Limited batch deliveries, which are formed by order picker
Zone picking	No zones
Wave picking	1 wave
Routes	❖ Current ❖ New
Warehouse Areas	1 option
Forward and reserve area	❖ Forward Aisle (FA) ❖ Upper Rack Reserve (URR)
Slotting strategy	❖ Expert opinion ❖ COI ❖ Route based ❖ Department based
Location of facilities	1 option

Table 13: options for the HOH

In the next chapter we explain the scores on the criteria, and why we choose a Flow rack, corridor and URR. After those decisions are made, only 7 scenarios remain. Table 14 lists those scenarios. As explained in section 4.3.3, the route based heuristic can only be combined with the new ABC-routes.

All scenarios consist of a Flow rack, Corridor, dedicated storage, no batch picking, limited batch delivering, no zones, 1 wave per day and the same warehouse areas division and facilities locations.

	Product allocation	ABC -Routes
1	Expert opinion	Current
2	COI	Current
3	Department based	Current
4	Expert opinion	New
5	COI	New
6	Department based	New
7	Route based	New

Table 14: Scenarios for the simulation

5.3 The simulation model

This section explains the the simulation. For the simulation, we used the discrete event simulation program Plant Simulation. We structured this section according to Law (2007), who recognizes the following steps in a simulation study: define conceptual model (section 5.3.1), data gathering (section 5.3.2), implementation of the model (section 5.3.3), and verification and validation (section 5.3.4). Later, the experiments should be designed, the model ran, and the output analyzed.

5.3.1 *Conceptual model*

The goal of the simulation is to determine how the 7 remaining scenarios score on the criteria A: Percentage of on time deliveries, G: The equality of the workload, and I: The efficiency of the picking process. In this section, we explain the requirements of the model, the simulation concept, and the simplifications and assumptions. A visualization of the simulation concept is depicted in Figure 22.

The purpose of the model is to test the different scenarios on the selected criteria. The scenarios consist of two components: a product allocation and ABC-Routes, as shown in Table 14. Therefore, we should be able to alter those in the model. When the model is run, it should provide data to calculate the scores on the criteria A, G and I. Therefore, the model should indicate the following:

1. The percentage of orders that is delivered on time (criterion A)
2. How long every order picker needs to handle all his orders on a day. From that we can calculate the difference in day length, between the order pickers (criterion G)
3. The average time that is required to pick an order (criterion I)

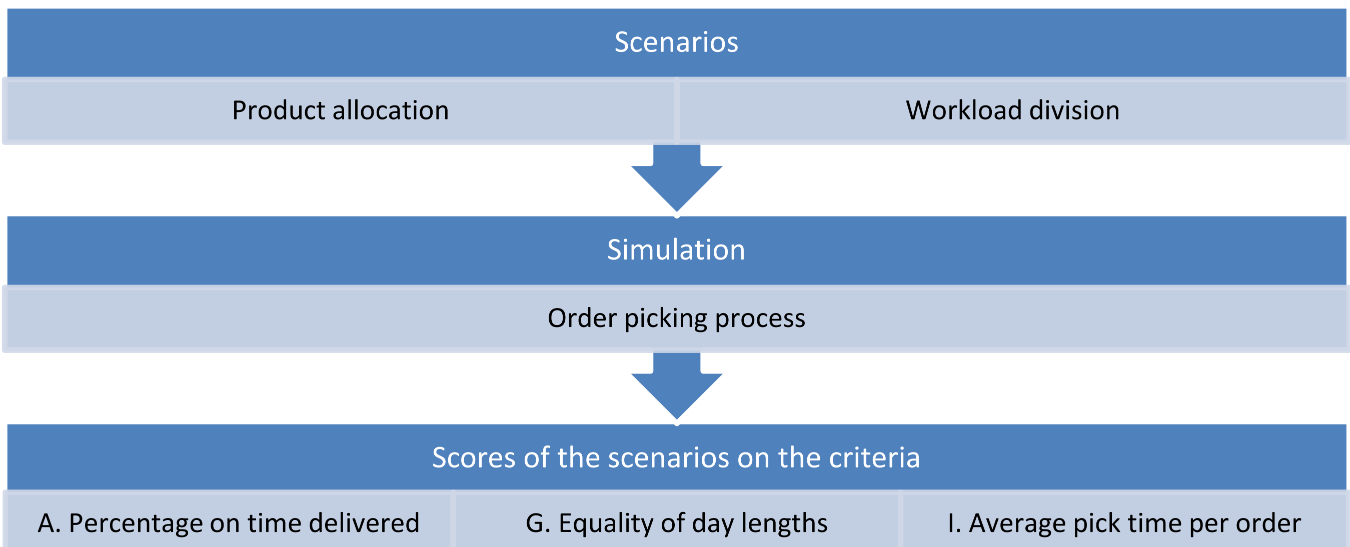

Figure 22: Simulation concept

The purpose of the simulation model is to score the scenarios on those criteria. As visualized in Figure 22: Simulation concept, this is done by simulating the order picking process. The order picking process consists of a couple of steps, listed below and depicted in Figure 23.

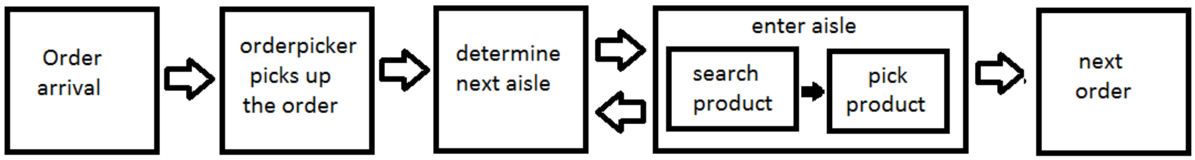

Figure 23: Steps of the order picking process

1. The orders arrive at the beginning of the day
2. The orders are divided over the order pickers, according to the ABC-route division
3. The order picker picks up the pick list of the next order from his subset of orders
4. The order picker enters the aisle that contains the next product that should be picked
5. The order picker visits all product locations on the picklist
6. The order picker searches, and picks the right product, in the right amount, at the product location

We did however, not construct a perfect model, since this would take too much time without substantial gains. Furthermore, this would require data that is unavailable. Therefore, some assumptions and simplifications are required. We first list the simplifications:

- In the model, all orders arrive on time. In reality departments sometimes place an order after the due date. But this is not taken into account because the way of placing orders will change. For the results this means, that the amount of late orders is probably slightly underestimated.
- Inside the model, orders are processed in random order. In reality this is not necessarily true, since order pickers have the option to alter this consecution, and for example, pick small orders first. But it is hard to simulate this, since it differs per day and order picker, whilst it is not expected to influence the results.
- The model only simulates the picking process. The percentage of on time deliveries furthermore depends on the time it takes to bring the products from the warehouse to the departments. This is however not taken into account, since this is not influenced by the warehouse layout, and there

is not enough data available to simulate this properly. The percentage of late deliveries thus neglects the delay caused at the delivery process, and the total percentage is probably higher.

The model is furthermore, based on a couple of assumptions. The assumptions of the model are:

- It is assumed that if a product is picked within 4 hours, it will be delivered on time. The current rule is that the orders should be picked in the afternoon and delivered in the morning. This indicates that the delivery of all orders could be completed within 4 hours, so there are 4 hours left for order picking. In reality, fast delivery can compensate a delay in picking, and deliveries can cause delays as well. This is neglected in the model.
- We assume that all products are always on stock and on the assigned location. But in reality, products go out of stock. Then, less products should be picked, so the actual required picking time is slightly lower.

5.3.2 *Data gathering*

For the simulation, we require data about the warehouse distances and sizes, demand characteristics, and the time required for the separate activities. In this section, we explain how this data was gathered.

1. <u>The warehouse distances and sizes</u>

This data is required to determine the time to travel through the warehouse, and is gathered by measuring the warehouse area.

2. <u>Demand characteristics</u>

This data is required to create a realistic set of orders. The orders in the simulation are actual orders of the last two months. This is other data than the data we used in the construction part, for example to determine the storage locations. Because of this independence, the results become more reliable.

3. <u>The time required for the separate activities</u>

For the simulation we need the time it takes to perform the separate activities: walking, searching for the right product, and picking a product. This data is however not available. It is furthermore, not possible to measure them, since the new warehouse is not in operation yet. The current situation is furthermore, unrealistic, because it contains many temporary locations. Therefore, this data is acquired from literature.

We used the time rates of Chan and Chan (2011), because they use a different picking time for different heights. This is preferable, since it is harder, and more time consuming to pick a product from a 2 meter high rack than from eye level. Furthermore, their walking speed is the average of many walking speeds we found, so it is likely to be reliable. Therefore, we use their time estimates:

- A walking speed of 0.8 meter per second
- The searching and picking time together of:
  - 27 seconds if the shelf is less than 2 meters high
  - 135 seconds if the shelf is 2 meters high or more

5.3.3 *Implementation of the model*

In this section, we explain how the conceptual model is translated into the simulation model depicted in Figure 24. We explain the entities of the program and how the process is simulated.

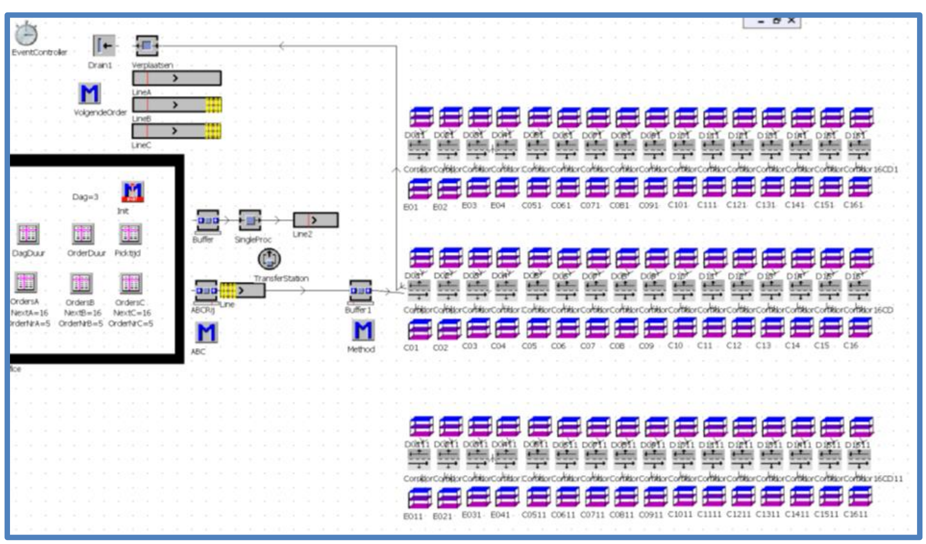

Figure 24: visualization of the simulation model

The simulation model consists of the following entities:

- ***3 order pickers***

  Every order picker is responsible for around one third of the orders.

- ***7 racks forming 3 aisles***

  A rack is only accessible through its connected aisle. The first aisle is connected to racks A and B, the second aisle is connected to racks C and D, and so forth. There is also a fourth aisle, but this aisle currently does not contain products and is thus not simulated.

- ***A set of orders***

  Every order is assigned to an order picker, and consists of a list of products that should be picked, in what amount and the location. The products on a picklist are already in the right picking sequence.

- ***112 storage locations.***

  Every rack consists of 16 storage locations, and only one order picker can have access to a storage location at a time. A storage location can contain 3 or 5 shelfs, and the time required to pick a product depends on the height of the shelf that contains that product.

Now we explain the order picking process. A visualization of the simulated process is shown in Figure 25.

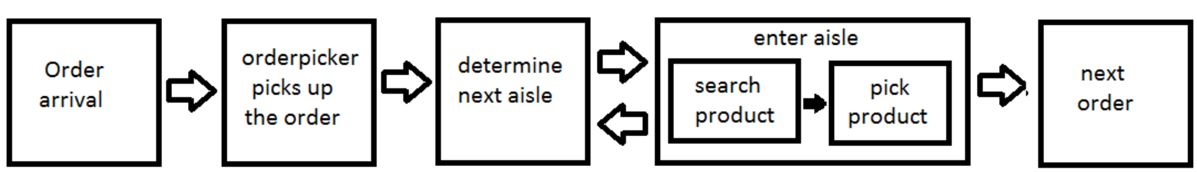

Figure 25: The order picking process

- Order arrival: The simulation starts at the beginning of the day, by creating all orders of that day.
- The order picker picks up an order of his route, which one is random.
- Then he enters the aisle of his first pick.

- When the order picker is inside the aisle, he first has to search for the right location.

  The program checks at every storage location whether the next pick is closer to the end of the aisle, at that storage location, or the beginning of the aisle. If he is at the right storage location he picks the product. Otherwise he walks in the direction of the next pick.

  If the order picker wants to pick a product, first it is checked whether the storage location is not blocked by another order picker. If it is, he has to wait until it becomes accessible. Then he picks the product. Picking takes 27 seconds for the lower levels, and 135 seconds for the highest shelf.

When the order picker has picked the right product, he goes to the next product on that list. If it is the last product on that list, he returns to the entrance of the warehouse and picks up the next picklist. If he has picked all his picklists on that day, his day ends. If all order pickers have picked all their orders, the day ends and a new day starts.

5.3.4 *Verification and Validation*

Before the simulation can be run, the model should be verified and validated. Verification is about determining whether the model is a good representation of the conceptual model. Validation is about checking whether the simulation is an accurate representation of reality (Law, 2007)*. In this section, we explain how the model is validated and verified.*

To verify the model, several techniques are available (Law, 2007). We used the following techniques.

1. The model is written, and debugged, in smaller sub-programs.
2. We classified the output as realistic, by running the model under a variety of settings and inputs.
3. The model is run with a small sample, which results matched the manual recalculations.
4. We determined that the route of the order picker is realistic by observing the simulation animations closely.

For the validation of the model, we used pilot runs to compare the outcomes with the reality. We expected values close to 4 hours, because this is the time available for picking. However, in the pilot, values of around 2 hours were received. But it also appeared the required time differs significant, so in 5 % of the cases, more than 4 hours were required. Furthermore, the picking process of the sterile area, and breaks are not taken into account. Finally, it is possible that the new warehouse is more efficient anyway. We therefore perceive those values realistic.

Preferably, the simulation model is tested on all criteria. In our situation it was however, not possible to determine realistic values for them, due to the evacuation of the warehouse, as explained in chapter 2.

6 Results selection method

The goal of this research is to design a warehouse layout, and order delivery routes, to make the processes efficient and non-sensitive to mistakes, while it remains suitable for growth. In the previous chapters we formed alternative solutions and set up a method for evaluating them. In this chapter we discuss the scores, resulting from this method, and the final solution. In the first section (6.1), we explain for every decision, what option is preferred and why. In section 0 we explain the scores on the scenarios. Then we explain how those scores are obtained on the qualitative criteria (section 6.3), and quantitative criteria (section 6.4).

Before we go into further detail, we like to point out that not all decisions influence all criteria. Table 15 lists what criteria are influenced by the decisions.

Decisions / Criteria	Flow rack	Corridor	Routes	Forward - Reserve	Slotting
A. Percentage of on time deliveries		X	X	X	X
B. Clarity of present inventory level				X	
C. Clarity of storage locations				X	
D. Ease of FIFO	X				
E. Low probability of mistakes	X			X	
F. Ability to focus on one task				X	
G. Equal workload			X		
H. Efficient usage of space	X	X			
I. Efficient picking process		X	X		X
J. Amount of tasks				X	

Table 15: Which criteria are influenced by the decisions?

6.1 The best option per decision

In this section we explain the preferred specifications of the warehouse, and why they are preferred. In later sections we explain the procedure that resulted in this outcome. We consider all decisions ***from chapter 4 that resulted in more than one*** option***. If a decision had only one option, we do not discuss it here any further. This concerns: dedicated storage as storage strategy, no batch picking, no zone picking, and one time based wave per day. In this section we discuss the remaining options.***

- ***Flow rack***

We conclude that the warehouse of the HOH should have a Flow rack, to assure that the perishable goods are picked in First-In, First-Out (FIFO) order. This system makes it easy to use a FIFO priority, though it limits the available space. In section 6.3.2 we explain our AHP analysis, from which we conclude that the ease of FIFO is more important.

- ***Corridor***

We propose to form a corridor, by removing the last rack. This makes it possible to trespass the aisles at the end, which is currently blocked. This improves the pick efficiency, but costs storage space. This is however not a problem since the available space is sufficient, and this rack can easily be placed back.

- ***Upper rack reserve - Forward and reserve area***

We propose to use the Upper rack reserve method (URR) for products that require more than one storage location. This means that the 19 SKUs that do not fit in the regular storage location, have extra storage locations on the highest rack. In section 6.3.1 we explain the AHP method, which we used to compare this option with the Forward Aisle method: place the remaining products in another aisle. We conclude that URR is better, since the employees have a better overview of the current inventory, the location of the reserve stock will be clearer, and it will take less time to restock the main storage location.

❖ ***Route division***

We propose to implement the new route division, because it spreads the workload more evenly. For the decision making, we formed 7 scenarios, consisting of a slotting strategy and route division. In the next section (0), we discus of the performance of those scenarios.

❖ ***Slotting strategy***

We propose to implement the Route based slotting strategy, because it minimizes the picking time and the required storage space. For the decision making, we formed 7 scenarios, consisting of a slotting strategy and route division. In the next section (0), we discus of the performance of those scenarios.

6.2 The scores on the scenarios

In this section we explain the results of the scenarios more explicit. The scenarios we investigate here, consist of a workload division and a product allocation. Table 15 shows that only criteria A, D, G, H, and I are influenced by those decisions. Therefore we limit here to those criteria. The scores of the scenarios on the criteria are listed in Table 16. In section 6.4 we explain how we obtained those scores. Those scores show that scenario ROU-New has the best score.

Scenarios / Criteria	*Exp-Cur* 1. Expert Current	*COI-Cur* 2. COI Current	*Dep-Cur* 3. Department Current	*Exp-New* 4. Expert New	*COI-New* 5. COI New	*Dep-New* 6. Department New	*ROU-New* 7. ROUTE New
A. % of days orders are delivered too late	5.2 %	7.7 %	6.3 %	3.4 %	5.6 %	4.0 %	0.5 %
D. % perishable goods in Flow rack	0 %	100 %	83 %	0 %	100 %	83 %	69 %
G. Equal workload - mean difference (hour)	.85	.84	.83	.73	.73	.70	.63
H. % storage areas occupied	98 %	88 %	84 %	98 %	88 %	84 %	82 %
I. Average picking time (minutes)	15.7	16.0	15.9	15.5	16.0	15.6	14.1
Final score	**.103**	**.131**	**.183**	**.202**	**.240**	**.306**	**.466**

Table 16: Scores of the scenarios (1 to 7) on the criteria

6.2.1 *Criterion A: percentage of days orders are delivered too late*

Criterion A counts the amount of days that picking requires more time than available. There are 4 hours available for picking, as we explained in section 5.3.1. Table 17 shows however, that the average day length is a lot lower. The frequency of all day lengths is shown in Figure 26.

Scenario	Exp-Cur	COI-Cur	Dep-Cur	Exp-New	COI-New	Dep-New	ROU-New
Average (hours)	2:09.52	2:10.03	2:08.59	1:59.57	2:03.09	1:58.35	1:44.15

Table 17: average day length of the scenarios

Based on those results, we conclude:

1. The capacity of the warehouse is sufficient, and late deliveries are due to variances in day length.

2. An even workload provides a more predictable day length, and lower variance. The new workload division (routes) is more even, so less days exceed 4 hours, and more orders are delivered on time.
3. The average day length is smaller if the product allocation minimizes the maximum distance. For example, the maximum distance with the Route based allocation, visits the beginning of all aisles and the end of only one. For COI, the worst case distance is a lot larger, since it visits all the aisles from beginning to end.

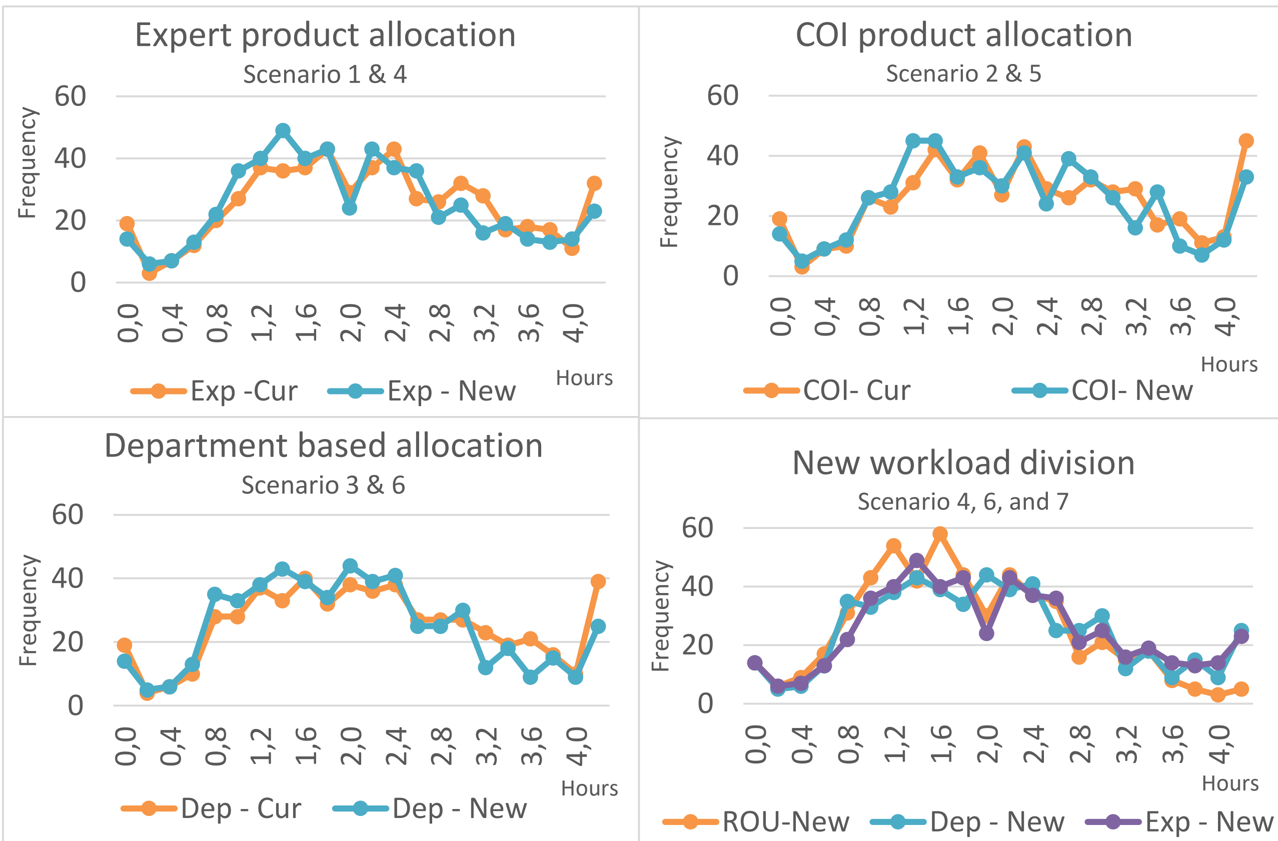

Figure 26: Frequency per day length

6.2.2 *Criterion D: The percentage of perishable goods inside a flow rack*

Criterion D depends on the storage location of the products, so it only depends on the slotting strategy. The expert opinion slotting did not consider a flow rack, and thus has the lowest performance. COI has the best performance, since it stores all perishable products inside this rack. For the department based and route based slotting, this was impossible. Those heuristics divide the products into several categories, which are all assigned to a location in the warehouse. This made it impossible to assign all perishable goods to the same aisle. It is however, possible to displace those products, outside its category, into this rack, though this probably lowers the pick efficiency. The calculations are explained in section 6.4.2.

6.2.3 *Criterion G: The difference in day lengths*

Table 18 shows the mean and variance of the difference in day length. The values show that in some cases the variance rises with the new workload division, compared to the current, and sometimes it drops. This is probably because the new workload division spreads the average workload more evenly, so usually the workload is more even. But when the division becomes unequal, the differences are more often very high: 11 of the 17 values above 3 hours difference belong to the new workload division. In the current workload division the differences in day length are higher, but more predictable. This is visualized in Figure 27.

	Exp-Cur 1. **Expert Current**	*COI-Cur* 2. **COI Current**	*Dep-Cur* 3. **Department Current**	*Exp-New* 4. **Expert New**	*COI-New* 5. **COI New**	*Dep-New* 6. **Department New**	*ROU-New* 7. **ROUTE New**
Mean (minutes)	51.0	50.4	49.2	43.8	43.8	42	37.8
Variance	.40	.37	.38	.42	.39	.37	.27

Table 18: Difference in day length

We explain this figure with an example: Dep-Cur had 44 cases with a difference beneath 0.2, whilst Dep-New had 94 cases. The difference, 50, is shown in the graph at point 0.2. Scenario Rou-new has no current-counterpart, and is thus not part of this comparison.

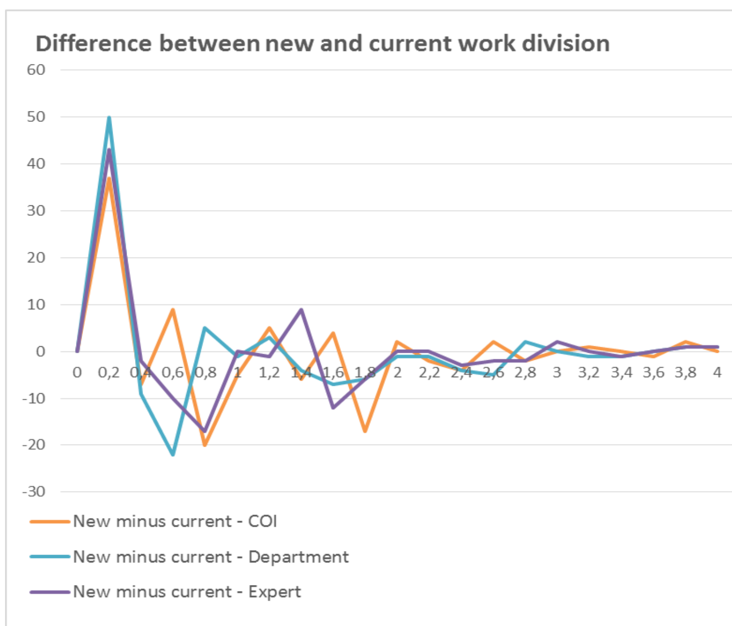

Figure 27: Difference in frequency of difference in day lengths

6.2.4 *Criterion H: The percentage of occupied storage areas*

This criterion measures the efficiency of the space usage. This is determined by the product allocation, thus only differs per slotting strategy.

The expert opinion has the worst performance, probably because it is determined manually and based on estimated space requirement. For the other heuristics, we calculated how many products could share a shelf, based on the dimensions of the products. This results in better space utilization, as the results show.

From the remaining heuristics, COI has the worst performance. Probably because it stores the smallest, most frequently picked products first. Therefore, the larger products are stored last, and there are no small products left to fill up the remaining spaces. Department and Route based work the other way around and store the largest, most infrequent product first. Therefore empty spaces can easier be filled, and less storage space is required. The amount of options is however limited since those heuristics divide the products up into several groups. Since the Route based heuristic has less groups, it performs better.

6.2.5 *Criterion I: The average picking time of an order*

The average picking time does manly depend on the slotting strategy. Figure 28 visualizes that the new and current workload division almost always score equal. The Route based slotting strategy has the best performance, the average lies around 10% lower than the second best alternative: expert opinion. We attribute this difference to the maximum walking distance.

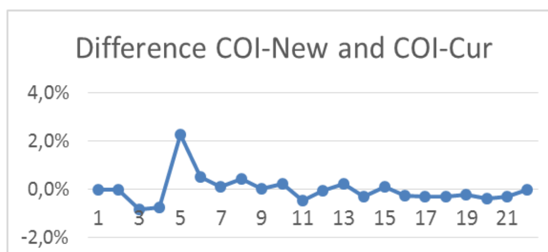

Figure 28: Small percentage difference in picking time (frequencies vs difference in minutes)

As Figure 29 shows, the COI heuristic has the highest probability of a small (4 minutes) and a long picking time (9 to 16 minutes). While the Route based allocation more frequently has a picking time of 5 to 7 minutes. COI minimizes the distance for small orders, while for a large order the whole area could be visited. The Route based slotting however, minimizes the maximum distance: in the worst case scenario a route visits the beginning of all aisles and the end of only the route specific aisle.

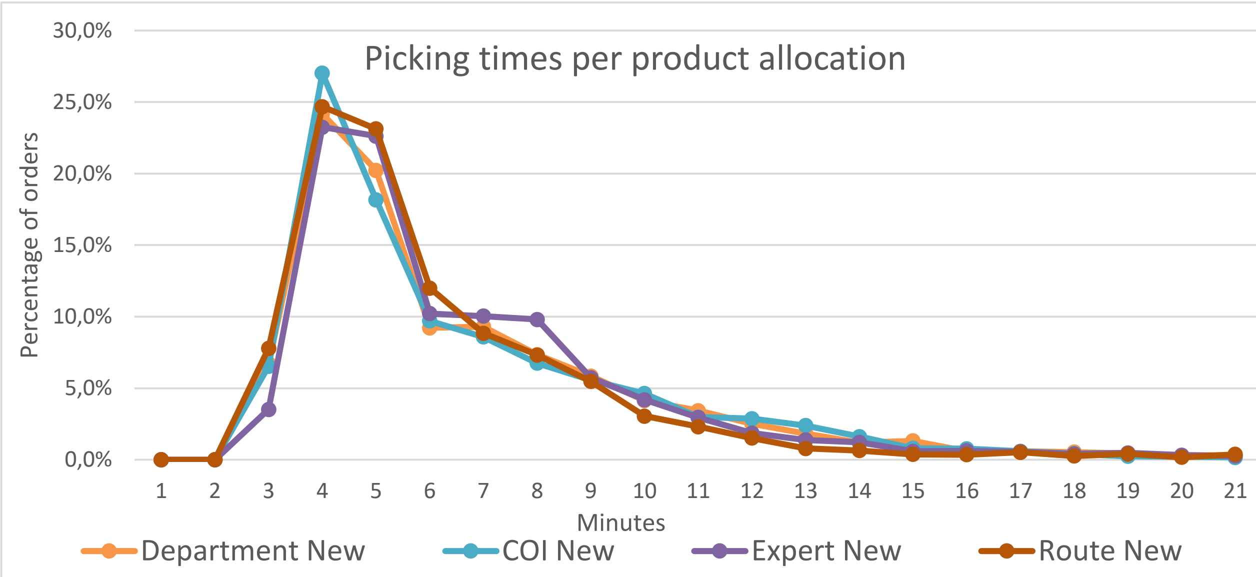

Figure 29: Spread of the picking times for the different product allocations for the new workload division

6.3 Explanation qualitative criteria analysis

In section 6.1, we stated that we decided to place a flow rack, and the Upper Rack Reserve (URR) method is preferred as forward and reserve method. In this section we explain the reason behind those decisions. Section 6.3.1 discuss URR, and section 6.3.2 the Flow rack. But first we explain the AHP method, which we used to make those decisions.

We used the AHP method to make those decisions, because it translates the large assessment into small, discussable decisions. The scores are determined by the employees and management of the warehouse, since they are the mayor stake holders. If a comparison has a score of 1, both are considered equal. 9 is the highest score, and means that the option very preferred over the other.

Those ‘comparison scores’ are then translated into a relative score, by dividing it with the sum of scores assigned to that criterion. If A, for example, scored 7 times better than B on a criterion, its relative score becomes $\frac{7}{7+1/7}$ =0.98. Finally we multiplied this value with the weight of that criterion, for example 0.17. This results in the final score of .17*.98 = .167. These scores are shown in Table 20 and Table 21.

6.3.1 *Forward and Reserve area: Upper Rack Reserve (URR)*

This section explains why we prefer Upper Rack Reserve (URR) over the Forward aisle (FA) method. The AHP method results in the comparisons listed in Table 19. Those comparisons concerns all the relevant qualitative measures. Table 15 shows that this decision influences criteria A, B, C, E, and J. All are quantitative, except criterion A: 'on time deliveries'. Table 20 shows that URR is preferred on those criteria.

Comparisons for the forward and reserve area					
B	Clarity of current inventory level	Upper Rack Reserve	**7**	X better than	Forward Aisle
C	Clarity of storage locations	Upper Rack Reserve	**5**	X better than	Forward Aisle
E	Probability of mistakes	Upper Rack Reserve	**2**	X better than	Forward Aisle
J	Amount of tasks	Upper Rack Reserve	**3**	X better than	Forward Aisle

Table 19: Comparisons AHP for URR and FA on criteria B, C, E, and J

	Difference = 3 *Small difference*		Difference = 9 *A very big difference*	
Criteria	URR	FA	URR	FA
A *(weight .28)*	*.28 * 1/3/(3+1/3)* **.03**	*.28 * 3/(3+1/3)* **.25**	*.28 * 1/9/(9+1/9)* **.00**	*.28 * 9/(9+1/9)* **.28**
B *(weight .17)*	*.17* 7/(7+1/7)* **.17**	*.17* 1/7/(7+1/7)* **.00**	*.17* 7/(7+1/7)* **.17**	*.17* 1/7/(7+1/7)* **.00**
C *(weight .14)*	*.14* 5/(5+1/5)* **.16**	*.14* 1/5/(5+1/5)* **.01**	*.14* 5/(5+1/5)* **.16**	*.14* 1/5/(5+1/5)* **.01**
E *(weight .09)*	*.09* 2/(2+1/2)* **.07**	*.09* 1/2/(2+1/2)* **.02**	*.09* 2/(2+1/2)* **.07**	*.09* 1/2/(2+1/2)* **.02**
J *(weight .02)*	*.02* 3/(3+1/3)* **.01**	*.02* 1/3/(3+1/3)* **.00**	*.02* 3/(3+1/3)* **.01**	*.02* 1/3/(3+1/3)* **.00**
Total score	**.440**	**.280**	**.412**	**.308**

Table 20: Total weight on the criteria for URR and FA

Table 20 shows the results when the score on criterion A is estimated. The scores show that even when FA scores way better on that criterion, URR stays preferred. We do however expect a small difference, since this decision only influences the picking time of infrequently accessed locations. We therefore conclude that URR is preferred.

6.3.2 *Flow rack*

As explained in section 6.1, we prefer to place a Flow rack, instead of keeping this space free, to provide room for growth. Before we elaborate on this decision, it is important to mention that there is enough space available to place a Flow rack. A flow rack requires that the rear rack is removed. But currently only 5 of the 7 racks are required to store all the products. In this section we explain that a flow rack is preferred, according to the scores on the AHP.

Recall from Table 15 that this decision influences criteria D: ease of FIFO, E: the probability of mistakes, and H: Volume flexibility. We used the AHP method to determine the scores. But since the employees of the warehouse never worked with a flow rack, we also test a variety of scores.

Options / Criteria	**All criteria important**		**Underestimating D and E**		**Neglecting D and E**	
	Flow rack	No Flow rack	Flow rack	No Flow rack	Flow rack	No Flow rack
FIFO (D)	*SCORE = 7*	*SCORE = 1/7*	*SCORE =2*	*SCORE = ½*	*SCORE = 1*	*SCORE =1*
Weighted score	.10	.00	.08	.02	.05	.05
Mistakes (E)	*SCORE = 7*	*SCORE = 1/7*	*SCORE = 2*	*SCORE =2*	*SCORE =1*	*SCORE =1*
Weighted score	.08	.00	.07	.02	.04	.04
Volume (H)	*SCORE = 1/9*	*SCORE = 9*	*SCORE = 1/9*	*SCORE = 9*	*SCORE = 1/9*	*SCORE = 9*
Weighted score	.00	.03	.00	.03	.00	.03
TOTAL	**.19**	**.03**	**.15**	**.07**	**.10**	**.13**

Table 21: ***List the scores of the Flow rack on the criteria, compared to the situation without a flow rack.***

We expect that all criteria are to a great extend influenced by this decision. This is shown in the first column. The second and third column show that even when the effect on criteria D and E is largely underestimated, a flow rack stays preferred over room for growth.

6.4 Explanation quantitative analysis

In this sections we explain how we determined the scores on the quantitative criteria, consisting of:

- ***The simulation runs (Section 6.4.1)***

  For the time based criteria, we used a simulation study. This model is explained in X, in this section we explain the runs, and the amount of replications.

- ***Calculations for criteria D and H (Section 6.4.2)***

  Criteria D and H are quantitative, but not time based. The scores are determined with calculations, which are explained in this section.

- ***Translating the scores into one final score (Section 6.4.3)***

  To be able to compare the scores, we translated them into one final score. In this section we explain how we did that.

- ***Sensitivity analysis (Section 6.4.4)***

  We performed a sensitivity analysis to determine that our final results are not very sensitive to the weights assigned to criteria.

6.4.1 *The simulation runs*

This section explains the simulation runs. As explained before, we run the simulation to measure the performance of the remaining 7 scenarios on the time based criteria: A: Percentage of on time deliveries, G: equal workload, and I: Average picking time. We set a run equal to one day, with no warm up period. We performed 180 replications, according to the replication/deletion method of Law (2007).

We set the length of a run equal to the length of a day, and no warm up period is required. Just like in reality, every day starts with a new set of orders. Therefore, the simulation is terminating when a day ends, and all days are independent of the previous one.

The amount of replications should be sufficient to give reliable scores to the three time-based criteria: A: Percentage of on time deliveries, G: the difference in day length, and I: average time for picking. We based the amount of replications on criterion G, since it concerns comparisons of the day length between the order pickers, thus it results in the lowest amount of data points.

We used the formula below, to determine the right amount of runs. Table 22 explains the parameters. According to this formula, we require 539 values. A run results in 3 comparisons, thus 3 values, so we require 539/3 = 180 runs. We therefore, used the data of the last 9 months, which is equal to 185 runs.

$$\frac{t_{n-1,1-\frac{\alpha}{2}}\sqrt{\frac{S^2(n)}{n}}}{\bar{X}(n)} \leq \gamma'$$

Sign	***Explanation***
n	Amount of replications (result)
$t_{n-1,1-\frac{\alpha}{2}}$	Student t-value, depending on the amount of replications and interval length
$1-\alpha$	Interval length, we used 95%
$S^2(n)$	Sample variance
$\bar{X}(n)$	Sample mean
γ'	Relative error, we used 5%

Table 22: parameters to calculate the required amount of replications

6.4.2 *The calculation for criterion D and H*

In this section, we explain how we calculated the scores on criteria D and H.

Criterion D represent the percentage of perishable goods stored in a Flow rack. To determine this, we listed all the perishable goods, and counted for every scenario whether or not it is stored in the Flow rack.

Criterion H is the percentage of occupied storage area. To calculate this, we divided the amount of occupied storage locations by the theoretical maximum available. 'Occupied' means that the rack stores at least one product, or is removed. A rack can for example be removed to form a corridor, or access the Flow rack at the rear rack. The theoretic maximum is the amount of locations when no rack is removed.

6.4.3 *Translating the scores to one score*

Table 16 *in section 0 shows the scores on the scenarios. It also shows a final score. This section explains how we translated those scores into one final score, so we can compare the scenarios.*

We calculated the final score by multiplying the scores with its weight, as shown in Table 23. The scores in Table 16*,* however, depend on the scale of the values. The final score changes for example, when hours are used instead of minute, whilst this does not influence the desirability of the outcome. In order to overcome this problem, we used relative scores. We rescaled the values to a scale of zero to one. Zero points are given to the worst scenario, and 1 to the best.

For this rescaling, we used the following formula:

$$Relative\ score_{C,S} = \left|\frac{Initial\ Score_{C,S} - Lowest\ score_{C}}{Highest\ score_{C} - Lowest\ score_{C}}\right|$$

This formula determines the relative score for scenario S on criterion C. First we calculate the difference between the initial score and the Lowest $score_C$, which is the score of the worst scoring scenario. If scenario S has the worst performance on this criterion, its relative score becomes 0. We divide this by the difference between the lowest and highest score. The relative score of Highest $score_C$ thus becomes 1.

Scenario / Criteria	*Exp-Cur* 1. **Expert Current**	*COI-Cur* 2. **COI Current**	*Dep-Cur* 3. **Departm. Current**	*Exp-New* 4. **Expert New**	*COI-New* 5. **COI New**	*Dep-New* 6. **Departm. New**	*ROU-New* 7. **ROUTE New**
A. % on time delivered	35%	0%	20%	60%	30%	53%	100%
** weight .28 =* ***Score***	.10	.00	.06	.17	.08	.15	.28
D. % perishable goods in a Flow rack	0%	100%	83%	0%	100%	83%	69%
** weight .11 =* ***Score***	.00	.11	.09	.00	.11	.09	.07
G. Equal workload - mean difference	0%	5%	11%	52%	53%	67%	100%
** weight .05 =* ***Score***	.00	.00	.01	.03	.03	.03	.05
H. Percentage of occupied storage area	0%	63%	89%	0%	63%	89%	100%
** weight .03 =* ***Score***	.00	.02	.03	.00	.02	.03	.03
I. Average picking time (minutes)	17%	0%	10%	27%	1%	21%	100%
** weight .03 =* ***Score***	.00	.00	.00	.01	.00	.01	.03
Final scores	**.103**	**.131**	**.183**	**.202**	**.240**	**.306**	**.466**

Table 23: Weighting of the scores

6.4.4 *Sensitivity analysis*

The final scores as given in Table 16, rely on the weight given to the criteria. Changing the weight can influence the results. A sensitivity analysis checks how the score on one aspect could change, before another scenario becomes preferred. In this case, scenario ROU-New is preferred on all criteria, expect criterion D. Therefore, we only consider altering the weight of criterion D. With a simple calculation we determined that the weight of criterion D has to rise to 83.9%, to give scenarios COI-New the same score. The current weight is 11%, so the results are not very sensitive to the assigned weights.

6.5 Conclusion

In this chapter we explained the results of the selection method described in chapter 5, in order to find a solution that meets the goal of this research: to design a warehouse layout, and order delivery routes, to make the processes efficient and non-sensitive to mistakes, while it remains suitable for growth. This results in scenario ROU-New, which consist of the options, listed in Table 24.

To determine the best option, we first narrowed the amount of scenarios down to seven, using quantitative criteria. We compared the remaining 7 scenarios on the remaining criteria through a simulation study. The resulting scores are given in Table 16. The scores in this table show that scenario ROU-New scores best on almost all criteria, therefore Rou-new is preferred.

Decision	Selected option
Flow rack	❖ Yes
Corridor	❖ Yes
Storage strategy	Dedicated storage
Batch picking	Batch deliveries, batches formed by order picker
Zone picking	No zones
Wave picking	1 wave
Routes	❖ Optimized for the locations
Warehouse Areas	1 option
Forward and reserve area	❖ Upper Rack Reserve (URR)
Slotting strategy	❖ Route based
Location of facilities	1 option

Table 24: Configuration of the selected scenario: Rou-new

7 Conclusion and recommendations

In the previous chapters we constructed alternative solutions and compared them. In this chapter we propose a warehouse layout for the HOH. This layout is described in section 7.1. We furthermore describe the limitations of this research (7.2), and do some recommendations for future research (7.3).

7.1 The resulting warehouse layout

The goal of our research is to design a warehouse layout and order delivery routes, in order to make processes efficient and non-sensitive to mistakes, while it remains suitable for growth. In this research we proposed and evaluated several layouts. Based on those results, we recommend the warehouse layout as specified in Table 25.

Implemented technique	Explanation
Flow rack	This rack stores 70% the perishable products and assures that the oldest product is picked first
Corridor	This is an opening at the end of the aisle, to facilitate trespassing at both ends of the racks.
Dedicated storage strategy	All products are assigned a fixed storage location
1 wave - wave picking	We propose wave picking, with one time based wave per day: All orders that arrive on a day become available for picking at the same moment and have the same due date. The next set of orders becomes available at the moment all previous orders are picked.

New routes	We proposed a new workload division, which is called a 'Route'. This division assures that neighboring hospital departments are delivered by the same order picker.
Forward and reserve area	When product require more than one storage location, the additional products are stored on the highest rack
Slotting strategy	The exact storage location is determined by the Route based heuristic. This heuristic assigns the end of an aisle to Route specific products, so only one order picker has to visit that route specific area.

Table 25: specifications recommended warehouse layout

Inside the warehouse, the equipment should also be assigned a location. We propose the allocation of the facilities and warehouse areas as visualized in Figure 30. This area is divided into an arrival area (yellow), a storage area (green), and a shipping area (orange), and it contains:

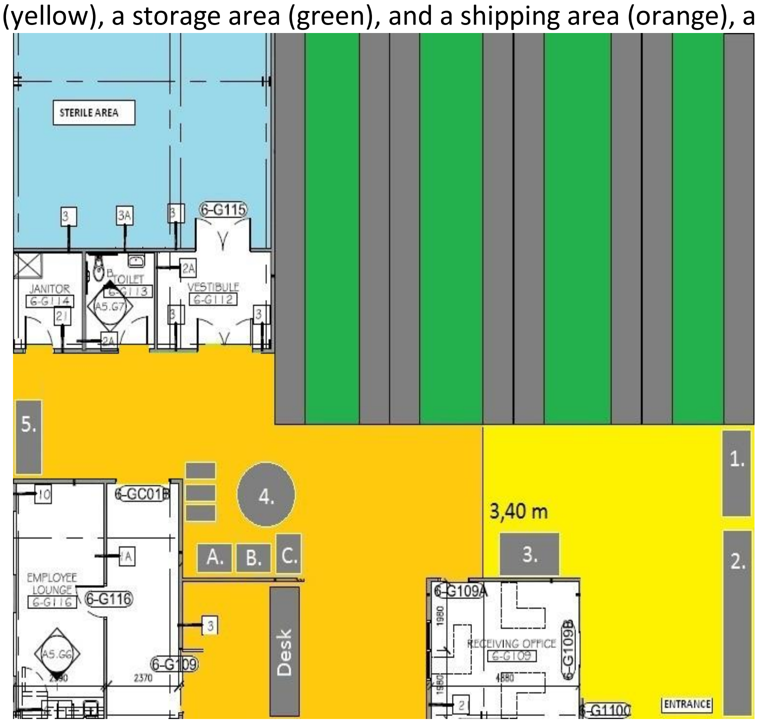

Figure 30 : Location of facilities

- Location 1: Pallet stacker
- Location 2: a short storage space for products that just arrived
- Location 3: a box disposal
- Location 4: pick & delivery carts
- Location 5: products that the departments order themselves

The proposed solution lowers the average picking time from 15.7 to 14.1 minutes, compared to the current situation[1], and the amount days that orders are delivered too late from 5.2% to 0.5%. It also uses less storage space: 72% instead of 98% of all storage space is used. The flow rack contains 69 % of the perishable goods. It is possible to place more products in this rack, though this lowers the efficiency of the picking process since those products will no longer be allocated according to the heuristic.

7.2 Limitations

In this section, we discuss the limitations of our research.

The most important limitation of this research is that we were unable to measure the current time performance of the warehouse. This became impossible when the existing warehouse was partly evacuated, and the products were spread over several buildings. This significantly increased both, the average distance and the time for searching. So it increased the average time to pick a product, a whole order, and all the orders that arrived on a day. Thus the current performance became unrepresentative. This limitation is twofold: the time estimates inside the simulation model were based on literature, instead of the real situation, and there was not enough data available to fully validate this simulation model.

Furthermore, the data inside the computer system was sometimes ambiguous. For example, some orders were manually entered in the system. This concerns mostly rush orders, which are beyond the scope of this research, but orders are also manually entered in case of a system failure. Even though this is rare, the system does not show the difference, so there is a slight chance that some orders were neglected because they were manually entered, thus considered a rush order.

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[1] The current situation is the situation as proposed by the warehouse, with the current workload division and a product allocation based on expert opinion.

7.3 Future research

During this research we came across some aspects that were interesting, but could not be investigated within the scope of this research. In this section, we do some recommendations for future research.

As our results show, late deliveries are mainly caused by daily fluctuations in ordered amounts. The average size of orders differ per department, and the actual size of the orders differ significant per day. We handled this by spreading the workload more evenly, but those daily fluctuations are too large to be fully leveled out in this way. Another way of approaching this problem, is to alter the ordering habits of the departments. There is already a plan to place this responsibility at the order pickers. Future research could investigate how the ordering habits should change, to assure that products are ordered more evenly over the year. If for example the local maximum and minimum inventory of products are lowered, that products will be ordered more often, in smaller amounts, and the ordering process becomes more predictable.

If the ordering habits become more predictable, lower inventory levels will be sufficient at the warehouse. We recommend to re-evaluate those inventory levels too, since they should be updated once in a while, to match the current demand. We think that the current inventory levels may be outdated, since during our observations inside the warehouse, we encountered many out-of-stocks. There is however no reliable data available to support this statement. We therefore also recommend to track those out-of-stocks more carefully, so better estimations can be made about the impact.

We also observed that the ordered amounts, which are calculated by a computer system, are all manually checked, because the system neglects box sizes, orders unused products, does not order some used products, and uses unreliable or outdated maximum inventories and reorder points. The system will be updated soon, what means that some of those problems will be eliminated. Future research should investigate whether this new system will resolve all problems, or if another solution is required.

We furthermore recommend to re-evaluate the ordering sizes of the products, especially for small, and cheap products, like pens and envelopes. Envelopes are, for example, ordered per 50. But the process of removing the boxes, and counting the right amount, probably costs more than the product itself. We therefore recommend to re-determine the ordering size, not only based on the ordering frequency, but also on the price and size of the product, the ordering cost, and the effects of delivering partial boxes.

We also observed that every day around 4 rush orders arrive. This process takes a lot of time, from many people, both, employees from the warehouse and the department placing that rush order. Future research can investigate how to make this process more efficient. For example by announcing the rush orders by email. In that way the rush order can be assigned to an order picker that is already close to the pick location of that product. He can bring that product to the desk, and go on with his main activity. This means that the process of the order pickers is less disturbed by this rush orders, and the employee of the department does not have to wait, because the product is already picked. It is also possible to let the order picker deliver those orders, since their labor is probably cheaper. Email, furthermore, makes it easier to reject an incoming rush order if it is not really urgent, for example in the case of pens and coffee.

We finally recommend to investigate additional purchases, which are beyond the scope of our research, but are required for batch picking and deliveries. Future research could investigate if it is possible to purchase carts that can be used for both, picking and deliveries, and can contain several orders simultaneously. If the carts can be used for both, picking and delivery, products do not have to be replaced. This saves time, and lowers the risk of mistakes, loses, and broken products. If several products can be stored simultaneously on the cart, time can be saved by picking and delivering several orders simultaneously, without the risk of mixing them up.

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Appendix A: Percentage of expired products

In this appendix we show the results of our sample test, to check the percentage of expired products in the current situation.

Sterile products	Total	Expired	Non-expired
110585	12	1	11
103545	4	0	4
102679	3	0	3
206060	6	0	6
566070	14	0	14
111204	17	0	17
103520	4	0	4
Zetuvit	12	0	12
234090	19	0	19
100946	7	2	5
105510	56	0	56
Sterican needle	22	0	22
3 lumen catheter	18	0	18
Trucut 14Gx15	7	0	7
Trucut biopsy	37	4	33
Discofix	31	0	31
GanCath	9	0	9
Gauze jelonet	8	0	8
Bactigras	13	0	13
170642	8	0	8
308033	27	0	27
163360	3	0	3
163352	5	0	5
170642	8	0	8
100978	2	1	1
100400	18	0	18
265822	3	0	3
109515	12	2	10
248210	10	0	10
Total	395	10	2.5%

Non-sterile	Total	Expired	Non-expired
EnsurePlus - strawberry	5	0	5
Pediasure- vanille	3	0	3
Ensure - strawberry	7	0	7
Glucerna Strawberry	5	0	5
Glucerna Vanille	5	0	5
Glucerna can 1 cal	13	6	7
Nepro cans	5	0	5
Similac Advance	1	1	0
Osmolite	13	0	13
Similac special	7	0	7
Ceres Kiwi	13	0	13
Perzik sap	2	2	0
102333	3	0	3
Ketjap	10	0	10
bami	5	0	5
conimex kruidenmix	4	4	0
knoflookpoeder	3	0	3
gember	2	2	0
custard	15	0	15
jello lime	3	0	3
jello cherry	2	0	2
maggi	3	0	3
pepper	6	0	6
babyfood apricot	2	0	2
verkade maria	6	0	6
babyfood poire	24	0	24
nescafe	50	0	50
cream of wheat	5	0	5
vanille flafor	10	0	10
Nutmeg	7	6	1
Total	239	21	8.8%

We counted a total of 634 products, of which 31 were expired. This means that in total 5.9% of the products were expired.

Appendix B: Calculations of the cost of expired products

In section 2.2 we stated that the cost of expired products is around 49 000 florin per year for the products in the regular warehouse. In this appendix we explain how we came to this value.

We like to start with stating that this value is based on the regular warehouse products. Sterile products also have an expiration date and around 2% expire. Though sterile products are less likely to expire, its prices are higher. We however did not calculate them because this research focusses on the regular warehouse.

Since 8.8% of the non-sterile, perishable products expire, the cost of the expired products per year is 8.8% of the cost of the perishable goods. In the table below we listed all the products that are non-sterile and perishable.

- In the first two columns we state the article code and description.
- In the third column we state the order up to level used by the warehouse management.
- In the fourth column we state how often the product was ordered in 2015.
- The fifth column states the cost per piece.
- The sixth column multiplies column 5: the cost per piece with column 4: the ordered frequency
- The seventh column multiplies column 5: the cost per piece with column 3: the stock level

The sum of column 6 is equal to the total cost of perishable goods per year. 8.8 % of that is 49 237 florin.

Article-code	**Descrpition**	**Stock level**	**Ordered per year**	**cost per piece**	**cost per year**	**cost current inventory**
211226	Glucerna Vanilla 8OZ Can	480,00	768	3,37	2588,16	1617,60
304617	Osmolite 1.2 Cal Abbott Nutrition	576,00	760	4,53	3442,78	2609,26
210984	Proteinex Proteine 275gr	48,00	946	25,83	24435,18	1239,84
211360	Garlic Granulated 26Oz Mcormick	30,00	438	18,00	7884,00	540,00
211392	Onions Granuleted	24,00	406	15,57	6323,38	373,80

211265	Nepro Vanilla 8OZ	360,00	568	4,45	2527,60	1602,00
101499	Koffie Nescafe Colombiana	60,00	1526	10,19	15542,31	611,10
112367	Pindakaas	24,00	398	19,13	7613,74	459,12
211191	Ensure Strawberry 8OZ	168,00	848	2,85	2416,80	478,80
308393	Vegetable Oil	120,00	997	10,08	10049,76	1209,60
112455	Coffee Mate Powder Light 16Oz	840,00	1568	5,54	8686,72	4653,60
218599	Halfvolle Melk 1 Liter	60,00	954	28,25	26950,50	1695,00
286555	Tuna Chunk Light 6/66.5 OZ	48,00	865	71,59	61926,60	3436,39
211201	Ensure Plus Institutional Vanilla	144,00	608	3,10	1884,80	446,40
213223	Juice Ceres Appel 1 Liter	50,00	736	41,00	30176,00	2050,00
194217	Aromat Strooi 5,5KG	20,00	114	138,55	15794,70	2771,00
145349	Cream Of Wheat 28oz	180,00	852	8,89	7574,28	1600,20
234157	Zetuvit Kompres 10x10Cm	30,00	211	10,52	2219,72	315,60
210744	Juice Ceres Mango	50,00	529	41,00	21689,00	2050,00
211240	Glucerna Vanilla Shake 8OZ	144,00	448	3,37	1509,76	485,28
328943	Ensure Powder Vanilla 400 Gr	24,00	145	17,82	2584,27	427,74
323906	Juice Ceres Cranberry & Kiwi	40,00	501	41,00	20541,00	1640,00
112303	Mayonaise (Pc)	20,00	314	30,87	9693,79	617,44
211353	Complete Seasoning	12,00	70	10,25	717,50	123,00
165487	Soda Crackers (pak)	120,00	922	2,04	1880,88	244,80
112247	Mihoen 250 Gram	120,00	420	2,94	1234,80	352,80
210751	Juice Ceres Orange	20,00	377	41,00	15457,00	820,00
211402	Paprika Powder	12,00	56	6,00	336,00	72,00
101805	Melkpoeder Similac Advance	24,00	99	12,15	1202,85	291,60
334683	Dux Crackers Integral 250Gr	120,00	505	2,19	1105,95	262,80
101210	Pears Halves Diet	36,00	486	22,17	10776,20	798,24
101481	Koffie Decaf Taster Choice 100 gram	48,00	295	8,96	2643,20	430,08
194150	Rode Bieten Diced 6/10#	30,00	480	56,50	27120,00	1695,00
100262	Drinkbouillon Naturel	40,00	104	6,08	632,32	243,20
194182	Azijn Blank 10Ltr	70,00	423	12,85	5435,55	899,50
112656	Fruit Cocktail Diet	24,00	402	23,19	9323,13	556,61
211219	Ensure Plus Institutional Strawberry	144,00	224	3,10	694,40	446,40
211280	PediaSure Vanilla 8 OZ	120,00	216	3,22	695,52	386,40
101178	Quaker Oats Old Fashion 42 Oz	144,00	660	6,67	4402,20	960,48
211233	Glucerna Strawberry Shake 8OZ	192,00	232	3,37	781,84	647,04
112705	Ketjap Manis	12,00	191	33,00	6303,00	396,00
194376	Custard 400 Gram	35,00	180	20,32	3656,98	711,08
101160	Nesquik Chocolate 400 Gr	48,00	484	5,09	2463,56	244,32
101227	Peach Halves Diet	30,00	282	21,25	5992,50	637,50

139729	Koffie Smith & Dorlas (CS6KG)	25,00	351	152,09	53381,84	3802,13
112670	Pineapple Sliced	24,00	258	11,74	3029,24	281,79
194087	Tomatenpuree 5Ltr	40,00	159	26,01	4135,59	1040,40
211321	Curry Powder	16,00	26	6,75	175,50	108,00
288908	Sweetener Splenda	15,00	158	58,00	9164,00	870,00
284340	Rijst Bruin 10 Lbs	60,00	618	9,91	6123,64	594,53
280867	Nutrilon 1 900GR	12,00	82	26,06	2136,92	312,72
211184	Ensure Vanilla 8OZ	144,00	112	2,85	319,20	410,40
112487	Mustard (Pc)	20,00	101	26,50	2676,50	530,00
211297	Bay Leaves Whole	12,00	21	12,50	262,50	150,00
211427	Basil Leaves Whole	6,00	18	5,69	102,38	34,13
112568	Jello Orange	3,00	57	60,10	3425,70	180,30
226956	Melkpoeder Cofee Mate Piece	50,00	155	87,05	13492,75	4352,50
211554	Peper Black Ground 16OZ	10,00	14	16,50	231,00	165,00
194070	Appelmoes 4250ML	60,00	264	21,03	5551,92	1261,80
367129	Verkade Mokkasticks	14,00	80	4,16	332,80	58,24
112536	Juice Prune 46 Oz	36,00	100	12,59	1259,00	453,24
194295	Zout PC 1Gram	10,00	36	17,11	615,96	171,10
112543	Jello Strawberry	3,00	42	60,10	2524,20	180,30
112550	Jello Cherry	3,00	40	37,81	1512,22	113,42
310205	Vermicelli 5Kg Fijn	12,00	64	37,60	2406,40	451,20
112712	Prunes Pitted Prepared	12,00	102	31,44	3207,23	377,32
367136	Verkade Maria	18,00	68	2,42	164,56	43,56
106708	Similac Human Milk Fortifier 0.90Gr	3,00	23	124,67	2867,41	374,01
367150	Verkade Nizza	24,00	86	2,81	241,66	67,44
100375	Zout Iodize	24,00	103	1,43	147,29	34,32
112494	Jam Strawberry (Pc)	4,00	41	35,35	1449,35	141,40
100424	Vanilla Flavor 16Oz	12,00	83	3,80	315,40	45,60
367143	Verkade Nobo Sprits Original	12,00	50	3,68	184,00	44,16
112600	Jello Lime	3,00	29	58,50	1696,50	175,50
100270	Sliced Dill Pickles	12,00	115	13,63	1567,45	163,56
112279	Jam Grape (Pc)	4,00	35	40,65	1422,75	162,60
100287	Sauerkraut	12,00	71	12,73	903,83	152,76
325420	Nutrilon 2	12,00	23	23,78	546,94	285,36
112582	Jello Orange Sugar Free	2,00	24	36,31	871,38	72,62
326047	Mie Nestjes	8,00	91	22,75	2070,25	182,00
112590	Jello Strawberry Sugar Free	4,00	20	35,76	715,16	143,03
112617	Jello Lime Sugar Free	3,00	19	34,10	647,95	102,31
194168	Aardappelpuree 4,5KG	14,00	25	48,32	1208,00	676,48
100022	Baby Food Apple 1st Food	2,00	12	14,57	174,84	29,14
211018	Juice Pineapple 46 oz	24,00	49	5,45	266,81	130,68
211307	Cinnamon Ground	4,00	5	5,75	28,75	23,00

112416	Prunes Pitted Dried 8Oz	4,00	21	69,50	1459,50	278,00
194320	Bami Mix 780Gram	12,00	15	64,50	967,56	774,05
194383	Maizena 5KG	20,00	47	54,01	2538,26	1080,11
101450	Spaghetti 20/1 Lb	4,00	33	75,24	2482,92	300,96
112328	Honing (Pc)	3,00	20	73,50	1470,00	220,50
100777	Sweet & Sour Sauce	12,00	77	31,63	2435,51	379,56
100431	Jam Assorted Sugar Free (Pc)	4,00	19	37,50	712,50	150,00
107187	Similac Speciale Care 24 Calorie Rtf	4,00	22	12,15	267,30	48,60
107109	Melk Similac Advance W/I Rtf	6,00	22	12,15	267,30	72,90
112399	Sambal Oelek	4,00	19	69,44	1319,36	277,76
112575	Jello Cherry Sugar Free	2,00	13	48,11	625,49	96,23
211410	Parsley Flakes	7,00	47	21,61	1015,74	151,28
112624	Kellogs Cornflakes	6,00	51	56,18	2865,39	337,11
101428	Macaroni Elleboog 16 Oz	4,00	35	33,50	1172,50	134,00
211314	Cloves Whole	8,00	3	13,25	39,75	106,00
211434	Thyme Whole Swiss Leaves	6,00	12	13,30	159,60	79,80
264748	Heavy Duty Greaser 1 Gln	8,00	47	96,82	4550,32	774,52
100008	Baby Food Apricot Mxd Fruit 2nd Foods	2,00	8	22,11	176,88	44,22
211378	Ginger Ground	12,00	2	13,30	26,60	159,60
100174	Baby Food Th Pear	4,00	6	18,13	108,78	72,52
112504	Jam Orange (Pc)	3,00	8	37,50	300,00	112,50
112286	Peper Zwart (Pc)	4,00	5	13,30	66,50	53,20
100167	Baby Food Banana 2nd Food	2,00	4	19,88	79,52	39,76
304871	Cornflakes Special K	6,00	29	63,50	1841,50	381,00
354246	Ceres Medley of Fruit 200ml	3,00	7	41,00	287,00	123,00
304889	Rice Krispies	6,00	20	63,50	1270,00	381,00
211000	Baking Powder 5 Pounds	6,00	3	16,31	48,93	97,86
354239	Ceres Apple 200ml.	3,00	3	41,00	123,00	123,00
330784	Hollandse Beschuit Volkoren 12/110Gr	10,00	4	27,50	110,00	275,00
318941	Kroepoek 10/60Gr	2,00	2	75,24	150,48	150,48
388334	Ketchup	10,00	2	26,50	53,00	265,00
374874	Ketchup	8,00	2	26,50	53,00	212,00
112261	Jam Apple (Pc)	4,00	0	37,50	0,00	150,00
296116	Ceres Red Grape 12/1 Ltr	40,00	0	41,00	0,00	1640,00
211096	Pork & Beans 6/10	12,00	0	21,61	0,00	259,34
					AWG 559.511,19	AWG 72.897,49

Appendix C: Program for optimizing the routes

This section explains the program written to optimize the way the hospital departments are divided over the employees. The goal of the program is to allocate the departments that lie close to each other to the same route, while ensuring that the amount of work per employee is feasible. We wrote a local search program for this purpose. First we will explain what a local search method is. Then we explain why we use a local search heuristic instead of an exact method. Then we will explain the program in more detail.

What is local search?

Local search methods are used when the amount of options is extremely large and the best solution can be translated into one value, which should be optimized. The heuristic takes an initial solution, makes many random, small adjustments, until a good solution is found. An example of an initial solution is the current ABC routes, and a small adjustment can be to move a random department to another route.

Many local search methods exists. In this program we use Simulates Annealing, what means that the adjustment is always accepted if it is better, or with a certain probability if it is worse. The probability of accepting a deterioration reduces every time and eventually will become zero. Because worse solutions are accepted in the beginning, the result is less depending on the initial solution. Therefore, it has a higher chance of finding the optimum. Simulated Annealing ends after a certain, high, amount of alternations.

Too many options for an exact method

The division of the departments over routes contain too many options to consider them all; more than $16*10^{67}$. The HOH has 80 departments, of which 58 are delivered once per week. For every department that is delivered once per week, there are 3*5 = 15 options to assign them to a day and a route. When we only consider the departments delivered once per week, this results in $15^{58} = 16*10^{67}$ options.

It is clear that even a computer cannot calculate all options in a considerable amount of time. Therefore, exact methods cannot be used and a heuristic is required. We use a local search method because those methods only consider options with the potential to perform well. It is however, a heuristic, so it does not necessary result in an optimal solution, but it is likely to result in a near optimal solution.

The program

In this section we explain the program. We start with an explanation of the entities, then we explain the procedure of forming alternative solutions, and acceptance probability and amount of runs.

The entities

In our program we distinguish the following entities:

1. Department, containing:
    a. Location of the department inside the hospital building
    b. Amount of ordering days
    c. Percentage of used ordering opportunities
2. Route
3. Days

Every department has a certain location inside the hospital building. We assigned an index number to every part of the building. The fifth floor of the first tower has for example location index 1.

Every department is also assigned a certain amount of ordering days. This amount is fixed, and equal to the amount of ordering days in the current situation. The ordering days represent the amount of opportunities available for a department to place an order. This does however, not mean that all opportunities are used. We therefore also calculate the percentage of used ordering opportunities. This is the used amount of opportunities divided by the available amount.

The last entities we specified are the routes and days. We distinguish routes A, B, and C, and days Monday to Friday. For every route, the expected amount of workload per day can be calculated. We set a maximum amount orders per day per route, to make sure the solution becomes feasible.

The procedure

In this program we use the current workload division as input, because it is a well performing and feasible solution. A good initial solution is not crucial but improves the probability of finding an optimal solution. Then we perform a random alternation to this solution. We do this by re-assigning a random department. We assign this selected department to a new route and new delivery days, as follows:

1. We draw a random number, between 0 and 3
    a. 0-1 is route A
    b. 1-2 is route B
    c. 2-3 is route C
2. We check the amount of delivery days assigned to that department and draw a random number that indicates the new delivery days.
    a. One delivery day: a number between 0-5, representing Monday to Friday
    b. Two delivery days: a number between 5 and 8

       5-6 Monday and Thursday

       6-7 Monday and Friday

       7-8 Tuesday and Friday
    c. Three delivery days: the delivery days are always Monday, Wednesday and Friday, to spread them evenly over the week.

Then we check if we should accept this alternation. First we check if the alternation yields a feasible workload by calculating the expected amount of orders per day. The expected amount of orders, on day x for route y, is the sum of the ordering probabilities of all departments that are part of route y and delivered on day x. This amount should not exceed the maximum amount of 4 orders day. We determined this maximum through trial and error. We concluded that this was the lowest amount of orders per day that yields a feasible solution. Since it is the lowest solution, it will result in the most equal workload division.

If the new solution is feasible, we check if this solution yields an improvement of the objective value. To determine the objective value we categorized all locations inside the hospital building. Accordingly we count per route the amount of locations that is visited, we call this the span of the route. The objective value is the sum of the spans of all routes A, B, and C. A visualization of the spans is given in Figure 31.

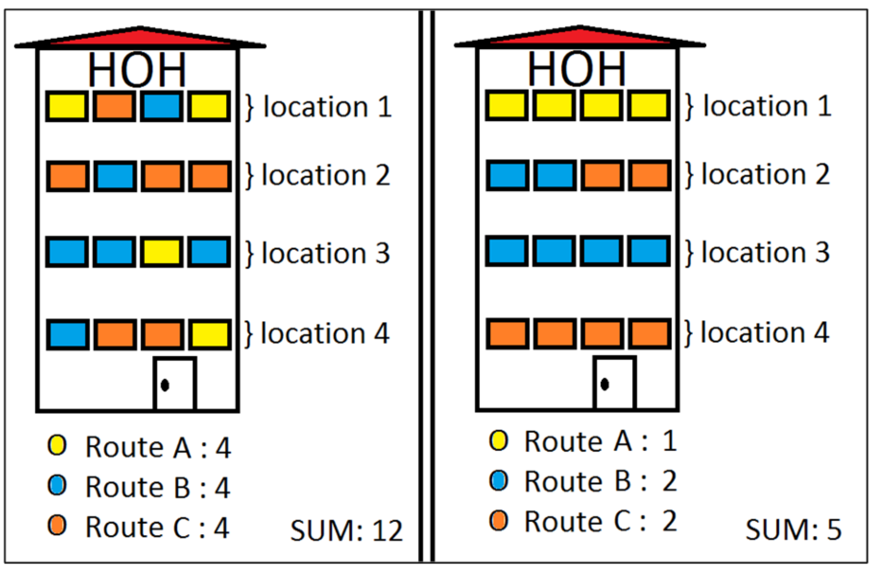

Figure 31: visualization of the objective value through an example.

If the new solution is rejected, a new random alternation will be set up and evaluated. If the new solution is accepted, the new solution becomes the initial solution. From this new initial solution a new alternation will be proposed and evaluated. In the next section: Acceptance probability and amount of runs, we explain that the heuristic stops when the cooling parameter drops beneath C_{stop}. When the heuristic stops, no new alternative will be formed and the current 'initial solution' becomes the final solution.

Acceptance probability and amount of runs

In this section we explain how the program decides if an alternation is accepted or not. The probability of accepting a better solution is always 1. The probability (P) of accepting a deterioration is determined with the following formula, which standard for simulated annealing:

$$P = e^{\frac{D_{Objective}}{c}}$$

With:

- $D_{objective}$: the difference between the previous and new objective value, this value is thus always negative since this formula is only used when the new solution is worse
- C: Cooling parameter. We start with a value of 1, which assured that in the beginning of the heuristic almost all alternations are accepted. After a couple of alternations, this value will drop.

After k iterations, the value of the cooling parameter is adjusted and becomes c*α, with:

- α: decreasing factor, in our case 0.9999
- k: Markov chain length, in our case 100

The heuristic stops when the cooling parameter becomes C_{Stop}. We set C_{Stop} equal to 0.0001. At that point the acceptance probability approaches 0. This results in around 900 000 runs.