Warehouse design for PoolPlaza

Author: Stan Kuipers
University of Twente
P.O. Box 217, 7500AE Enschede
The Netherlands

First supervisor: Dr. D. Demirtas (Derya)
Second supervisor: Dr. P.C. Schuur (Peter Cornelis)

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Stan Kuipers, 6th of April 2022, Losser.

Contents

Management Summary

Motivation

Due to the recent entrance of new shareholders and employees into PoolPlaza, the company has undergone significant growth. Due to this growth, it quickly became apparent that PoolPlaza's current warehouse was not suitable anymore for the direction the company was going. In the current situation, all the functional areas are combined in one area without a dedicated office or shop area. Next to that, the warehouse itself is too small and a random intuition-based storage policy is applied which causes longer travelling times among pickers.

Central research question

The central research question that is answered in this thesis investigates what would be an adequate warehouse design for PoolPlaza (given the lot size constraints). This research question is split up into sub research questions starting on the strategic level which is concerned with the general layout of the warehouse. Once the strategic level is defined the sub research questions focus on the tactical level which encompasses space allocation and storage allocation.

A brief overview of methods used

For the general layout of the warehouse, the functional areas that apply to PoolPlaza are identified and the dimensions for the functional areas are determined. For the fast pick area and the reserve area, a specific linear programming model is utilized to determine the best ratio between these two areas.

To determine how much space each SKU (Stock Keeping Unit) requires in the warehouse the demand of each SKU is analysed and classified with an ABC-XYZ classification. Based on this classification an inventory policy and fill rate are assigned. Using analytical models, it is determined for each SKU what the average and peak stock level will be and the corresponding space requirement. The space allocation section of this thesis is also concerned with assigning SKUs to the fast pick area and their corresponding number of unit loads assigned. Based on the labour efficiency heuristic SKUs are assigned (fully) to the fast pick area and with the square root formula of the fluid model, the number of units loads assigned to the fast pick area per SKU are determined.

The final step in the warehouse design addresses the storage allocation problem. In the fast pick area, a dedicated storage policy is chosen to gain the most benefits in reduced travelling times. Because all the storage and retrieval transactions are single command transactions at PoolPlaza the cube-order-index(COI) approach provides the optimal solution and is therefore chosen for assigning SKUs to a storage location in the fast pick area.

For the reserve area, it is chosen to store SKUs based on ABC zones because on a large scale a dedicated storage policy cannot be maintained without an ERP that supports a routing strategy. To add to that, since most of the pickings are done via the fast pick area, the most benefits in terms of travelling distance are already achieved by implementing a dedicated storage policy in the fast pick area. By implementing an ABC zoning policy in the reserve area there are still significant improvements compared to a random storage policy with relatively little effort.

Results

For the general layout of the warehouse, nine functional areas are deemed applicable for PoolPlaza. Seven of these functional areas are assigned square meters based on logical deduction in cooperation with PoolPlaza. Out of the 1200 m^2 available, 510 m^2 is assigned to the seven functional areas mentioned above and 690 m^2 is devoted to the fast pick area and reserve area. The linear programming model determined that the fast pick area should be 85 m^2 and the reserve area should be 605 m^2. However, with the placement of pallet racks, the size of the fast pick area was adjusted to 115 m^2 due to the sizes of the pallet rack blocks and adjacent aisles.

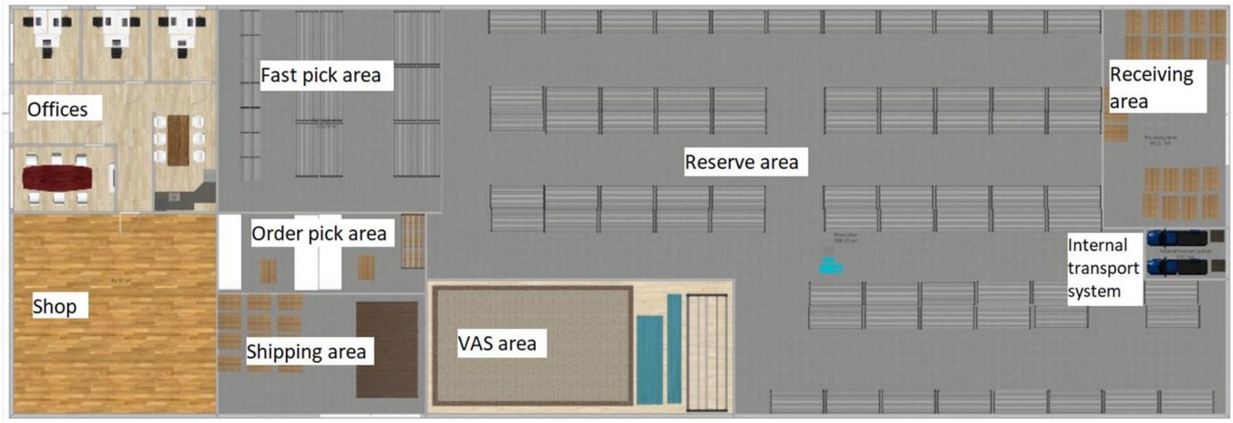


Figure 1 - Final warehouse layout

In terms of space allocation, the total peak stock volume amount to 8272 units in total which occupy 129.13 m^3. Consequently, for each SKU it was determined, based on the peak stock level and order characteristics, whether to store an SKU in a pallet rack or a box rack. In total, 102 SKUs were assigned to pallet racks and 294 SKUs were assigned to box racks.

Out of the 397 SKUs in total, 92 are assigned to the fast pick area and 305 are assigned to the reserve area only. With the SKUs assigned to the fast pick area known, it is analysed how much space is to be assigned to each SKU in the fast pick area. It was found that 2203 unit loads (19.3 m^3) were assigned to the fast pick area and resulted in a net savings of €828.93 in handling and storage costs compared to a situation without a fast pick area.

With regards to the storage allocation, the COI approach provided a valid allocation of SKUs to storage locations in the fast pick area for both pallet rack SKUs and box rack SKUs. Compared to a random assignment, the COI approach performed 53% better for box racks and 38% better for pallet racks in terms of travelling distance. For the reserve area, a floor plan is provided that indicates the various picking zones and based on an ABC analysis SKUs are assigned to the picking zones.

Recommendations

For recommendations, the main takeaway from this thesis is to run the models again, once more data is available. With more data available the demand will show less variability which will improve the output of the inventory policy parameters. It might also be that some SKUs should be or should not be assigned to the fast pick area or should be assigned to the fast pick area in different quantities.

Next, it is recommended that PoolPlaza maintains good communications between the departments to ensure inventory parameters or SKU assignment to the fast pick area can be amended if deemed necessary. This thesis is based on historical data and theoretical models and reality can be different. PoolPlaza must remain flexible in these cases.

Furthermore, with the current data available, this thesis deems the current warehouse size of 1200 m^2 too large. Of course, a lot can change in two years but if after two years the models are run again and the same results are presented it would be recommended that PoolPlaza would rent out a part of their warehouse to decrease their monthly costs and increase their liquidity to keep growing.

Finally, since the current warehouse design implies warehouse personnel has to learn the locations of SKUs by heart it could be useful to colourize the pickings zones in the reserve area and use plasticized cards with SKU information in the fast pick area for each storage bin to indicate storage locations of SKUs.

1 Introduction

In the first chapter, the background information and problem context of PoolPlaza will be presented. Based on the problem context provided, the research questions, scope and deliverables are discussed.

1.1 Background information

PoolPlaza is a company that operates in the market for pools and accessories for pools since 2007. The business model of PoolPlaza can be split into two different sections of the company. On the one hand, the company delivers and installs inground pools. The main product, the pool, is made-to-order and therefore not kept in stock and the products surrounding the pool that is required to make it functional are kept in stock. Examples of these products are sand filtration systems, heat pumps, chemical dosing devices, pool covers and many more. These products are kept in stock since these products cannot be a bottleneck for selling an inground pool and because those products are also sold on the website. The inground pools are delivered straight from the production facility to the customer, and on the day of delivery, the technicians also go to the customer along with the supplemental products required to make the pool operational. In about one to five days the technicians install the pool and supplemental products, after which the project is finished.

The latter part nicely introduces the other side of the business model of PoolPlaza which are sales that are being generated via the website/web shop. Besides delivering complete inground pool projects from start to finish, PoolPlaza also has a website in which all products can be purchased individually or combined by the customer himself. PoolPlaza also offers the service that customers can call or email to get a specified quotation to their requirements and wishes. Customers order their products online after which the products are then shipped from the warehouse. Besides the web shop, there is also a physical shop present inside the warehouse where customers come and collect their web shop orders or purchase products from the physical shop itself.

PoolPlaza initially started as a supplementary earning for the founder from 2007 till 2019 while the founder had a full-time job at another company. Next to that, there were 2 part-time employees during the seasonal months of the selling season. During this period the revenue stayed within the same range each year without much growth. At the start, PoolPlaza hired a small warehouse in Losser and over the years expanded enough to move to a larger warehouse in Gildehaus where the company is still today. The size of the current warehouse is about 450 m^2.

A change of pace

In recent years (2020 and 2021) there has been a change in the organizational structure with new shareholders in the company and new employees being hired. With this new energy, mission and vision the company was able to capitalize on the potential of the knowledge inside the company and the relatively large customer base developed over the years. There has been a large increase in the product range that PoolPlaza can offer and in the revenue of the company. Based on the growth of the company, future market potential and shortcomings of the current warehouse there is a desire to construct a new warehouse because the current warehouse is not suitable for the future of the company.

In recent years, the revenue has grown significantly where the revenue tripled over the years 2019 to 2021 and the number of employees increased to 9. In the coming year, the two new shareholders will finish their studies and intend to work full time at PoolPlaza to further help grow the company. Based on the characteristics mentioned above PoolPlaza would still be considered a start-up company.

A new warehouse

There are various reasons why the current warehouse is not suitable for the future and why the company wishes to construct a new warehouse. Below these reasons are discussed.

In the past, inventory control was purely based on intuition and there was no ERP system to track how many items were in stock which caused SKUs to be out of stock often. Since July 2020 a new ERP system was implemented that registers the quantity on the stock of Stock Keeping Units (SKUs) and provides purchasing advice based on minimum stock levels and order quantities. Next to that, a Kanban control policy was implemented to ensure that consumables were always sufficiently on stock. Consumables are often low-value SKUs of which the stock is not registered in the ERP system. Because of the new ERP system, Kanban control policy and an expanding product range due to growth, SKUs are more often kept in stock and in larger quantities which requires more space in the warehouse.

The second reason for a new warehouse is the lack of a proper physical shop in the current warehouse which leads to the following three problems:

- As depicted in Figure 2 and Figure 3 below, the physical shop is located in the middle of the warehouse which implies that customers block the inward and outward flow of goods into the warehouse.
- Because customers do arrive at the warehouse, the front half of the warehouse needs to be open due to safety considerations and because customers need to feel comfortable which leads to very inefficient use of warehousing space.
- As shown in Figure 4, there is no proper way to display the products. There is a desire from PoolPlaza to have a proper shop with products on display that can attract customers and professionalize the customer experience.

Figure 2 - Overhead door

Figure 3 - Cashier counter

Figure 4 - Product display

The third reason for a new warehousing facility is the fact that there are no proper offices which for obvious reasons would be beneficial. Currently, there is a small wooden cabin in the warehouse which serves as an office and a mezzanine where the Kanban stock of most small items is being kept.

Finally, there is no proper way to receive customers for inground pools currently. There are no inground pools at the warehouse to serve as an example and there is also no conference room to discuss the wishes of the customer. Because each of the inground pools customers generate a substantial amount of revenue PoolPlaza deems it necessary to properly receive these customers and therefore also increase the probability of customers conversion.

1.2 Problem context

1.2.1 Research problems

The causes and need for a new warehouse give rise to a new set of research problems that need to be solved. Firstly, it is important to get a basic layout of the different functional areas in the facility. For example, how much space is devoted to the various functional areas and where are these functional areas located. When deciding upon the facility layout it is important to consider the municipality streets to which the warehouse is connected and to identify where customers and deliveries of materials come in. The flow of materials also must be considered when deciding where to put the various areas and where to put doors and overhead doors.

After the general layout, there needs to be a design for where incoming goods arrive, and where they are stationed and processed before moving to their destination inside the warehouse. The flow of materials from the main stock location to the fast pick area and finally the flow of materials for outgoing goods and customers that are picking up their orders. The management of PoolPlaza has already decided upon the use of a fast pick area since they are convinced of the benefits. Next to that, PoolPlaza currently has a mezzanine and has a strong favour towards having a mezzanine because a lot of products are stored in box racks and by using a mezzanine an extra floor can be created where box racks can be located. A Mezzanine is an intermediate floor level in a building that is partly open or does not extend over the whole space of the lower level. With regards to the offices, parking spaces, garden and shop it is not important to design this internally it should only be considered for the flow of materials inside the warehouse and to the shop and as a restricted factor on the space available for the warehouse.

After the general layout and flow of materials have been designed and the sizes of the various functional areas have been determined the research should aim toward the storage space allocation problem. Per SKU it must be determined how much space is required in the reserve area and in the fast pick area to satisfy a certain service level. Of course, before determining the space devoted to each SKU in the fast pick area it first must be determined which items are devoted to the fast pick area.

For determining the space required per SKU the lead time of the suppliers also must be considered. For example, the company has a supplier in China which delivers products about two to four times with a container load. So, these items will have a high peak stock level after such delivery and therefore these products would need a lot of dedicated stock. However, maybe a combination between dedicated stock and random stock is also beneficial so that the dedicated stock of these long lead time items are not empty pallet racks for half the lead time duration. It might be useful that for example 50% of the required space for these items is dedicated stock and the other 50% is put in random stock locations.

Next to the lead time, the storage mediums also must be considered, and it must be determined per SKU how to store it. Smaller items, for example, the small Kanban items, are currently stored in box racks and it would be very inefficient to stock these items in pallet racks. In the current warehouse, intuition determines which products get assigned to box racks and which items to a pallet rack. For the new warehouse, for each SKU the storage mediums will have to be revaluated. The management of PoolPlaza has already decided upon using pallet racks and box racks in combination with forklifts.

Once the space requirements per SKU have been determined it is important to determine where to store the various SKUs because it has the potential to save a lot of time and therefore costs. In a warehouse, the travel time of an order picker is approximately 50% of the total time consumed by all the order picker's time-consuming activities (Tompkins, White, Bozer, Frazelle, & Tanchoco, 2003).

However, to answer this question, it first must be determined to what level of detail SKUs will be grouped and how they will be grouped. It should also be investigated whether the grouping of SKUs is beneficial in distribution warehouses.

1.2.2 Activity profiling

To get a good understanding of the purpose of the current and new warehouse activity profiling is used. ''Warehouse activity profiling is the careful measurement and statistical analysis of warehouse activity. This is a necessary first step to almost any significant warehouse project: Understand the customer orders, which drive the system.'' (Bartholdi & Hackman, 2005)

First, to start with the basics the new warehouse of PoolPlaza including the offices and physical shop will approximately be 1200 m^2 with roughly 630 SKUs where currently 1 to 3 pickers are operating. In the off-season, only one picker is required and in the high demand seasons usually, 3 pickers are operating. These pickers are not operating full time during the whole week and daytime but there does need to be room to accommodate the maximum number of pickers. In Appendix A the seasonality is shown by the number of orders per day and the revenue per month.

To give an idea about which SKUs matter the most, an ABC analysis is made and shown in Appendix B and also the yearly volume of these SKUs is shown. As can be seen, the yearly revenue and volume are mostly aligned. Class A SKUs are 20% of SKUs and represent 90.72% of the total revenue and 82.26% of yearly volume. Class B SKUs are 30% of SKUs and represent 9.04% of the total revenue and 17.61%% of yearly volume. Class C SKUs are 50% of SKUs and represent 0.23% of the total revenue and 0.13% of yearly volume.

To examine the SKUs in more detail, the top ten SKUs with regard to revenue can be seen in Appendix C. From this analysis, it can be seen that the top ten SKUs represent 35% of the revenue already and that items with low picking frequencies can attain a high ranking in the ABC analysis and for a warehouse, the picking frequency might be even more important than the revenue because for a warehouse the main focus is reducing operating times.

The previous ABC analysis was based on the revenue but picking frequency is also an important attribute for warehousing design. In Appendix D, the cumulative picking frequency is shown in the ABC analysis graph. As we can see from the figure, the number of pickings is lagging on the cumulative revenue. At 20% of the SKUs, 90.72% of the revenue is attained but only 64.06% of the pickings have been attained. This indicates that the items in the top with regards to revenue attain more revenue per picking. However, if we sort the SKUs based on picking frequency the figure in Appendix E is obtained. If we would define the ABC classes once more based on picking frequency instead of revenue the following can be said: class A which represents 20% of SKUs accounts for 83.00% of the picking frequencies. Class B which represents 30% of SKUs accounts for 15.74% of the picking frequencies. Class C which represents 50% of SKUs accounts for 1.26% of the picking frequencies.

To get a good understanding of the orders that flow through the warehouse the number of lines on an order is also important. This can also be related to the fraction of orders and the fraction of pickings. As can be seen in Appendix F, 80% of the orders only have a single order line but they only account for 40% of the pickings.

For the activity profiling, it can be concluded that there is a strong presence of the 80-20 rule because with PoolPlaza it is a more 90-20 distribution. The 80-20 rule refers to the Pareto principle which implies that 80% of the outputs are caused by 20% of the inputs. However, it is also shown that the picking frequency is lagging on the cumulative revenue. This might indicate that for PoolPlaza it might be better to focus on picking frequency rather than a revenue-based analysis for storage locations of SKUs. ''In fact, dollar-volume will be of little interest to us because it represents a financial perspective, while we are interested mainly in efficient warehouse operations. Consequently, we will want to see the extent each sku consumes resources such as labor and space.'' (Bartholdi & Hackman, 2005) The dollar-volume term above refers to the amount of revenue an SKU produces. If the SKUs are sorted based on picking frequency a strong 80-20 rule distribution is also found. Furthermore, the seasonality is illustrated, and it is shown that about 80% of the orders only have a single order line which could justify the single command picking policy at PoolPlaza.

1.3 Research question

Based on the core problem and research problems the following research question and sub research questions can be formulated:

What would be an adequate warehouse design for PoolPlaza (given the lot size constraints)?

Sub research questions

- What should be the layout of the new facility?
  - What functional areas can be defined and how many square metres should be devoted to different functional areas?
  - What size should the fast pick and reserve area be?
  - Where to place the functional areas in the layout to provide an optimal flow of goods and personnel?
  - How to place pallet racks inside the fast pick area and reserve storage area?
  - What measures need to be taken into the design to facilitate routing (strategies) in the future?
  - Where should overhead doors and regular doors be placed?

- How much space will be devoted to each SKU in the regular storage area and the fast pick area?
  - Which items should be stored in pallet racks and which items should be stored in box racks?
  - How much space in the regular stock area is reserved per SKU?
  - What items are devoted to the fast pick area?
  - How much storage do SKUs get in the fast pick area?

- Where should each SKU be stored in the new warehouse design? (grouping of products)
  - What storage methods should be used for the various SKUs?
  - Where should different products or products groups be stored in the fast pick area?
  - Where should different products or products groups be stored in the reserve area?

- What will be the final layout of the warehouse to the level of detail where storage locations are assigned to SKUs?

1.4 Scope

The design of a warehouse is, of course, a large project and not all aspects of it can be handled in a thesis project. In this section, the aspects that will be covered and those that will not be covered are mentioned. When a warehouse project would start from scratch it would be necessary to determine the size of the warehouse and the location of the warehouse. However, this information has already been provided by PoolPlaza due to various reasons and the lot has already been assigned to PoolPlaza. This also applies to the roads among the lot which cannot be influenced and are determined by the municipality.

Since the lot size and location have already been determined the size of the warehouse is also more or less pre-determined to 1200 m^2 and will therefore also be the input for the research. Because the investment of a warehouse is closely related to the size of the warehouse this will also be left out of the scope of the project.

Another factor that could greatly influence the investment costs is the level of automation in the warehouse. For example, PoolPlaza could implement an Automatic Storage/Retrieval System (AS/RS) but since PoolPlaza is a start-up/small company it is not worth it. As mentioned before, it has been pre-determined by PoolPlaza that such expensive automation systems are not beneficial yet and therefore in the new warehouse pallet racks, box racks and forklifts will be utilized. PoolPlaza does however acknowledge the value it might bring in the future and therefore would like to investigate measures that can be taken now to prepare for future automation or advanced warehousing policies such as a routing policy. Since the equipment for warehousing operations comes down to forklifts and lift trucks the selection of equipment is also out of the scope. There are of course tools required for non-warehousing operations, but this is also out of the scope because it is not relevant for the design of the warehouse, they are required regardless.

There are however also functional areas of which the size and dimensions will be determined but the actual internal layout of these functional areas will not be researched due to the impact of subjective preferences. The functional areas to which this applies are the following: offices, shop/showroom, demo garden with inground pools outside the warehouse.

What is included in the scope is the determining, sizing, dimensioning and placing of the various functional areas and with it the flow of materials and information. Furthermore, it will be determined how much space each SKU will obtain in the new warehouse and which storage locations these SKUs will get for both the forward area and the reserve area.

1.5 Methodology and deliverables

The methodology used per research question is very divergent and is therefore in each chapter itself where each chapter is concerned with their sub research question. In short, this thesis will make use of literature sources, historical data from PoolPlaza and interviews with employees of PoolPlaza.

With regards to deliverables, each sub research question builds to a more detailed floor plan. So, the end delivery will be a floor plan in which the different functional areas and overhead doors are placed, and the functional areas also have dimensions. For the actual warehouse, there will also be a detailed floor plan per functional area, this implies locations of pallet racks, box racks, forklift, pick and pick locations, VAS area and room for receiving and shipping of products. Finally, each pallet rack and box rack will be assigned to a product or product class in the floor plan.

2 Literature study

In the literature study of this thesis, various articles and other sources are analysed in order to provide a stepwise approach for designing a warehouse for PoolPlaza. Roughly every subchapter in this literature study is dedicated to a sub research question provided in chapter 1.

In the paper from Rouwenhorst et al. (2000), a structured approach for a warehouse design is provided. This literature review is built up in a similar where it starts with the larger more strategical problems and works down to the tactical and operational level problems. On the strategic level, the process flow and the selection of types of warehousing systems are determined. The process flow is incorporated in the facility layout chapter and the selection of warehousing systems has mostly been pre-determined by the company.

On the tactical level, the dimensions of picking zones, forward area and reserve area, docking areas, and shipping areas are determined and these problems are included in the first paragraph facility layout. Next to that, replenishment policies, storage concepts and overall layout over where to locate items are discussed on the tactical level. The replenishments policies are discussed in the paragraph space allocation which also determines which SKUs are devoted to the fast pick area and in which quantities. Storage concepts and overall layout are discussed in the paragraph's storage methods and storage allocation respectively.

On the operational level, the main decisions are concerned with the assignment and control of people and equipment. To sum up, this includes the following: assignment of replenishment tasks, allocation of incoming goods according to tactical level designs, batch formation and order sequencing, assignment of picking tasks to order pickers and routing policies. These decisions are not included in this thesis and literature review since there is a single command picking policy which means batching, routing, order sequencing and assignment of picking tasks are not relevant decisions. Assignment of replenishment tasks and the allocation of incoming goods are also not included since PoolPlaza is a small company with relatively a small frequency of incoming goods and replenishment tasks.

2.1 Facility layout

The impact of warehousing on the performance of a business has been proven many times in the past (Jacyna-Gołda, 2015). Regardless of the type of warehouse and its role, each warehouse has its own different functional areas that are each concerned with a specific phase of the physical material flow (Jacyna, Lewczuk, & Klodawski, 2015). Overall, the most common functional areas in warehouses are (Rouwenhorst, et al., 2000) (Chen, Guo, Lim, & Rodrigues, 2006) (Konrad, 2016):

- Receiving area
- Storage (reserve) area
- Order picking area
- Sorting and consolidation area
- Value-Adding Service (VAS) area
- Shipping area
- Inter-department buffering areas
- The internal transport system

As has been proven in the past, the layout of a facility has a significant impact on its performance (Allegri, 1984) (Apple, 1997). An example of a proven approach is the systematic layout planning tool (SLP) which is a procedural layout design approach (Yang, Su, & Hsu, 2000). Even though the original SLP method was introduced decades ago by Muther (1973) many researchers extended and elaborated on the concept. An advantage of the SLP is that it combines qualitative and quantitative data about the logistics between departments. However, in some cases, quantitative data is hard to determine and, in these cases, a rough idea of high, medium or low interaction could suffice (Tompkins, White, Bozer, Frazelle, & Tanchoco, 2003). This implies that SLP can be done by only having a qualitative input. These qualitative data inputs can be collected through surveys. The disadvantage of SLP, and especially in the latter case, is the fact that the qualitative input of the model can be very subjective.

Rouwenhorst et al. (2000) and de Koster et al. (2007) are often used as a basis in this thesis to find various literature sources on the design of a warehouse. Rouwenhorst et al. (2000) briefly touch on the subject dealing with the design of the process flow which could be interpreted as to where to locate the various functional areas. However, the few sources mentioned do not apply to PoolPlaza or can help with the relative position of functional areas. ''In conclusion, the number of publications concerning design problems on a strategic level appears to be limited, despite the fact that at this level the most far-reaching decisions are made.'' (Rouwenhorst, et al., 2000)

With regards to the layout of a warehouse, Rouwenhorst et al. (2000) does provide some more sources that could be used. For example, Pandit and Palekar (1993) investigate the usefulness of various layouts in the storage area of a warehouse. However, in this paper, a random storage policy is assumed which makes the probability of moving towards locations in a warehouse equal. This setting is not applicable in the case of PoolPlaza because random storage will not be applied in the future. The model also does not aid in the layout of the various functional areas inside a warehouse.

Larson et al. (1997) provide a procedure for the layout of the storage area and specifically mention that the paper focuses on single command retrievals with forklifts which would apply to PoolPlaza. However, due to the assumption that all primary aisles are parallel and of the same length this results in only two possible layouts which are horizontal aisles or vertical aisles. Cross aisles are not considered which could bring benefits to the average travelling time. It could be argued that this paper is more focused on the warehouse that also includes floor stacking.

Eynan and Rosenblatt (1994) mention that square warehouses perform better compared to rectangular warehouses even though they acknowledge the reality that rectangular warehouses do occur more often. If $\sqrt{b}$ is the width of the warehouse and $1/\sqrt{b}$ the length of the warehouse they advise based on computational results that decreasing b below 0,6 might be quite costly.

According to de Koster et al. (2007), the layout can be divided into the facility layout problem and the internal layout design or aisle configuration problem. The facility layout problem is concerned with the decision of where to locate the different functional areas whereas the aisle configuration determines the number, length and width of aisles. Koster et al. (2007) refer to Tompkins et al. (2003), Meller and Gau (1996) and Heragu et al. (2005) for the facility layout problem. However, the facility layouts methods provided in Meller and Gau (1996) are also mentioned in Tompkins et al. (2003). With regards to the width of an aisle, the book of Richards (2011) provides useful practical insights into the width of an aisle based on the handling equipment used.

Tompkins et al. (2003) devote a section to the space requirement of the production area. However, even though it is stated to be a systematic approach, it factors in the space of various equipment and operating space. In chapter 4 of Tompkins et al. (2003) the space requirements for employees are determined by providing guidelines with regard to the following issues:

- Water closets
- Lavatories
- Parking space
- Food services
- Office requirements

Tompkins et al. (2003) also discuss the SLP method in chapter 6 to decide the relative position of functional areas which would further strengthen the validity of the approach. Besides SLP there are also several algorithms provided for the layout of the functional areas for both improvement and creation layout algorithms. Since improvement layout algorithms are irrelevant for PoolPlaza since the layout must be built from scratch these algorithms are discarded. This leaves the following construction algorithms:

- Graph-based method: has a lot of similarities to SLP.
- Craft: uses from-to input
- BLOCPLAN: uses a relationship chart and from-to input
- MIP approach: requires minimal and maximal width and lengths of departments
- LOGIC: uses from-to input
- MULTIPLE: uses from-to input

However, most of these algorithms require quantitative input, which is not available at PoolPlaza, or the minimal and maximal lengths and widths would need to be selected but there is no procedure on how to do this so this would also be a guessing game as a basis. Other algorithms and methods discussed in Tompkins et al. (2003) are heavily based on production warehouses or other functional areas that are irrelevant for PoolPlaza since it is mainly a distribution warehouse.

It is also difficult to find literature about how many aisles to place, where to place them and how many cross aisles to place. Koster et al. (2007) do refer to Roodbergen (2001), Caron and Marchet (2000) and Petersen (2002) for the aisle configuration problem. Roodbergen (2001), proposed a non-linear objective function for determining the aisle configuration in random storage warehouses. However, this would only be applicable if PoolPlaza chooses random storage. Caron et al. (2000) provide an optimal length of each aisle as a function of the number of pick stops per tour and the total length of the picking shelves. However, also this model cannot be applied at PoolPlaza since there is a single command structure in place and there are no picking tours. Petersen (2002) investigates various aisle configurations but limits the research to 4 aisles as a maximum. The report did conclude the following: ''We found that for larger picking zones and a small pick list a zone configuration with three to four aisles resulted in less picker travel.'' (Petersen, 2002)

Sooksaksun et al. (2012) provide an optimisations algorithm to determine the number of storage aisles, the length of the storage aisles and allocate storage locations to classes in a class-based storage policy. However, this model also assumes there are multiple pickings in a tour which is not the case at PoolPlaza. Therefore, a much simpler model could be applied, and this model is overcomplicated.

Much of the remaining references to literature by Rouwenhorst et al. (2000) refers to research concerned with automated systems that are not applied at PoolPlaza due to the size of the company and budget restrictions. ''In conclusion, many papers at the tactical level concern the performance of, mostly automated, warehousing systems.'' (Rouwenhorst, et al., 2000)

Basically, for PoolPlaza it would be interesting to know how large the various functional areas should be and where to place these functional areas relative to each other. After consulting various literature sources, it can be concluded that, besides the forward area and the reserve area, there are not many to no literature sources to determine the dimensions of the functional areas. Only Tompkins et al. (2003) provide some guidelines for this. After determining the dimensions of the various functional areas, the remaining square meters should be assigned to either the fast pick area or the reserve area. Rouwenhorst et al. (2000), Koster et al. (2007), papers they refer to and other literature sources provide few useful models on this specific situation. Both Rouwenhorst et al. (2000), Koster et al.

(2007) eventually refer to or lead to Heragu et al. (2005) or Bartholdi and Hackman (2005) as models that could be applied for PoolPlaza.

The first one is the model from Heragu et al. (2005) who provide a mathematical model for the warehouse design and product allocation. By solving the mathematical model, the results will be a fraction devoted to the fast pick area and a fraction devoted to the bulk area. These can be multiplied by the space left over for these two areas that were determined in the previous section.

The other alternative method discussed in the book of Bartholdi and Hackman (2005) quantifies for each fast pick area size the net benefit of having an SKU in the fast pick area compared to having that SKU only in the reserve area. Items are added to the fast pick area until the fast pick area is full, or the net benefit stops increasing.

To conclude, many of the functional areas' dimensions should be based on guidelines and by discussing with the company. The remaining square meters for the forward and reserve area could be assigned with the models of Heragu et al. (2005) or Bartholdi and Hackman (2005). To determine the relative location of each functional area the best solution would be to adopt the SLP approach because it does not require much quantitative input. Finally, to determine whether the aisle configuration there were many papers consulted however in a single command warehouse this is not very relevant, only when routing strategies are applied, and multiple items are retrieved in one picking run does this becomes interesting.

2.2 Space allocation

In this section, it will be discussed how much space each SKU will require in the warehouse and what is the total required space. If this exceeds the available space some compromises must be made. In the first subsection the reserve area will be discussed, in other words, how much stock and with that how much space is required per SKU. In the second subsection, it will be discussed which items and with which quantity will be assigned to the fast pick area.

2.2.1 Reserve space allocation

Rouwenhorst et al. (2000) refer Berry (1968) to the size and layout of a conventional warehouse however this assumes there is no restocking until a whole stack is emptied and it assumes it is already known how much storage space is required. At PoolPlaza restocking takes place continuously and the amount of storage space is precisely what is to be answered in this section.

A more recent paper by Horta et al. (2016) argues that most of the literature about warehousing design is focused mainly on product storage and the picking process. However, in more recent years more warehouses operate on a cross-docking basis which is part of a just-in-time distribution operation. However, this model is not very applicable for PoolPlaza since there is no just-in-time distribution operation and cross-docking rarely occurs.

A paper by Önüt et al. (2008) provides a mathematical model to determine the optimal number of storage spaces along a shelf and the optimum number of shelves which implies that the model determines the length, width and height of the warehouse. As input, the total capacity, throughput rate, total storage spaces per item and lengths of the aisles/shelves are required. Because the warehousing area is already determined in the facility layout section, this model does not help any further with the problem of how much space each SKU require.

Lee and Elsayed (2005) present an optimization model with a procedure to solve the problem that determines the optimal storage capacity. In the model, the total cost of owned and leased storage spaces per unit time is minimized while satisfying a given service level. An application of the model to systems operating under the economic-order-quantity (EOQ) inventory model is presented. However, the model assumes EOQ is used for every item and assumes leased storage space can be accessed which is not the case for PoolPlaza. Lee and Elsayed (2005) do stress the need for more strategical level warehousing capacity which further supports the claim made earlier in the facility layout section.

Rouwenhorst et al. (2000) also refer to Rosenblatt and Roll (1988) to determine the required storage capacity based on the different product and order characteristics. However, in this case, only one (r,Q) is considered as an inventory policy while Silver et al. (2016) suggest applying different inventory policies to various products based on an ABC analysis. However, the formula for the nominal capacity requirement (NCR) presented in this paper could be adjusted to be applied to multiple storage policies. Once a storage policy has been determined for an SKU based on the ABC analysis the peak and average storage level can be determined per SKU and therefore also the totals over all SKUs. The idea of an ABC analysis starts with the concept that a small portion of the SKUs account for a large portion of the total revenue and these SKUs that account for a larger part of the revenue of a company should get more management attention (Silver, Pyke, & Thomas, 2016). In Table 1 rules of thumb for choosing an inventory policy based on the ABC classification is shown:

	Continuous Review	*Periodic Review*
A items	(s, S)	(R, s, S)
B items	(s, Q)	(R, S)

Table 1 - Rules of thumb for inventory policy selection

''For C items, firms generally use a more manual and simple approach (which can be equivalent to simple (s, Q) or (R, S) systems). Less effort is devoted to inventory management because the savings available are quite small.'' (Silver, Pyke, & Thomas, 2016)

Based on the storage required and the storage methods applied for various products the number of box racks and pallet racks can be determined which in terms provides information about how many square meters are required for the storage reserve area. The book by Richards (2011) also provides some practical calculations for calculating how much space is required by also considering the dimensions of the storage mediums.

As mentioned before if this exceeds the available storage space determined in the facility layout compromises must be made. Larson et al. (1997) do provide a heuristic for determining storage mediums for products in a single command forklift warehouse scenario however this is applied to floor stacking mostly and pallet rack storage is left mostly unattended in this paper. At PoolPlaza there are box racks and pallet racks and no floor stacking which makes this module not very applicable for PoolPlaza.

To choose which storage medium to use for an SKU a rule of thumb was obtained from Richards (2011) based on the amount of volume that is on stock during peak stock levels.

- Drawers: 0 to 0.125 m^3
- Box racks: 0.125 m^3 to 1.5 m^3
- Pallet racks: 1.5 m^3 and higher

This implies that for example, SKU X has 0.00015 m^3 per unit and PoolPlaza we would stock 200 of this SKU which would be 0.03 m^3 in total. This means that this SKU falls into the box racks category and should be stored in a box rack.

There is also a paper by Roll et al. (1989) which propose a procedure for determining the optimal size of a warehouse container. However, this paper assumes an AS/RS is being used and it is assumed that there is one container size for each product. At PoolPlaza there is a need to determine which items go in box racks and which items go in pallet racks. For this reason, the model of Roll et al. (1989) does not fit the problem situation of PoolPlaza.

1.2.2 Fast pick space allocation

Rouwenhorst et al. (2000) refers to van den Berg (1998) present a procedure for the forward-reserve problem. The forward-reserve problem addresses the problem of deciding which SKUs should be stored in the forward area and in which quantities. Van den Berg (1998) extend on previous models which assume that one trip from the reserve area can replenish the forward reserve area while Berg and Sharp argue that there is no need to assign more than one unit to the forward area because they can be replenished instantaneously. However, the assumption of the antecedent models is a realistic assumption that holds in most situations at PoolPlaza and therefore the antecedent previous models could be investigated.

Hackman et al. (1990) presented a model for the forward-reserve problem which simultaneously considers both the assignment and allocation of products. Bartholdi and Hackman (2005) further discuss this problem and conclude that to decide which SKUs get into the fast pick area the labour efficiency factor could be used which results in a near-optimal result. "The skus that have strongest claim to the fast-pick area are those offering the greatest labor efficiency.'' (Bartholdi & Hackman, 2005)

For the labour efficiency heuristic, the annual pickings of each SKU and the flow of each SKU are required. It is also mentioned that if an item is put in the fast pick area it should have a minimum amount of stock in the fast pick area according to theorem 8.6 which can be found in the book. The labour efficiency can be calculated for each SKU and then sorted decreasingly. Keep adding the best SKUs to the fast pick area until the net benefit starts increasing. The more SKUs there are in total the more negligible the worst-case error of the labour efficiency heuristic is. ''In other words, for all practical purposes, this procedure solves the problem of stocking the fast-pick area to realize the greatest possible net benefit.'' (Bartholdi & Hackman, 2005)

However, it should also be determined how much space an SKU obtains in the fast pick area. For this problem, Bartholdi and Hackman (2008) provide a greedy heuristic formula. Gu et al. (2010) also further extends on the model of Hackman et al. (1990) and Bartholdi and Hackman (2008) by providing an alternative algorithm that can find a guaranteed optimal solution efficiently. In this paper, it is also mentioned that there can be a large optimality gap between the heuristic and the optimal solutions. However, as also stated by Bartholdi and Hackman (2008), Gu et al. (2010) state that the optimality gap will become smaller as the number of SKUs increases. ''The results verify that, although the greedy heuristic might result in a large optimality gap in some small examples, when it is applied to practical problems the solutions are so close to the optimum that the difference can be ignored from a practical point of view.'' (Gu, Goetschalckx, & McGinnis, 2010)

For more recent works on the forward-reserve problem the paper by Walter et al. (2013) further extends on the model of Hackman et al. (1990) by making the forward-reserve problem discreet. As also stated by Bartholdi and Hackman (2005) a lot of the extensions on the original model thus far assume the forward area can continuously be partitioned among SKUs. ''Clearly, this simplifying assumption might be justified if merely an approximate benchmark solution is sought. However, for a detailed stocking plan of the forward area, the fluid model shows some severe drawbacks" (Walter, Boysen, & Scholl, 2013) However the model also implies that fully dedicated storage is being utilized which in reality is not achievable at PoolPlaza over longer periods. Therefore, the benefits of researching this exactly cannot be gained in the future operations of the company. Thus, a rough estimate would be sufficient in this case to bring significant benefits compared to the current situation.

To conclude this section of the literature study, for the reserve storage space there are a lot of models but often the total space required is an input which is precisely what needs to be determined for PoolPlaza. The model of Rosenblatt and Roll (1988) can be adapted in combination with the storage policy determination from Silver et al. (2016) and the rules of thumbs for storage medium assignment.

Starting from both Rouwenhorst et al. (2000) and Koster et al. (2007) the models provided eventually lead back to heuristics provided by Bartholdi and Hackman (2005) and Bartholdi and Hackman (2008). There are more recent works that extend on the model of Hackman et al. (1990), however, for each model, it was found these were either not applicable or it was concluded that the heuristics provided a sufficient near to optimal solution with enough SKUs.

2.3 Storage methods

The first issue concerning inventory policies is the grouping of products. At PoolPlaza there is a difference between products and variants. So, for example, an aluminium frame pool is available in three sizes. So, there is one product and three variants. It has already been decided by the company that different variants are stored in the same area or the same pallet rack in the reserve area to prevent confusion among the pickers. However, this still leaves the question of which storage policy is going to be utilized and on what level. ''Products can be assigned to storage locations either arbitrarily or based on certain criteria. The first option is often referred to as "random policy"; we will refer to it as the "haphazard policy". The second option is referred to as "dedicated storage". Haphazard storage assigns SKUs to locations chaotically over planning horizon while with the dedicated storage the location is kept for specific products in a warehouse." (Bahrami, Piri, & Aghezzaf, 2019)

There is also a combination of the above-mentioned policies which is regarded as the class-based approach. The classes have dedicated locations in the warehouse but within each class the storage policy is randomized. This combination is designed to capture the benefits of both randomized storage and dedicated storage (Bahrami, Piri, & Aghezzaf, 2019). In the summation below there are some examples of SKU data that could be used for determining the classes:

- Part number (historical and now mostly obsolete)
- Turnover
- Picking frequency
- Cube-per-order
- Duration-of-stay
- Flow per SKU
- Correlation (locates SKUs together that are often sold together)

For the configuration of the classes, it is advised to keep the number of classes to a minimum. For example, Rao and Adil (2013) state that a maximum of three classes is sufficient to get significant benefits from the class-based policies. Guo et al. (2015) claim that a class-based storage policy with a small number of classes with five or less is optimal.

Malmborg (1996) also investigated whether a dedicated storage policy indeed performs better than a randomized storage policy. ''The model enables a direct comparison of the space and retrieval efficiency of randomized and dedicated storage policies without assuming a fixed space requirement." (Malmborg C. J., 1995) It was found that randomized storage can actually perform better than a dedicated storage capability if the fit parameter of the ABC analysis is larger than 0,5. If the fit parameter is indeed above 0,5 the storage capacity advantages from randomized storage start to outweigh the advantages of the reduced travel times of dedicated storage. Larson et al. (1997) also further supports the claim that a dedicated storage policy reduces the material handling cost with a trade-off of more storage space required.

According to Goetschalckx and Ratliff (1990), the space requirements with a dedicated storage policy are much larger compared to the class-based storage because with a dedicated storage policy the warehouse needs to be large enough to store the sum of all product's maximum inventory levels. This is an important advantage of a class-based storage policy.

Hausman et al. (1976) show the improvements of turnover based assignment over the random assignment and provides improvements of class-based turnover assignment over random assignment which in both cases are very significant. It should be mentioned that this paper provides a very basic model, but this reasoning also applies to layout with multiple aisles.

In the paper of Goetschalckx and Ratliff (1990), it is shown that in a fully balanced system, where for any period, the number of products received with a certain duration of stay is equal to the number of products departed with a certain duration of stay, a class-based storage approach based on the DOS is more optimal with travel times compared to the turnover class-based policy. Even though this is an ideal situation, it does provide insights into the fact that turnover based classes might not always be the optimal strategy.

The performance of the class-based approach is further supported by Eynan and Rosenblatt (1994) to be significant in decreasing the travel times compared to random storage. Both Eynan and Rosenblatt (1994) and Hausman et al. (1976) provide evidence that the larger the fraction of revenue that the 20% best-selling products generate, the larger the benefits of the class-based turnover storage policy. Eynan and Rosenblatt (1994) also provide an analysis of the number of classes to be utilized and conclude that having more than six classes has negligible results in time savings.

As mentioned in the sources above there are also other methods besides turnover to define the classes for the warehousing storage methods. Other inputs to determine the classes of products could be product categories, picking frequency and picking quantity. For example, it would be better to place large, frequently picked items with a medium contribution to the revenue closers to the picking area than small, non-frequently picked items with a large contribution to the revenue because it would save travel time. From a warehousing perspective, the only thing minimized is the travelling time. If it is assumed larger quantities than one on the same order can be picked in the same picking run the picking frequency is also more beneficial compared to the picking quantity. This assumption mostly holds for PoolPlaza since when larger items are bought, like sand filters or pools, customers usually order one piece and items that are often ordered in larger quantities are usually smaller items to build the pool. It could also be possible to define the classes based on product categories so that similar items are always close to one another which makes it easier for the picker to know where to be if storage locations are not present on the packing list which is currently the case for PoolPlaza.

To conclude this section a class-based storage approach seems to be the most fitting for PoolPlaza where the number of classes should be between three and five as it is stated to be the optimal number. With regards to measures that could be taken in the current design with regards to future routing, policies have mainly to do with the placement of cross aisles and pallet racks. Of course, in a single command warehousing operation, a cross-aisle would not benefit the travel times since the number of meters vertically and horizontally remains the same. However, in the future, if multiple items would be picked in a picking run these cross aisles would save a lot of time and could therefore be implemented in the initial design because once these pallet racks are placed and filled it is difficult to move them.

2.4 Storage allocation

The cube-per-order index, also known as the COI is a commonly used tool in warehousing policies to help with the decisions of allocating space to SKUs (Heskett, 1963). The COI encompasses the ratio of space required for an SKU and the number of times it is picked/retrieved from a storage location. The SKUs are then sorted in ascending order and in that order, the SKUs are allocated closest to the input/output location in the warehouse, also known as the I/O point.

$$\text{COI} = \frac{\#\ \text{required storage locations}}{\#\ \text{trips in/out of storage per period}}$$

Figure 5 - COI formula

This COI was proven by many researchers to be the optimal solution under the condition that a single command order picking is utilized in the warehouse. (Malmborg & Bhaskaran, 1989). ''A critical observation of these slotting strategies reveals that they are not always the best way of slotting, because the assignment of SKUs to locations assumes that all storage and retrieval transactions are single-command transactions. In other words, the order picker begins from the I/O point, performs a retrieval transaction and then returns to the I/O point. However, in reality, multiple items in an order are picked from their respective locations in one tour that begins at the I/O point, visits these locations in a specified sequence and returns to the I/O point.'' (Mantel, Schuur, & Heragu, 2007) In the general case, when storage and retrieval transactions are not single-command transactions, the worst-case behaviour has been proven to be infinitely bad. (Schuur, 2015)

In case the latter is true, Mantel et al. (2007) propose an order-oriented slotting (OOS) strategy be adopted. With OOS items that are often ordered together are also considered to minimize the total lengths of the order picking routes. However, in this case, it is also mentioned that OOS does not work well with order batching.

It should also be noted that, for example, if a fully dedicated storage is used and storage and retrieval transactions are not single-command transactions it is important to investigate the correlations of SKUs in their category. In the other case, if a class-based storage policy is utilized in the new warehouse design the classes are the variables that need to be allocated. If for example, product categories will be the classes then these categories will be allocated in the warehouse based on for example the COI or OOS strategy and within these classes, the storage will be random.

To further extend upon the COI approach, Malmborg (1995) mentions that multiple aisles are in general not a problem for the COI index. ''Multiple aisles do not necessarily present a difficulty in COI applications where the same item can be located in multiple aisles. In such cases, each individual storage location in the facility can be rank ordered, and each unit (or pallet) of an item can be assigned independently based on the average transactions demand for the item.'' (Malmborg C. J., 1995) However, it is stated that if zoning constraints are present the COI cannot guarantee an effective assignment of items to storage locations. To tackle this ''aisle'' problem, Malmborg (1995) presents a simulated annealing algorithm extension on the COI model. However, since zoning constraints are not present at PoolPlaza this simulated annealing algorithm extension on the COI model is irrelevant.

A model by Lai et al. (2002) also provides a solution where storage locations are assigned to various items. However, the model in this paper is very specific. In previous models, each item would require one or more storage cells and cells are not shared with other items. However, in the paper reel layout problem it is allowed that paper reel types of the same class share a cell. Furthermore, the classes of products are based on their diameters instead of turnover rate because they can be stacked, and each cell can only store products from the same class. Due to the model being so specific it is not a good fit with the situation at PoolPlaza.

In previous research, warehousing decisions are often made in a sequential procedure according to Roodbergen, Vis & Taylor (2014). They also state that of ''more than 2500 different realistic layout problems, Roodbergen and Vis (2006a) showed that sequential decisions do not necessarily give the same quality of results as a procedure that takes simultaneous decisions on layout and control policies.'' (Roodbergen, Vis, & Taylor, 2014) The model of Roodbergen et al. (2014) is a more recent study that investigates the layout while simultaneously selecting from a multitude of control policies. However, in the model of Roodbergen et al. (2014), the sequence locations are also defined in the control policy and at PoolPlaza currently a single command order picking procedure is applied which means this model is not a good fit.

Rouwenhorst et al. (2000) refers to Hausman et al. (1976), Goetschalckx and Ratliff (1990), Kouvelis and Papanicolaou (1995) for analysing the class-based storage with single commands and an AS/RS. Besides that, the AS/RS, which can be easily assumed to be a forklift since it works basically the same, these papers analyse the similar situation for PoolPlaza if indeed a class-based approach is utilized.

Hausman et al. (1976) consider the assignment of pallet loads to storage locations while assuming single commands and each pallet holding only one item type. However, the assumption that only a single two-sided aisle is being considered is not realistic in the case of PoolPlaza. Goetschalckx and Ratliff (1990) further build upon the model of Hausman et al. (1976) by using a class-based storage approach based on the individual unit load duration of stay (DOS) instead of the average product turnover.

Kouvelis and Papanicolaou (1995) develop mathematical formulas to determine the optimal boundaries for a two-class-based storage policy but also mention this can be extended to derive the optimal boundaries in an n-class-based storage policy. The boundaries are determined by the access frequency of storage areas 1 and 2. The formulas of Kouvelis and Papanicolaou (1995) would indeed be valid but the assumption that each storage cell is equal in size and holds only one type of item is very important for it to be valid. For example, if the access frequency of both areas would be equal the reasoning of Kouvelis and Papanicolaou (1995) would result in two equal-sized areas. However, if the first area would hold very large items this would of course not work. Since this assumption is too constraining the model of Kouvelis and Papanicolaou (1995) cannot be applied in the case of PoolPlaza.

To conclude this section in a single command warehousing operation it would be best to determine the locations of the classes or items based on the COI index. For future research, the storage locations might be rearranged once picking runs are implemented in which a routing policy is applied.

2.5 Performance criteria

In the previous sections models and theories were discussed to solve the research question of this thesis. However, once the research questions are solved and a design has been constructed it is also important to investigate the performance of the layout. As mentioned before, PoolPlaza has a warehouse with distribution being the main function. ''The number of different products in a distribution warehouse may be large, while the quantities per order line may be small, which often results in a complex and relatively costly order picking process. Therefore, distribution warehouses are often optimized for cost-efficient order picking. The prominent design criterion is the maximum throughput, to be reached at minimum investment and operational costs.'' (Rouwenhorst, et al., 2000) Also, de Koster et al. (2007) state that the most common performance criteria for finding the ''best'' layout is the travel distance. In the paper, the investment costs are also discussed as a criterion however this is out of the scope of this project.

Rouwenhorst et al. (2000) refer to Pliskin and Dori (1982) for a multi-criteria analysis of the performance of warehouse layouts. However, this model assumes all the areas have minimum space requirements and after those minimums, there is still some leftover space. In the multi-criteria analysis, it is determined which areas get these additional spaces and how much of the total leftover space these areas obtain. This is done by asking the decision-maker multiple questions about space allocation. With a mathematical model, the ratios of how much each area obtains are determined. However, this approach helps in assigning leftover space but does not evaluate the performance of various layouts with performance indicators. Next to that, another drawback is that it is purely based on the answers of the decision-maker and the final layout cannot be measured in its performance.

For the location of products in the warehouse, it would be possible to evaluate the travel distance and thereby the performance by calculating the total distance travelled for a given set of orders. If there are various layouts, these can be compared in the same way and a conclusion can be made on which would be the best among the candidate solutions.

However, for the space allocation in the reserve area and fast pick area, the above-mentioned method would not work. For this it could be possible to determine a service level based on historical data however this is already included in determining the space each SKU obtains in the new warehouse. However, if the SKU require more space than is available according to the facility layout and comprises must be made, it might be useful the measure the service levels to compare and evaluate various comprises.

For the facility layout, it would be best to look at the flow of information and materials between the various functional areas which is already included in the SLP analysis.

To conclude the overall literature review it can be argued that overall, the simplified models apply better to the situation of PoolPlaza since it is a relatively small company with a single command picking a policy. For the sizing of various functional areas, it is important to closely discuss with the company the needs and personal preferences for such areas. The remaining space for the forward and reserve area can be allocated with the models of Heragu et al. (2005) or Bartholdi and Hackman (2005). The model of Rosenblatt and Roll (1988) can be adapted in combination with the storage policy determination from Silver et al. (2016) and the rules of thumbs for storage medium assignment to determine the amount of space required per SKU. In terms of how to locate items and where to locate them a class-based storage approach in combination with the COI index seems most fitting due to the small optimality gap when these methods are applied with many SKUs.

3 Stepwise approach for the warehouse design

From the literature study in chapter two, a stepwise approach is defined to design the warehouse of PoolPlaza. In this stepwise approach theories and models are combined to answer the research question of the thesis. In the literature study, it is mentioned why some models and theories do not fit PoolPlaza and why other models are, at the end of each paragraph. In most cases, the theories and models chosen are influenced by the size of PoolPlaza, the availability of data and the capabilities of the ERP system.

The present chapter of the thesis provides a roadmap of steps that need to be taken. Each further chapter in this thesis is concerned with a part of these steps which in turn answer a sub research question. The stepwise approach is mostly based on the literature review by Rouwenhorst et al. (2000) which is also a stepwise approach on how to define a warehouse. The stepwise approach of Rouwenhorst et al. (2000) starts at the strategic level, after which the tactical level is discussed and finally the operational level is addressed. However, the stepwise approach in this thesis is modified to fit the situation of PoolPlaza.

1. General layout – strategic level
    a. Determine and dimension the functional areas.
    b. Determine the dimension of the fast pick area and reserve area with a linear programming model provided in chapter 2.1
    c. Determine an adequate layout of the warehouse with an SLP approach provided in chapter 2.1.
    d. Determine where and how to place pallet racks taking into account cross aisles.
2. Space allocation – tactical level
    a. Determine per SKU what their ABC-XYZ classification, fill rate and inventory policy is. The inventory policy parameters are required to determine the average and peak stock levels of the warehouse and therefore the space allocation per SKU is determined.
    b. Determine per SKU in what storage medium to store them based on their peak stock levels.
    c. Assign SKUs to the fast pick area based on the labor efficiency heuristic provided in chapter 2.2.
    d. Determine per SKU that is assigned to the fast pick area how many unit loads should be assigned to the fast pick area.
3. Storage allocation – tactical level
    a. Determine for both the fast pick area and the reserve area what storage methods should be applied.
    b. Determine for both the box racks SKUs and pallet racks SKUs which storage locations are assigned per SKU in the fast pick area. This storage allocation is done via the COI approach provided in chapter 2.4.
    c. Determine the ABC picking zones in the reserve area and assign SKUs to a picking zone.

4 Facility layout

In the literature study of this thesis, the various functional areas of the layout of a warehouse, in general, were identified. In this chapter, the appropriate functional areas are identified for Poolplaza's functional areas. For the size of the fast pick area and reserve area a mathematical model is utilized and the sizes of the remaining functional areas are based on the requirements provided by the company.

4.1 Functional areas for PoolPlaza

To sum up the type of functional areas that are most used (Konrad, 2016):

- **Receiving area**, unloading, identification and control, labelling, addressing and changing the type of units by packaging or forming.
- **Storage (reserve) area**, (long-term) depositing of materials to feed shipping and order-picking areas.
- **Order-picking area**, constructing non-uniform shipping units in line with customer orders.
- **Sorting and consolidation area**, forming and merging units, consolidation of shipments for different transport relations, recipients and time windows.
- **VAS area**, services increasing the value of products, typically the final stage of production process differentiating final products on client request.
- **Shipping area** functions similar to receiving area.
- **Inter-department buffering areas**, eg. between production department and warehouse facility.
- **The internal transport system**, communication between functional areas and material handling within the areas''

However, as also mentioned in the literature study, it could of course be possible that some functional areas are not applicable for PoolPlaza and maybe also that some functional areas are missing. From the selection above the following functional areas are left out:

- **Sorting and consolidation area**
  This functional area is not relevant for PoolPlaza because in general all goods first go to the storage area. There are some rare cases that incoming shipments can be sent out directly upon received but this is such a rare event that the receiving area can also fulfil this functionality in these rare cases.
- **Inter-department area**
  The inter-department area is not relevant for PoolPlaza because the only product that takes place is the production of GeoBubble solar covers for the swimming pools. These are made exactly to the dimensions of the pool of customers and are therefore make-to-order. For this reason, the products can be packed and moved to the shipping area straight after the production process is complete.

The shop and the offices are the functional areas that are missing from the selection out of the literature. These functional areas are of course irregular for normal production and warehouse facilities upon which the literature was based. However, since PoolPlaza is still a relatively small company the offices and shop will be integrated into the warehouse since this costs considerably less. In practice this does often occur, an example is depicted in Figure 6 below.

Figure 6 - Integrated office example

For a shop, it is very hard to define how large this should be because it all, depends on what you want to showcase and how you want to showcase it. An assumption is made that this would take about 100 m^2.

For the offices, the company already provided information about the requirements at the start of this research project. PoolPlaza requires there to be about 8-10 working spaces available because soon there will be two full-time employees and there are currently five part-timers working at the current facility. So currently there are already seven working spaces required at the peak occupation. Because PoolPlaza would like to stay in this warehouse for about five years it is important to consider that more full-time employees will be working at PoolPlaza over these next five years. For this reason, PoolPlaza argues that about 8-10 working spaces will suffice for the coming years. This might seem like a pessimistic estimation as there are currently already seven people working at PoolPlaza at peak occupation, however one must consider that one full-time employee can replace approximately two to three part-time employees in terms of the amount of work that they can deliver. Next to the working space there also needs to be a kitchen, a place to have lunch, a bathroom and some storage for kitchen and office supplies. By sketching with these requirements, a room of about 100 m^2 would suffice and is shown in Appendix G.

4.2 Dimensioning of the functional areas

With the functional areas identified and a rough estimation of the offices and shop areas, the next step is to start dimensioning the functional areas that are part of the warehousing operations. This refers to step 1a from the stepwise approach.

The receiving area, internal transport system, VAS area, and order-picking area are dimensioned in the same way as the offices and the shop. Based on actual current information and requirements of PoolPlaza the areas are sketched in RoomSketcher. Based on these sketches a good estimation of the square meters required for each functional area can be given. It should be noted that these are an estimation and are not the exact dimensions in reality. If the estimation for the shipping area would be 50 m^2 for example and, this would be 54 m^2 in reality this is not a huge problem. For these reasons, RoomSketcher can be a perfect tool to transform the requirements into a good estimation of the square meters.

Receiving area
The space required for the receiving area can be based on the peak incoming number of pallets and the room required to store them temporarily and move them if necessary. According to the company at a peak operating level and with the future kept in mind around 20 pallets would be sufficient for the receiving area. Using RoomSketcher the following design has been constructed that could serve as an example layout. In this design, the overhead door at the bottom can be seen with enough space to move from the overhead door to all the other locations. For each pallet, extra room has been taken into account in front to be able to still move these pallets around if necessary. For example, if there are 20 pallets, all these 20 pallets should be able to be moved without moving a lot of other pallets and preferably without moving any other pallets. With these requirements defined, the receiving area approximately requires 60 m^2 and a sketch is provided in Appendix H.

Shipping area
For the required space for the shipping area, the same school of thought applies. How many pallets are required to be stored there when peak demand is present. Currently, there are three pallets at PoolPlaza where orders and website orders are being stored for customers to pick them up. In the future, PoolPlaza would like to upgrade this to 6 pallet places based on the current need for them and keeping growth in mind. Next to that, there is a larger trailer that needs to be stored inside which is used to load the pallets upon and drive the parcels to the transporter on the other side of the industrial area. Lastly, the pick and packers always put the parcels of website orders on pallets and manoeuvre them to the shipping area. For the number of shipments per day, there would be enough space with 10 pallets locations reserved. The design for the shipping area can be seen in Appendix I, as can be seen from this design there is about 60 m^2 required for the shipping area.

Internal transport system
For internal transport systems, there is currently one hand pallet truck and one forklift available at the warehouse at PoolPlaza. For hand pallet trucks there does not need to be a dedicated space where they can be parked because, at the end of the day, they can easily be shoved under a pallet park. For forklifts, this is different, because firstly, the machinery is much bigger and secondly PoolPlaza currently has an electric forklift that needs to be charged. So, the best solution would be to have dedicated parking space for the forklift which is also the charging station. Considering the future growth of the company and the size of the warehouse area increasing significantly two forklifts are estimated to be required over time, so the internal transport system requires to have to park and charging stations for the forklifts. The dimensions of the forklift are 300x100x220cm (lxwxh). Since the RoomSketcher tool is not originally designed to sketch warehouses there is no good depiction of a forklift, for this reason, a pickup truck is given the correct dimensions and put into the sketch. Behind the pickup truck are the charging stations which each have the dimension of a euro pallet. In total this would require about 10 m^2 of space for the parking and charging of two forklifts and the sketch is shown in Appendix J.

VAS area
The Value Adding Services area or VAS area can be described as the processes which add value to the products such as assembly or production processes. For PoolPlaza there is only one production process which is the production of GeoBubble solar covers. From sales data, it can be shown that most of the solar covers do not exceed 10 meters in length with some exceptions of 12 meters and 13 meters. However, to keep dedicated space free for these few exceptions is not economically favourable. Furthermore, if these extra meters are required it is usually not a problem to create some extra free meters from other functional areas. For example, in the configuration shown in Appendix K, it is easy to take some extra meters from the shipping area temporarily. The production process of such a solar cover takes four hours maximum so by the end of the day the shipping area is back to its usual boundaries in this case. Another argument to take 10 meters in length instead of the 12 or 13 meters is because the inground pools that PoolPlaza sells are a maximum of 8 meters in length. PoolPlaza does

have steel wall pools with a total length of 10 meters or 12 meters in their product range, but these have not been sold yet to this day and will therefore also not sell that often in the future.

The GeoBubble material is stored in a verify specific storage rack on rolls of 50 meters long and five or six meters in width. There are two of these storage racks currently and the dimensions of these storage racks are 440x130x250cm (lxwxh) and 540x70x350cm (lxwxh) respectively. Furthermore, PoolPlaza also requires extra storage capabilities because currently, the number of rolls that are ordered per single order is too many to put in these storage racks. For this reason, there needs to be an extra bulk storage location. The best option would be to put these rolls on a pallet rack. A roll takes up about five to six pallets in width, and preferable, they should not be stacked. Lastly, there should also be tools available for the production process and in general for the warehouse. To give one example of a non-production process that requires tools: PVC pipes sometimes must be cut to the appropriate size. However, as the pick area also needs easy access to these tools the tool station will be located in between the pick area and the production area. This does assume that the pick area and production area are closely located to one another. If the SLP analysis determines that these two functional areas should not be located near each other both areas should get a smaller but separate tool station.

So, to sum this all up the following requirements for space can be identified:

- The production floor of 10x5 meters is nominal but taking into account room to move around and properly work it would require 10x6 meters.
- The storage rack of 5-meter width rolls
- The storage rack of 4-meter width rolls
- Access to a station with tools required for the production process
- A pallet rack of six pallets in width is required for extra storage

In total, the VAS area would require about 100 m^2 as shown in Appendix L. The blue sections represent the storage racks and the grey structure with the wooden pallets in it represents the pallet rack.

Order-picking area

In the current warehouse, there are one or two pickers and currently, there is an area of about 4x2,5m where the computer, printer, label printer and tool station are for the pickers to pack the products into boxes or to prepare pallets. There is also a separate table or pallet stacked upon each other with a top layer that can be utilized for this process. The storage of boxes, tapes and other supplies and materials should also be considered. Currently, above and under the table with the computer and printer there are spaces where boxes are being stored. Furthermore, there are three pallets spaces additionally to store boxes. In the current situation, boxes are picked from both locations during the day.

However, in a new situation, this could be done more effectively. Instead of two employees both operating on the same desk, it would be better to allocate one desk to each employee with their tools, computer, label printer their own small stock of boxes. Because each employee will have their stock on boxes there is also no need to retrieve boxes from the bulk storage of boxes that take up the three pallet places. In the current situation, the desk with two computers a printer and a label printer take up 3,8 x 1,2m. In the future design, the desks will have the same dimensions and by removing the second computer there is enough space in total under, above and on the desk for the boxes and additional supplies that a picker will require on a day. Initially, one or two full-time pickers will be enough and taking future growth into account room for a third picker is desired from PoolPlaza.

In the future situation, three pallet spaces will also suffice for the number of boxes required to be kept in stock. This is because currently in these three pallet locations 1200 boxes of the smallest size and 120 boxes of the largest can be stored here. The middle sizes box is stored above and under the desk with the computer which can hold about 200 to 300 of these boxes. Until 09-11-2021 there were 2192 sales orders in total and if it is assumed that each shipment requires one box to ship the products to the customer the 1620 boxes would only have to be restocked once during a year which means that the stock of boxes is more than sufficient because these can be restocked more than once a year. One could also argue that the space dedicated for the stock keeping of boxes should be less however this is usually not very beneficial due to economies of scale advantages of buying larger quantities. The assumption that each sales order requires one box to ship the order to the customer is of course also not true. However, some sales orders have multiple shipments over time or require more than one box because of size restrictions at the transporter. In other cases, customers pick up their products or the box of the product itself is already fit for shipping or a pallet is used to ship the products. With these two points taken into account, the assumption is argued to be accurate enough to estimate the required number of boxes per year.

With all the requirements considered, a preliminary design was created which can be seen in Appendix M. The white section represents the tables for the pickers and in between, there is room to put pallets if pallet shipments need to be prepared. To the right is the pallet rack for the bulk storage of boxes and there is enough room on the top size to manoeuvre with pallets considering that the adjacent functional area is fully utilized with pallet racks or box racks. In this initial design, there is also an easy connection to the shipping area which is also assumed to be present after the SLP since these two functional areas are closely related for obvious reasons. All in all, the picking area would require about 40 m^2.

Based on the requirements of PoolPlaza's current processes and considering future growth, the functional areas require the following spaces:

- Shop 100 m^2
- Offices 100 m^2
- Receiving area 60 m^2
- Shipping area 60 m^2
- Internal transport system 10 m^2
- VAS area 100 m^2
- Picking area 40 m^2

4.3 Dimensioning the storage area and fast pick area

When these areas are subtracted from the total space of the warehouse, which is 1200 m^2, there are 690 m^2 left. To determine the ratio devoted to the fast pick area and the reserve area the mathematical model of Heragu, Du, Mantel & Schuur will be used (2005). Below the original model and its parameters are presented:

<u>Parameters:</u>

i	number of products, i = 1, 2, ... , n
j	type of material flow, j = 1, 2, 3, 4
λ_i	annual demand rate of product i in unit loads
A_i	order cost for product i
p_i	average percentage of time a unit load of product i spends in reserve area if product is assigned to material flow 3
$q_{i,j}$	when product i is assigned to material flow j = 1, 2 or 4; $[d_i]$ + 1 when product i is assigned to flow j = 3, where di is the ratio of the size of the unit load in reserve area to that in the forward area and $[d_i]$ is the largest integer greater than or equal to di,

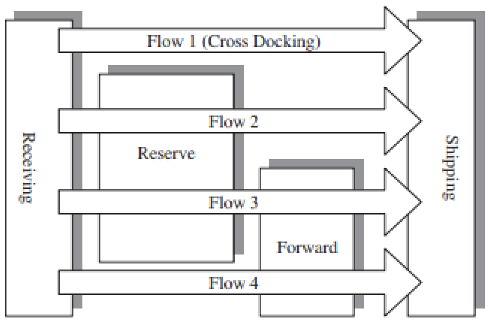


Figure 7 - Flow representation in a warehouse

a, b,c levels of space available in the vertical dimension in each functional area, a = cross-docking, b = reserve and c = forward,
r inventory carrying cost rate
$H_{i,j}$ cost of handling a unit load of product i in material flow j
$C_{i,j}$ cost of storing a unit load of product i in material flow j per year,
S_i space required for storing a unit load of product i, (m^3)
TS total available storage floor space (m^2)
Q_i order quantity for product i (in unit loads)
T_i dwell time (years) per unit load of product i
LLCD, ULCD lower and upper storage space limit for the cross-docking area
LLF, ULF lower and upper storage space limit for the forward area
LLR, ULR lower and upper storage space limit for the reserve area

Decision variables
$X_{i,j}$ 1 if product i is assigned to flow type j; 0 otherwise,
α, β, γ proportion of available floor space (area) assigned to each functional area, beta reserve and gamma forward. α = cross-docking β = reserve, γ = forward

Objective function

$$\min: 2\sum_{i=1}^{n}\sum_{j=1}^{3} q_{i,j}H_{i,j}\lambda_{i,j}X_{i,j} + \sum_{i=1}^{n}\sum_{j=1}^{3}(q_{i,j}C_{i,j}Q_iX_{i,j}/2)$$

Modifications to parameters

However, some adjustments have been made to the model for this thesis. The parameter $q_{i,j}$ has been left out of the model which represented the ratio of the unit load in the reserve area to that in the fast pick area. Excluding parameter $q_{i,j}$ is rather easy since it only occurs in the objective function. The reason why this parameter is excluded is that the breakdown process does not always apply at PoolPlaza. If products are moved from the reserve area to the fast pick area the complete pallet or box is moved, and the unit loads are not unpacked in every situation. Next to that, if a pick is done from the reserve area usually one unit load is taken off the pallet or out of the box and the rest is put back. Without $q_{i,j}$ the model fits better to the situation at PoolPlaza.

Also, the auxiliary parameter d_i has been introduced to aid in the calculation of $H_{i,j}$. d_i represents the minimum of the number of unit loads that are in a replenishment cycle of SKU i and the order quantity of SKU i. For the cost of replenishment, an average cost per box or pallet has been taken so that the costs of a replenishment are spread out among the number of unit loads in the replenishment. So, for example, if a replenishment contains 100 products of SKU i and the replenishments costs are x. Then the replenishment costs for SKU i per unit load are x/100. In this example, the d_i is 100 units.

The following parameters have also been added and are elaborated upon when discussing the objective function:
RTTF fraction that represents the costs of travel time in the forward area handling costs
RTTR fraction that represents the costs of travel time in the reserve area handling costs

Furthermore, r, T_i, LL_f, UL_f, LL_r, UL_r have been left out of the model which represents the inventory carrying cost rate, dwell time (years) per unit load of product i, lower and upper storage space limit for the forward area and lower and upper storage space limit for the reserve area. This is because the objective function has been modified which makes the upper and lower limits obsolete and r and T_i are not used since realistic order quantities are provided by PoolPlaza instead of the EOQ model.

Finally, Flow 1 has been left out of the model since there is no cross-docking at PoolPlaza. This means that flow 2 becomes flow 1, flow 3 becomes 2 and flow 4 becomes 3. This also implies that alpha and ''a'' are left out of the model.

Modified objective function
After running the initial model, it became apparent that when items were put in the fast pick area and therefore the fast pick area grows, the benefits of putting SKUs in the fast pick area did not decrease. However, when more items are assigned to the fast pick area, the fast pick area becomes larger, the travelling times will increase and therefore the savings per pick from the fast pick will decrease compared to the costs of picking from the reserve area. The objective function was modified to increase or decrease handling costs based on the actual values of gamma and beta.

Firstly, to reduce the length of the objective function the letter R and F are introduced which represent the following and are explained further down below:

$$R = \left(\frac{\beta}{0{,}8} * RTTR + (1 - RTTR)\right)$$
$$F = \left(\frac{\gamma}{0{,}2} * RTTF + (1 - RTTF)\right)$$

Secondly, the handling costs of flow 2 are based on the handling cost of flows 1 and 3 in this model. In the original model, these costs were static and could be calculated beforehand and used as input. However, since the handling costs of flow 1 and 3 are now influenced by the decision variables they need to be calculated with each alteration to the solution space and are therefore now incorporated into the objective function. Below the modified objective function is shown and in Appendix N the objective function is shown without R and F replacing parts of the expressions.

$$\min: 2 * \left(\sum_{i=1}^{n} RH_{i,1}\lambda_i X_{i,1} + \sum_{i=1}^{n}\left(FH_{i,3} + \frac{(FH_{i,3} + RH_{i,1})}{d_i}\right)\lambda_i X_{i,2} + \sum_{i=1}^{n} F\,H_{i,3}\lambda_i X_{i,3}\right) + \sum_{i=1}^{n}\sum_{j=1}^{3}(C_{i,j}Q_i X_{i,j}/2)$$

A detailed explanation of the modified objective function
These expressions R and F in the objective function influence the travelling cost component of the handling costs based on the decision variables gamma and beta. To fully understand further explanation of the objective function the following statement is very important: <u>All the handling costs are calculated based on an 80/20 ratio</u>. So, for example, let's say the handling costs in the reserve area/flow 1 is 10 euros under an 80/20 ratio and the RTTR is 70% which means seven euros is due to travelling costs and three euros is due to other costs components. Suppose the model chooses a beta of 0.9 instead of a beta of 0.8, upon which the handling costs were based, the travelling cost component of the handling costs in the reserve area should be increased by a factor of 0.9/0.8 which is represented by the $\frac{\beta}{0{,}8}$ part of the formula. If the rest of the formula is also filled out the following is obtained: $\left(\frac{0.9}{0.8} * 0.7 + (1 - 0.7)\right) = (1.125 * 0.7 + 0.3) = 1.0875$. This implies that the handling costs are increased by 8,75% by increasing only the travelling cost component by 12.5%. This also works vice versa if the beta is decreased.

Another expression that needs a proper explanation focuses on the calculation of the handling costs of flow 2 based on the handling costs of flow 1 and 3:

$$\sum_{i=1}^{n}\left(FH_{i,3} + \frac{(FH_{i,3} + RH_{i,1})}{d_i}\right)\lambda_i X_{i,2}$$

Flow 2 encompasses the cost from flow 3 plus the costs of replenishments. First off, the costs of flow 3 are incorporated because a pick is being made from the fast pick area. Secondly, to perform a replenishment order an employee must walk in both the fast pick area and the reserve area, which is represented by $H_{i,1} + H_{i,3}$. However, multiple unit loads are replenished in one replenishment run so the costs need to be spread over the number of unit loads in the replenishment run which is equal to d_i. The costs of packaging in $H_{i,1} + H_{i,3}$ are still taken into account for the breaking down of pallets or the unpacking of products from boxes if necessary or any other handling components involve d with replenishment.

Non-linearity

A problem that does arise by modifying the objective function this way is that the linear programming model changes into a non-linear programming model because decision variables are multiplied by one another. However, solvers like AIMMS are shown to compute this model in a matter of seconds and the solver automatically recognizes the non-linearity of the problem. Even though AIMMS can solve this mathematical problem it would be even better to linearise the problem to guarantee an optimal solution. In the next section, the appendix of a paper is quoted which deals with linearising the product of binary-continuous variables which is the case with the mathematical model in this thesis because the beta and gamma are continuous and the x(i,j) variable is a binary variable. "To find a linear expression for the production of a binary variable (u) and a bounded continuous variable (P), we use a new continuous variable (Z) and the following inequality constraints:

$$P - (1-u)\bar{P} \leq Z \leq P - (1-u)\underline{P} \qquad (37)$$
$$u\underline{P} \leq Z \leq u\bar{P} \qquad (38)$$

If u = 1, then (37) enforces Z = P and (38) limits P within its bounds. If u = 0, then (38) enforces Z = 0 and (37) is the bounds on P. Therefore, Z is equivalent to u × P." (Shabanzadeh, Sheikh-El-Eslami, & Haghifam, 2017) To translate this to our problem the variable $\hat{\beta}_{i,j}$ would be the product of $X_{i,j}$ and β and the variable $\hat{\gamma}_{i,j}$ would be the product of $X_{i,j}$ and γ. The extra constraints that would be required are shown below where the upper and lower bounds of 1 and 0 are already implemented. In fact, constraints (5) and (6) give more precise bounds and are rewritten mathematically in a shorter way. Nonetheless, the upper bounds and lower bounds for the linearity constraints are kept at 0 and 1 because this way if the bounds in constraints (5) and (6) are changed the bounds in (7) (8) (9) (10) do not have to be changed which makes the model more flexible with other inputs.

$$\beta - (1 - X_{i,j}) * 1 \leq \hat{\beta}_{i,j} \leq \beta - (1 - X_{i,j}) * 0$$
$$X_{i,j} * 0 \leq \hat{\beta}_{i,j} \leq X_{i,j} * 1$$
$$\gamma - (1 - X_{i,j}) * 1 \leq \hat{\gamma}_{i,j} \leq \gamma - (1 - X_{i,j}) * 0$$
$$X_{i,j} * 0 \leq \hat{\gamma}_{i,j} \leq X_{i,j} * 1$$

The linear modified objective function is as follows:

$$
\min: 2 * \left(\sum_{i=1}^{n} \left(\frac{\hat{\beta}_{i,1}}{0,8} * RTTR \right) H_{i,1}\lambda_i + \sum_{i=1}^{n} (1 - RTTR) X_{i,1} H_{i,1} \lambda_i \right.
$$

$$
+ \sum_{i=1}^{n} \left(\left(\frac{\hat{\gamma}_{i,2}}{0,2} * RTTF \right) H_{i,3} + \frac{\left(\left(\frac{\hat{\gamma}_{i,2}}{0,2} * RTTF \right) H_{i,3} + \left(\frac{\hat{\beta}_{i,2}}{0,8} * RTTR \right) H_{i,1} \right)}{d_i} \right) \lambda_i
$$

$$
+ \sum_{i=1}^{n} \left(X_{i,2}(1 - RTTF) H_{i,3} + \frac{(X_{i,2}(1 - RTTF) H_{i,3} + X_{i,2}(1 - RTTR) H_{i,1})}{d_i} \right) \lambda_i
$$

$$
\left. + \sum_{i=1}^{n} \left(\frac{\gamma}{0,2} * RTTF + (1 - RTTF) \right) H_{i,3} \lambda_i X_{i,3} + \sum_{i=1}^{n} \sum_{j=1}^{3} (C_{i,j} Q_i X_{i,j}/2) \right)
$$

$$
+ \sum_{i=1}^{n} \left(\frac{\hat{\gamma}_{i,3}}{0,2} * RTTF \right) H_{i,3} \lambda_i + \sum_{i=1}^{n} (1 - RTTF) X_{i,3} H_{i,3} \lambda_i + \sum_{i=1}^{n} \sum_{j=1}^{3} (C_{i,j} Q_i X_{i,j}/2)
$$

Constraints

$$
\sum_{j=1}^{3} X_{i,j} = 1 \ \forall i \tag{1}
$$

$$
\sum_{i=1}^{n} \left(\frac{Q_i S_i X_{i,1}}{2} \right) + \sum_{i=1}^{n} \left(\frac{p_i Q_i S_i X_{i,2}}{2} \right) \leq b\beta \mathrm{TS} \tag{2}
$$

$$
\sum_{i=1}^{n} \left(\frac{(1 - p_i) Q_i S_i X_{i,2}}{2} \right) + \sum_{i=1}^{n} \left(\frac{Q_i S_i X_{i,3}}{2} \right) \leq c\gamma \mathrm{TS} \tag{3}
$$

$$
\beta + \gamma = 1 \tag{4}
$$

$$
0,7 \leq \beta \leq 0.9 \tag{5}
$$

$$
0,1 \leq \gamma \leq 0.3 \tag{6}
$$

$$
\beta - (1 - X_{i,j}) \leq \hat{\beta}_{i,j} \leq \beta \tag{7}
$$

$$
0 \leq \hat{\beta}_{i,j} \leq X_{i,j} \tag{8}
$$

$$
\gamma - (1 - X_{i,j}) \leq \hat{\beta}_{i,j} \leq \gamma \tag{9}
$$

$$
0 \leq \hat{\beta}_{i,j} \leq X_{i,j} \tag{10}
$$

$$
X_{i,j} = 0 \text{ or } 1 \ \forall i, j \tag{11}
$$

Constraints (1) ensure that a product can only be assigned to one flow. Constraints (2) and (3) ensure that the space used by products in a functional area does not exceed the available space devoted to that functional area. Constraints (4) ensure that the ratio of floor space divided between the reserve area and the fast pick area is exactly 1 so that there is no unused floor space, and no floor space is assigned that is not available. Constraints (5) and (6) ensure the upper and lower limits of the functional areas are maintained. For this, the fast pick area can be a maximum of 30% of the total space in the warehouse and a minimum of 10% because fast pick areas smaller than this are not realistic and larger than this do not bring enough gains because the fast pick area will start becoming evenly large as the reserve area. Finally, constraints (7) till (10) are required to make the problem linear and (11) are the sign restrictions.

Defining parameters

i: number of products, i = 1, 2, ... , n

The total number of SKUs that are stock holding at PoolPlaza is 625. However, because the problem is NP-hard it would be beneficial for the computational time to reduce the number of possible decision variables. Products that have not been sold in the past year have been left out which are 226 products. Next to that, SKUs with less than 0.1 m^3 yearly volume sold are left out which are 228 SKUs. This amounts to 4.61 m^3 yearly volume on a total yearly volume over all products of 259.49 m^3. In practice, one extra box rack could handle this 4.61 m^3 yearly volume so it would make no sense to include this in the mathematical model and increase the computational time immensely. By excluding these products 170 SKUs remain which means n = 170.

Annual demand rate of product i in unit loads

This parameter is based on the number of units loads sold per year and it provided by PoolPlaza

Order cost for product j

For the order cost per supplier, an estimation has been provided about how much email it takes to place an order with an average of five minutes per email which results in costs against an hourly rate of €26.25 per hour for an average purchaser. Next to that, per supplier, it has been determined whether the amount of time it takes to handle incoming goods is low, medium or high representing 10, 20 or 30 minutes on average respectively per order. The costs are then calculated against an hourly rate of €20 for an average warehouse employee. There are no fixed order costs per supplier that are charged by the supplier itself.

Average percentage of time a unit load of product i spends in reserve area if product is assigned to material flow 3

For this parameter, an estimation of 90% is chosen. It should be mentioned that this parameter relates to the decision variable gamma. Because if overall items spend less time in the fast pick area can become smaller but with more replenishments and vice versa. This is an aspect that is considered with the fluid model that chooses the number of units in the fast pick area based upon the size of the fast pick area instead of the other way around. Even though gamma, beta and p(i) are loosely connected by the constraints (2) and (3), it could be possible to connect them more closely by connecting p(i) and beta directly by an equality based on the fluid model. However, this would also make the model much more complicated and therefore increase the computational time. Furthermore, in the quality based on the fluid model, there would still be estimation required which comes down to estimating p(i). All this complexity does not weigh up to the benefits that it brings since the outcome will only be used for two other parts in this thesis:

- The SLP analysis in the next section of this chapter which determines the rough layout and if, the fast pick area would become 10% larger or smaller it would have little to no effect on the outcome of the floor plan.
- Determining how many unit loads of certain SKUs are put in the fast pick area. Once the final layout of the warehouse has been implemented it would also be little effort to run the analysis again and reimplement the new amount of unit loads per SKU.

Another reasoning for p(i) of 0.9 would be based on a practical example: with a certain sand filtration system, there are about 16 units in the “fast pick” in the current warehouse with about 180 units on stock in total. This is a scenario just after a replenishment cycle from a stock level of 0 and with other top-performing SKUs, this percentage tends to be around 10%. So, if 10% of the stock is in the fast pick area and 90% is in the reserve area this is also the dispersion of time an SKU spends in the fast pick area.

All in all, the p(i) parameter is chosen at 0.9 based on practical examples and a sensitivity analysis will be performed to see the effect of this parameter on the costs.

b,c levels of space available in the vertical dimension in each functional area, b = reserve and c = forward,

The reserve area should be used as efficiently as possible, and it is assumed that the pallet racks reach the roof. The building is 8m tall so let's assume we can build pallet racks seven meters high which makes b = 7.

The forward area should maybe be kept lower because you would want to pick SKUs fast without using forklifts or other heavy lifting equipment. Let's initially take b = 2m. Above this fast pick area, a mezzanine can be made to make up for the lost space. However, this is excluded from the scope due to its complexity.

Cost of handling a unit load of product i in material flow j

Flow 1 encompasses that products are stored in the reserve area and retrieved from it. If it is assumed that the fast pick area is 20%(138 m^2) of the total area (690 m^2) the area would be something like 24x24 and the average travel distance would be 48m which would take about 35 seconds with a traversal speed of 5km/h. Furthermore, 38 seconds are taken for the average time to prepare a package for shipping. However, SKUs in the fast pick area are often stacked in pallet racks for which heavy lifting equipment is required and the products also need to be packed for shipment. To incorporate costs of heavy lifting equipment, authorized personnel to operate them and storing a product in the reserve area the cost is increased from 35 + 38 seconds to 3*35 + 38 = 143 seconds. With an hourly rate of 20 euros, this would result in 0.79 euro handling costs on average per item.

To make the handling costs dependent on the volume of an SKU, the following formulas are provided with 0.02 m^3 being the average volume of an SKU and 0.7865 m^3 being the maximum. The minimum costs here are 0.53 cents and the maximum costs are 1.59 cents:

$$for\ 0.0001 \leq\ v_i \leq 0.02 : H_{i,1} = 0.53 + \frac{v_i}{0.02} * 0.26$$

$$for\ 0.02 <\ v_i \leq 0.7865 :\ H_{i,1} = 0.79 + \frac{v_i}{0.7865} * 0.79$$

For example, if v(i) is 0.01 which is an SKU half the size than the average SKU the formula would obtain 0.53 + 0.01/0.02 * 0.26 = 0.66. An SKU with a v(i) of 0.02 would result in 1.50 euro costs. For an SKU with a volume above the average with v(i) is 0.1 the cost would be 0.79 + 0.1/0.7865 * 0.79 = 0.92 euro.

The formula was cut up into two sections to ensure that the average costs were right at the point where the average volume per unit would be and that from there on picking costs would reduce or increase based on volume.

Flow 3 encompasses that products are stored in the fast pick area and retrieved from it. Using the same calculating method as with flow 1 it takes 17 seconds on average to pick an SKU from the fast pick area and this is increased to 55 seconds to account for the time to pack the product for shipment which would cost 0.31 cents to pick something from the fast pick area. The same formulas with flow 1 can be used here. The minimum costs here are 0.20 cents and the maximum costs are 0.62 cents.

$$for\ 0.0001 \leq\ v_i \leq 0.02 : H_{i,3} = 0.2 + \frac{v_i}{0.02} * 0.11$$

$$for\ 0.02 <\ v_i \leq 0.7865 :\ H_{i,3} = 0.31 + \frac{v_i}{0.7865} * 0.31$$

As explained in the objective function, the costs for flow 2 are based on the costs of flows 1, 3 and the replenishment size d_i.

Cost of storing a unit load of product i in material flow j per year

As mentioned in the paper of Heragu, Du, Mantel & Schuur (2005), storage costs should not be confused with inventory holding costs. The fast pick area should have a prime cost per m^3 as opposed to the reserve area to make the trade-off between handling costs and storage costs. The yearly costs of the warehouse are approximated by PooPlaza at 40.000 euros. There is 690 m^2 * 7m = 4830 m^3 available for the fast pick area and reserve area. At PoolPlaza wide aisle pallet racking is used due to the usage of forklifts. Due to the usage of wide aisle pallet racking 50% of the floor space is utilized and 70% of the height (Richards, 2011). By reducing the available storage space with this unutilized space, the following cubic meters of storage is obtained: 4830 * 0.5 * 0.7 = 1690,5 m^3. If 40.000 is divided by 1690.5 the costs per m^3 per year are obtained which is € 23.66. The fast pick area in this model is 2 meters high and the reserve 7 meters high. It is convenient to make the fast pick area 7/2 = 3.5 times more expensive in holding costs which is € 82.82 per m^3 per year. This price per m^3 per year can be multiplied by the volume per SKU to make the storage costs a function of the SKU volume. For flow 3, 90% of the dwell time is against the lower tariff and 10% against the higher tariff.

$$C_{i,2} = v_i * 23.66$$
$$C_{i,3} = v_i * 23.66 * p_i + v_i * 82.82 * (1 - p_i)$$
$$C_{i,4} = v_i * 82.82$$

Sometimes the storage costs are rounded to 0.00 euros because the SKUs are so small. In these cases, 0.01, 0.02 and 0.04 euro has been taken as a minimum for flow 1, 2 and 3 respectively.

<u>Si space required for storing a unit load of product i,</u>

The volume size of a single unit is provided by PoolPlaza

<u>TS total available storage space</u>

The total space for the fast pick and reserve area is 690 m^2. As mentioned before 50% of the floor space is lost due to the wide aisle pallet racking which leaves 435 m^2.

However, when the model was first initialized it was found that the current data does not require 435 m^2. This is because PoolPlaza purchases a warehouse to prepare for the next coming years and therefore with the current data the warehouse would be too large. To make an appropriate model the total space was reduced to be in line with the currently available order quantities and annual demand. The peak volume of the order quantities overall SKUs amounts to 109 m^3. With a p_i of 0.9, an upper limit of 0,3 for gamma and a height of 2 meters the following average height of the warehouse can be calculated in the case that the fast pick area is as large as possible and therefore the square meters (TS) to accommodate for the SKUs needs to be the largest:

$$\big((1 - p_i) * 0.3 * 2\big) + \big((1 - p_i) * 0.7 * 7\big)$$

This way TS is largest enough for each possible value of gamma and beta. If we divide the peak volume for all SKUs by the average height calculated for the scenario with a gamma of 0,3 the following TS is obtained:

$$\frac{109}{\big((1 - p_i) * 0.3 * 2\big) + \big((1 - p_i) * 0.7 * 7\big)} = 24.38$$

<u>Qi order quantity for product i (in unit loads) (based on EOQ)</u>

Originally the model Heragu, Du, Mantel & Schuur (2005) uses the EOQ model for the order quantities. However, since the number of SKUs was limited to 170, PoolPlaza was able to provide realistic order quantities which they would use. This would represent the reality of PoolPlaza better and is therefore used in the modified model.

RTTF and RTTR

As explained in the section on the objective function, RTTF and RTTR ensure that the gamma and beta only increase or decrease the travel time costs of the handling costs. For the fast pick area, the travel time is 17 seconds, and the packing time is 38 seconds therefore the RTTR is 31%. For the reserve area, the travel time is 105 seconds, and the packing time is 38 seconds therefore the RRF is 73%.

Results

By running the model in AIMMS the following results are obtained:

- Total costs: € 8085.70
- Beta: 0.88
- Gamma: 0.12
- SKUs assigned to flow 1: 62 SKUs assigned to flow 2: 108 SKUs assigned to flow 3: 0

It should be noted that both the nonlinear modified objective function and the linear modified objective function provide the same solution which is also a nice way of proofing the non-linearity is executed successfully.

To run a sensitivity analysis on p_i the model has also been run for 0,7 and 0,8 p_i and the following results are obtained:

- With $p_i = 0.8$
- Total costs: € 8528.52
- Beta: 0.87
- Gamma: 0.13
- SKUs assigned to flow 1: 81 SKUs assigned to flow 2: 86 SKUs assigned to flow 3: 3

- With $p_i = 0.7$
- Total costs: € 8786.53
- Beta: 0.84
- Gamma: 0.16
- SKUs assigned to flow 1: 92 SKUs assigned to flow 2: 74 SKUs assigned to flow 3: 4

However, by discussing the results with PoolPlaza, the p_i only increases the costs due to the need for a larger fast pick area. Next to that, checking various SKUs the initial model with $p_i = 0.9$ assigns more "logical" flows to certain SKUs. For example, SKU 3 is a top-selling item that is picked often during the swimming season which is assigned to flow 2 with $p_i = 0.9$ but assigned to flow 1 with $p_i = 0.7$ which makes less sense. Furthermore, in general, it is seen that large SKUs with few units on a pallet or inside a box are put in flow 1 which makes sense because it is expensive to replenish larger products with few unit loads in a replenishment. Due to these reasons, the solution provided with $p_i = 0.9$ has been accepted as final. This means the fast pick area is assigned 12% of the available 690 m^2 which amounts to 82,8 m^2 which is rounded to 85 m^2 for the sake of simplicity. The reserve is assigned the remaining 605 m^2.

With all the square meters assigned to each functional area, the initial layout constructed is shown below in Figure 8. The idea of this initial layout is that the materials flow through the warehouse in an inverted U shape (represented by the blue arrows) and the offices and shop are connected to the side where the most activity is between the warehouse, shop and offices (represented by the red arrows).

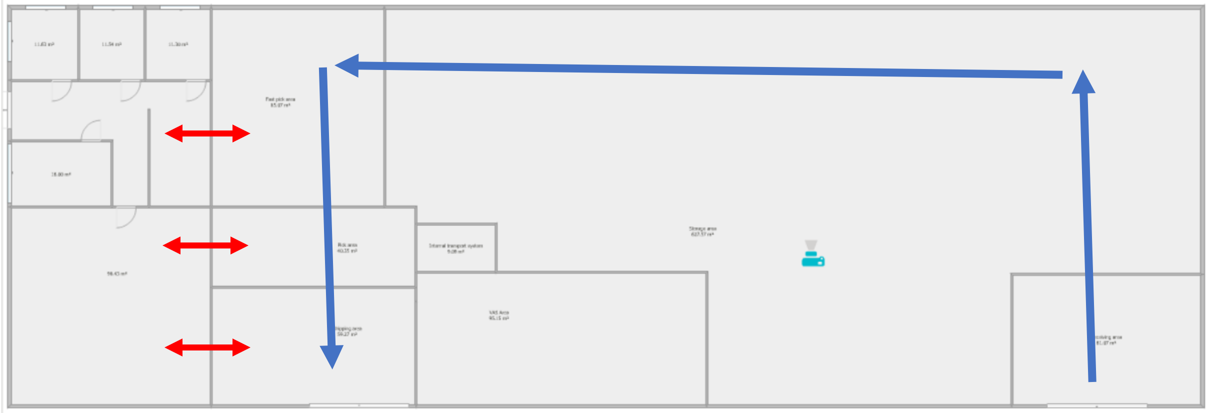


Figure 8 - Initial layout

Optimality gap

To determine how optimal the solution is the values of gamma and beta can be fixed to make the model linear once more. The nonlinear objective function in Appendix N can be used in this instance because if gamma and beta are fixed the objective function is linear again. It has also shown that both the linear modified objective function and the objective function provided the same optimal solution. The reason why the linearized objective function is not used for this is because gamma, beta and x(i,j) are mixed into their new variables providing a double purpose. If each new variable is fixated on beta 0.88 and gamma 0.12 it also immediately implies that x(i,j) = 1 for each i and j which is not feasible.

As shown below the optimality gap is only € 14.67 which is only a difference of 0.18%. Also, the assignment of SKUs to the flows is almost the same except for one SKU which changes from flow 1 to flow 3.

- Total costs: € 8071.03
- Beta: 0.88
- Gamma: 0.12
- SKUs assigned to flow 1: 62 SKUs assigned to flow 2: 108 SKUs assigned to flow 3: 0

To further test the optimality of our solution the binary variables can be relaxed to take any values between 0 and 1. However, the exact same results were found as with the first relaxation. To prove that the relaxation of binary variables do work properly the model was also run with a p_i of 0.8 and it was found that x(5,1) = 0.45 and x(5,2) = 0.55.

4.4 Systematic Layout Planning (SLP)

Now that the exact square meters per functional area are known and an initial layout of the warehouse has been made, the layout should be optimized with a systematic layout planning approach to minimize congestion with regard to the flow of materials and people. This refers to step 1c from the stepwise approach.

''SLP begins with PQRST (Product, Quantity, Routing, Supporting and Time) analysis for the overall production activities. There are three main steps in SLP: relationship diagram, Space relationship diagram and evaluation. The relationship diagram shows the importance of each department/ area concerning each other. It includes logistics relationships diagram, non-logistics relationships and comprehensive relationships.'' (Lin, Liu, Wang, & Liu, 2013)

In Lin et al. (2013) the logistic relationship chart is based on the logistic intensity which is then given a closeness rating. ''Closeness rating matrix determines how desirable it is to place certain facilities close to each other.'' (Samarghandi, Taabayan, & Behroozi, 2013) In the paper of Lin et al. (2013) the ratings were divided into A, E, I, O, U with A being the most favourable with 4 points and U the least favourable with 0 points. The codes below represent the reason why a certain relationship is given a closeness rating:

1. Quantity of flow
2. Cost of material handling
3. Equipment used in material handling
4. Communication needed
5. Personnel needed
6. Separation needed

To create a comprehensive relationship diagram both the non-logistics relationship diagram and logistics relationship diagram are required. However, at PoolPlaza there is no tracking of information flows or material flows between departments so it will be hard to quantify this. To determine the closeness rating a survey will be conducted at PoolPlaza where the employees are asked which departments, they think, should be close to one another and for what reason. The survey and the results of this survey can be found in Appendix O. Before employees will fill out the survey, they will first be introduced to various factors that could be contributing to departments being near to each other. This is to make sure that the employees take not only material flows into account which might be the first intuition when asked this question.

Based on the information retrieved from the survey the following closeness ratings are determined based on rounded averages. The comprehensive diagram and the activity relationship diagram resulting from the surveys are shown in Appendix P.

The first block layout is presented in Appendix Q. As can be seen from the block layout there are a lot of conflicts between links crossing each other. However, on the other hand, it can also be seen that the connections with three or four links are often next to each which is a good thing because this implies that the most important relations are close to each other. But with so many departments and connections, it can be easily derived that the solution becomes very restrictive and hard to solve.

To relax the model, each letter in the activity relations diagram is downscaled one level and the resulting first block layout is shown in Appendix R. Only the departments that are necessary to connect remain in the model and the connections that are of lesser importance are removed to obtain a reasonable solution. As shown in Appendix R, the first block layout has four conflicts. In Appendix S other block layouts are presented and by providing alternative solutions, a better solution was found with only one conflicting link. The block layout with the least amount of conflicting links is also shown below. Other block layouts were also evaluated but the alternatives in the appendix were the most promising. The final layout of the warehouse will be presented in section 3.4 after discussing the pallet rack placement.

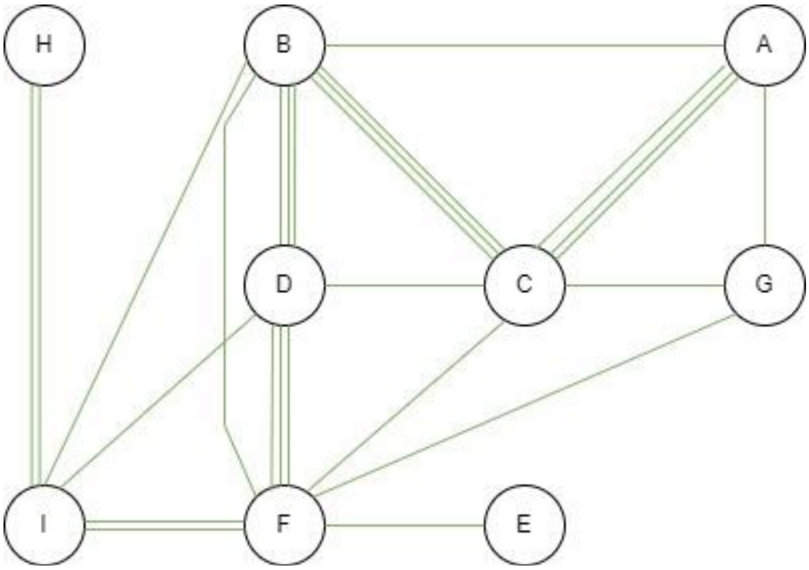


Figure 9 - Best found block layout. A = receiving area, B = Fast pick area, C = Reserve area, D = Order picking area, E = VAS area, F = Shipping area, G = Internal transport system, H = Offices, I = Shop

4.5 Pallet racks placement and cross aisles

At this point, an optimized layout has been determined with the SLP analysis. The next step (1d) in the stepwise approach refers to the placement of pallet racks and cross-aisle which are part of the layout of the warehouse.

Because there is a single command picking strategy the average walking distance is always the same no matter how the pallet racks are placed and whether cross aisles are implemented or not. It will always be the horizontal meters plus the vertical walking meters. However, it was found with the sketching program that with a horizontal setup more pallet racks could be placed and for that simple reason, the horizontal pallet rack placement is chosen. There are also cross aisles implanted even though in theory this does not help the average travelling distance in a single command warehouse. There are three reasons why cross aisles are still implemented:

- In the future routing policies might be applied and the single command structure might be replaced. In this situation, cross aisles are preferred.
- If a picker or warehouse employee makes a mistake by going in the wrong aisle it can be easily corrected by choosing a cross-aisle.
- If a picker wants to pick multiple items on a single run based on intuition, he/she can use cross aisles to reduce the travelling distance. If an employee wants to deviate from the single command policy to reduce the travelling distance based on choosing an intuition-based route this is of course allowed.

On further notice, the fast pick area is slightly increased to about 110 m^2 because that way exactly two pallet rack rows and one box rack aisle fit in the fast pick area and otherwise there is wasted space. With the dimensioning of all the functional areas, the SLP provided layout, the placement of pallet racks and the adjustment to the fast pick area the final layout of the warehouse is provided below and in Appendix T.

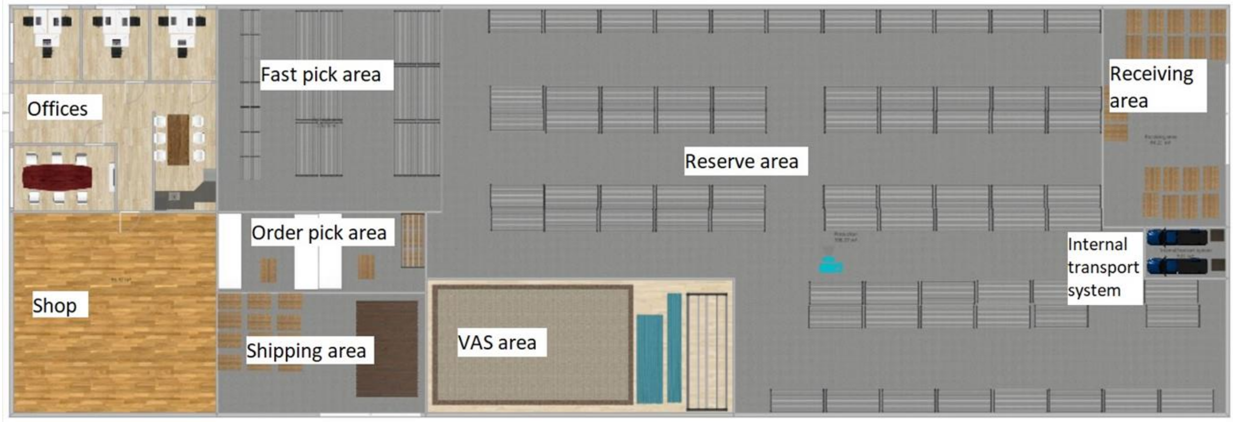


Figure 10 - Final layout of the warehouse

4.6 Facility layout conclusion

The most important takeaways from the facility layout chapter are that 510 m^2 is devoted to the supporting functional areas which are not storing SKUs and 690 m^2 is devoted to the fast pick area and the reserve area. With a linear programming model, it was found that 85 m^2 is devoted to the fast pick area and 605 m^2 to the reserve area. The 85m2 is increased to 115 m^2 due to the pallet rack block's fixed dimensions and room for aisles. The initial layout is improved with an SLP approach which resulted in the layout shown above. Finally, the pallet racks in the fast pick area are placed vertically, in the reserve area horizontally and cross aisles are included to make the warehouse future proof.

5 Space allocation

With the layout and pallet rack placement known the next step is to determine the peak stock level the warehouse needs to be able to handle and in what storage mediums to store SKUs. Next to that, it should be determined which SKUs are stored (also) in the fast pick area and how many unit loads per SKU should be assigned to the fast pick area. This is done by the labour efficiency heuristic in combination with the fluid model in sections 5.3 and 5.4. This refers to steps 2c and 2d from the stepwise approach.

One might argue that the peak stock level is not required if the purchasing orders and receiving of goods are planned not to all arrive at once. However, at PoolPlaza this could be the case due to the demand of the market. In this thesis, the warehouse is prepared for a worst-case scenario. Leftover space can always be used for growth, new products or products for which the demand has stagnated. To determine the peak stock level each SKU is assigned a fill rate and an inventory policy in 5.1. Based on historical data the policy parameters will be determined from which the peak stock level can be determined and based on the peak volume storage medium can be chosen. The peak stock volume is used to determine the storage medium since this represents the number of unit loads received. This refers to steps 2a and 2b from the stepwise approach.

5.1. Space assignment reserve area

In this chapter of the thesis, the focus is mainly on how to store SKUs and in what quantities to store them in the reserve area and the fast pick area. To determine how much to store of each SKU, the peak on-hand inventory levels should be calculated, and these can be determined by the inventory policies assigned to each SKU. The inventory policies do require some preliminary analyses which are as followed:

- Inventory policy assignment
- Lead time
- Review period
- Fill rate (based on an ABC-XYZ analysis)
- Inventory carrying cost rate

Inventory policy assignment

To determine which inventory policy should be assigned to SKUs an ABC analysis is performed. The idea behind determining inventory policies based on an ABC analysis is that the SKUs that account for most of the revenue get inventory policies that are more complex but also more rewarding and therefore SKUs that account for more revenue receive more attention. The s,S model has shown to outperform the s,Q model in total costs (replenishment, inventory and shortage costs) but a fixed variable lot size may not always be practical due to material handling. However, it also mentions that it is harder to find good approximations for the input of the s,S system. (Silver, Pyke, & Thomas, 2016) This perfectly describes that inventory policies for class A perform better and require more attention to define good input parameters although also justified because these SKUs are in class A.

Below is a summary of the ABC analysis at PoolPlaza where the volume is the yearly volume sold:

Class	% of SKUs	Cum revenue %	Revenue %	Cum volume %	volume %
A	20%	90,72%	90,72%	82,26%	82,26%
B	30%	99,77%	9,04%	99,87%	17,61%
C	50%	100%	0,23%	100,00%	0,13%

Table 2 - Revenue ABC analysis over all SKUs

As explained in the literature study the following inventory policies are assigned to the ABC classes (Silver, Pyke, & Thomas, 2016) It should be mentioned that SKUs without sales data are excluded from the inventory policy analysis because without data the parameters cannot be calculated.

ABC class	Continuous inventory policy	Periodic inventory policy
A	s,S	R,s,S
B	s,Q	R,s,Q
C	R,S	Simple R,s,Q or R,S

Table 3 - Inventory policy assignment based on ABC classification

Review period and lead times

For PoolPlaza it could be argued that the review period is one day because the system that PoolPlaza works with checks inventory levels daily and can create concept purchase orders based on those levels. However, for the sake of purchaser time savings and transportation savings, it is beneficial to review these products each respective period. For suppliers further away this review period is set higher compared to suppliers close. This is because, for example, with a supplier in China you might have to fill a whole container to get the order shipped and there are about three containers per year arriving from a specific Chinese supplier so this would mean the review period should be around 120 days. On the other hand, suppliers in Germany and the Netherlands often have free shipping costs after 200 euros for example and therefore these review periods could be set to lower values. Based on the supplier of a product the review periods and lead times are defined.

Origin supplier	Lead time	Review period
Netherlands, Germany	3	15
Czech Republic	10	30
China	120	60

Table 4 - Lead time and review period of suppliers per country of origin

To get the average demand during the lead time and review period the daily demand is simply multiplied by the duration of the period. To obtain the standard deviation of the lead time or review period, the daily standard deviation is multiplied by the square root of the duration of the period. (Silver, Pyke, & Thomas, 2016)

Item fill rate

Next to the ABC analysis, inventory policies, lead times and review periods the item fill rates are also required as input for the inventory policies. The item fill rate refers to the percentage of demand fulfilled directly from stock. (Silver, Pyke, & Thomas, 2016) Based on an ABC analysis in combination with an XYZ analysis fill rates can be assigned. An XYZ analysis refers to the uncertainty of demand of an SKU and is based on the coefficient of variation. This implies that if the demand of an SKU is uncertain it is assigned a lower item fill rate. The coefficient of variation of an SKU can be obtained by dividing the standard deviation of the daily demand by the average daily demand of an SKU. If the coefficient of variation is below 0.5 an X is assigned, if the value lies between 0.5 and 1 an Y is assigned and if it is higher than 1 a Z is assigned. In Table 5 below the item fill rates per ABC and XYZ combination are provided:

Combination	Item fill rate	Combination	Item fill rate	Combination	Item fill rate
AX	0.99	BX	0.9825	CX	0.975
AY	0.9825	BY	0.975	CY	0.95
AZ	0.975	BZ	0.95	CZ	0.95

Table 5 - Fill rate assignment based on ABC-XYZ classification

Inventory carrying cost rate

Another parameter that is required for the inventory policies is the inventory carrying cost rate. The inventory carrying cost rate encompasses the expenses a business incurs when it stores inventory. For example, rent and utility expenses can account for a business's carrying costs if it uses warehouse space or another facility to house its inventory. Insurance on unsold products is also a type of carrying cost, as is the opportunity cost of the value of the inventory that hasn't been sold yet. Many sources discuss and explain the carrying cost rate, but none provide an easy formula for companies and assume this is a given parameter (Silver, Pyke, & Thomas, 2016) (Nahmias & Olsen, 2015). (Silver, Pyke, & Thomas, 2016) further mention that for smaller companies this rate should be higher due to less liquidity.

There are however some sources that provide indications. "Typical holding costs, another name for inventory carrying costs, vary by industry and business size and often comprise 20% to 30% of total inventory value, and it increases the longer you store an item before selling it.'' (McCue, 2020)

Another paper by Rajhans (2015) indicates that generally, the inventory carrying cost rate is 18% and provides a mathematical model to calculate this. However, this model would be too time-consuming to solve for a single parameter for the mathematical model in the chapter of the thesis.

Finally, a paper by Durlinger (2005) mentions that on average companies use 25% for the inventory carrying cost rate. He further specifies that it constitutes of three parts: Risk (10-16%), Space (3-6%), and Risk (2%-30%). Following the methodology provided by Durlinger (2005) a risk percentage of 14% seems realistic for PoolPlaza in consultation with PoolPlaza.

For space, it can be calculated that the cost per m^3 would be € 28,39 for PoolPlaza and that on average in a single m^3 1046,98 euros worth of products can be stored based on the average purchasing price and average product size. If we divide the cost per m^3 of € 28.39 by € 1009.41 an answer of 0.0234 is obtained. This means that the spacing cost for PoolPlaza would be 2.34%. Of course, this is a rough assumption, but it would provide enough indication that PoolPlaza would be at the lower end of the range for spacing which means 3% can be taken. Finally, for the products of PoolPlaza, there is little risk of products becoming obsolete but not as little as it is with rough materials such as steel and salt. Therefore, a percentage of 8% seems fitting for PoolPlaza. Adding all three components a percentage of 25% is obtained.

If the average is taken over all sources 22.67% is taken and considering that PoolPlaza is a small company and liquidity is scarce this percentage can be increased to 23.5%.

5.1.1 A SKUs: R,s,S

The approach that is used in this section is the approach from Silver, Pyke and Thomas (SPT) on pages 335/336. (Silver, Pyke, & Thomas, 2016) The review periods are already determined based on the origin of the supplier and resulting from this approach the reorder-level s and the order-up-to level S are derived, also taking undershoot into account. With R,s,S undershoot must be taken into account and therefore E[z] is integrated into the formulas which are shown in Appendix U. Below a graphical representation of the R,s,S inventory policy is provided.

Graphical representation R,s,S:

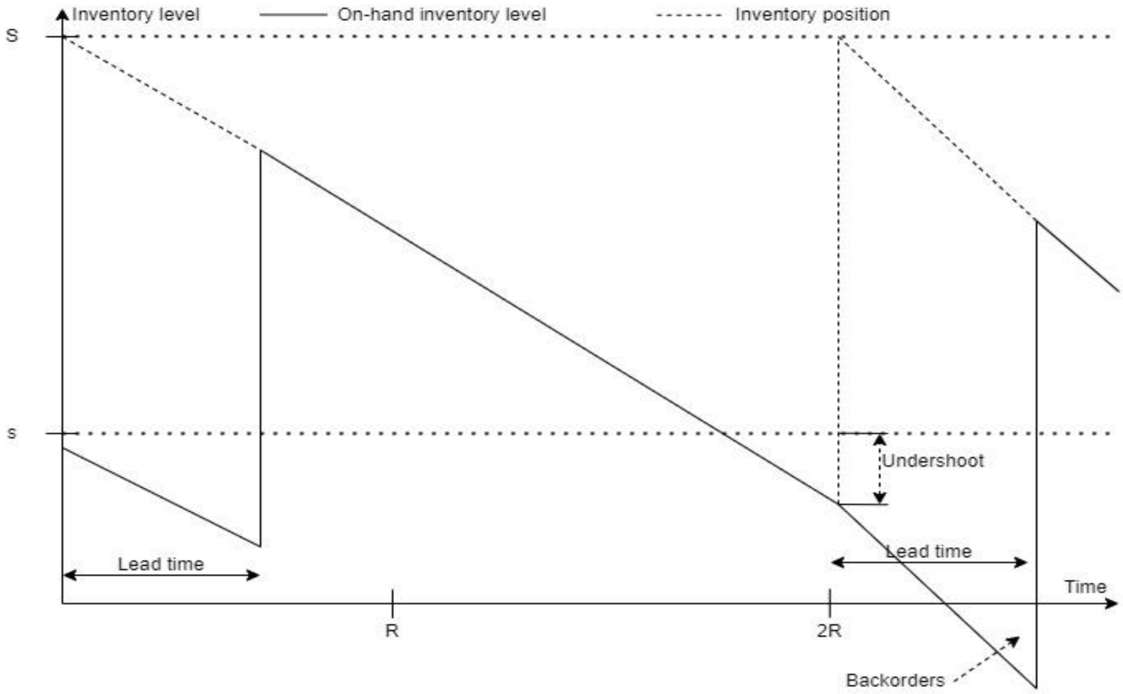


Figure 11 - Illustration of R,s,S inventory policy

5.1.2 B SKUs: R, S

The stepwise approach to transforming the (s,Q) policy into the (R,S) policy is obtained from Silver, Pyke and Thomas (2016) on page 278. The formulas can be found in Appendix V and a graphical representation of the (s,Q) policy is presented below.

Graphical representation R,S:

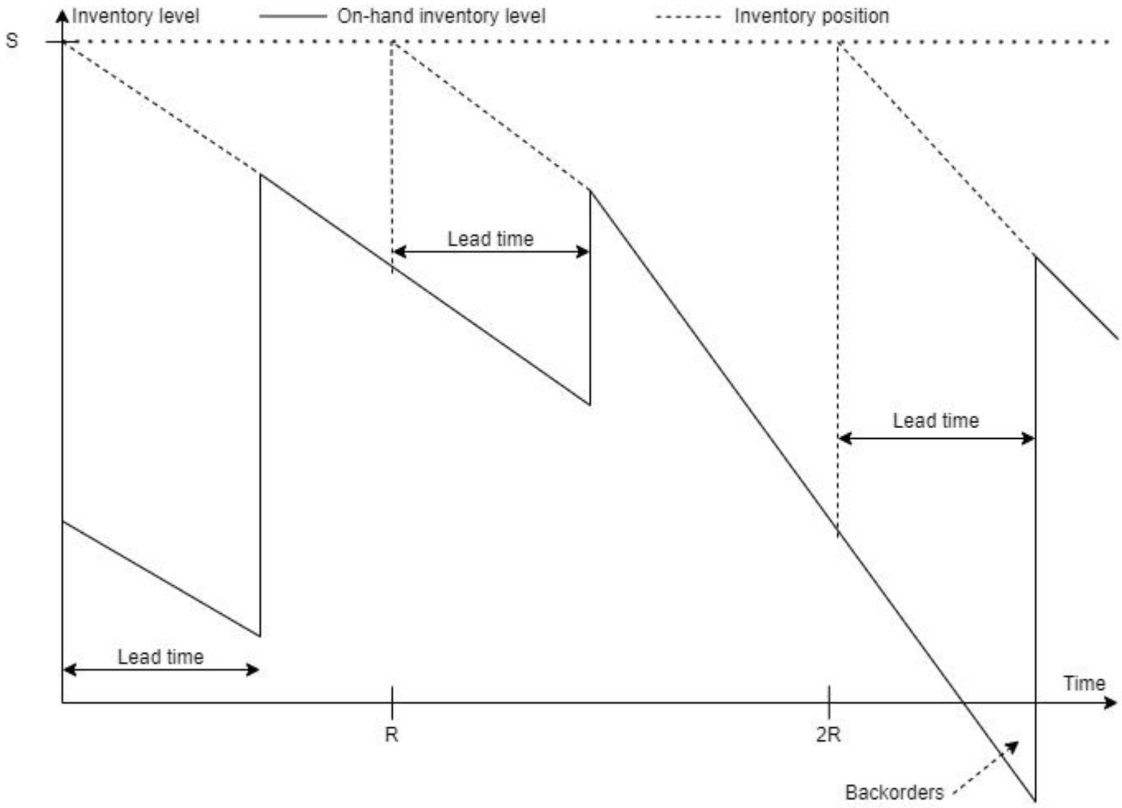


Figure 12 - - Illustration of R,S inventory policy

5.1.3 C SKUs: R,s,Q

As these SKUs are not as important as the A and B-SKUs the parameters are determined in an easier and quicker method. For the reorder point a simple approach based on the time between stockout occasions (TBS) is used. With this method, a very high TBS of 50 years is used to calculate k and make sure the SKUs are always sufficiently on stock. (Silver, Pyke, & Thomas, 2016) Even with this high TBS the safety factor (in this analysis) still only reaches a maximum value of 3.15 which ensures that the policy parameters are not becoming unrealistically high. In Appendix W the formulas are shown and a graphical representation of the R,s,Q inventory policy is provided below.

Graphical representation R,s,Q:

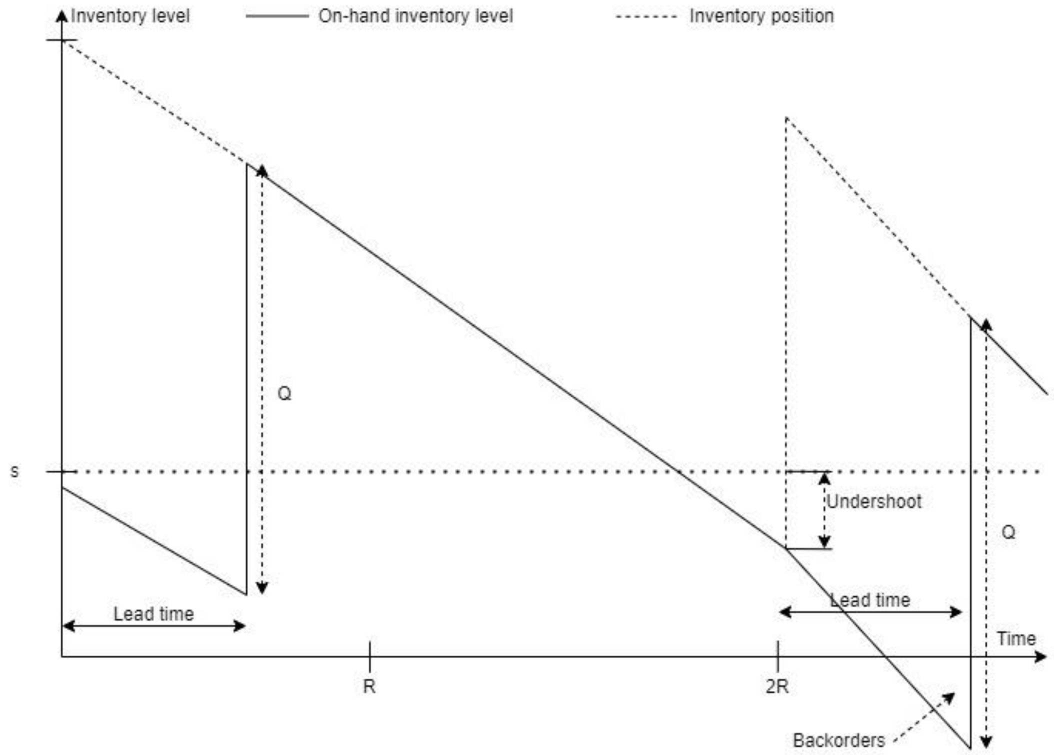


Figure 13 - Illustration of R,s,Q inventory policy

5.1.4 Discussion of results

For R,s,S everything with an s/S ratio above 70% was modified to an S level of s + Q. This was done because often the difference between s and S is so small that it makes no sense to order so little. Furthermore, sometimes the s and S level would both be 1 and this of course also does not make sense because those SKUs would need to be ordered constantly but always with an order quantity of zero. These illogical s and S levels can be explained due to the rounding of demand and very little demand over the lead time and review period. With R,S and R,s,Q there are no abnormalities detected and therefore no modifications applied.

With all the policy parameters defined the average stock and peak stock can be calculated in unit loads and in cubic meters. For each policy the average stock levels and peak stock levels are shown below:

- Average inventory level with R,s,S = $(S - D_l + s - D_{r+l})/2$
- Peak inventory level with R,s,S = $S - D_l$

- Average inventory level with R,S = $(S - D_l + S - D_{r+l})/2$
- Peak inventory level with R,S = $S - D_l$

- Average inventory level with R,s,Q = $(s + Q - D_l + s - D_{r+l})/2$
- Peak inventory level with R,s,S = $s + Q - D_l$

The peak and average inventory levels can be easily multiplied by the volume per SKU to express these levels in cubic meters. The following summarized data is obtained over all SKUs:

Sum of average inventory level (units)	4955
Sum of peak inventory level (units)	8272
Sum of average inventory level (m^3)	81,05
Sum of peak inventory level (m^3)	129,13

Table 6 - Summarized results of average and peak warehouse volume

5.2 Storage mediums

For each SKU the space required in the warehouse is now known. However, it is not known yet whether SKUs are stored in a box rack or a pallet rack which is addressed in this section. This refers to step 2b of the stepwise approach.

To determine whether SKUs should be stored in a box rack or pallet rack (or drawer) a rule of thumb is provided by Richards (2011) based upon the volume during peak stock levels which were also discussed in the literature study:

- Drawers: 0 to 0.125 m^3
- Box racks: 0.125 m^3 to 1.5 m^3
- Pallet racks: 1.5 m^3 and higher

However, with this rule applied only 22 SKUs of the 396 SKUs in total are assigned to pallet racks and the rest to box racks because drawers are not present at PoolPlaza. There are also some SKUs that are large SKUs that are ordered on a pallet that cannot be placed in box racks. If the rule of thumb is modified to the following the assignment of SKUs to storage mediums makes more sense:

- Box racks: 0 m^3 to 0.5 m^3
- Pallet racks: 0.5 m^3 and higher

With these parameters, 56 SKUs are assigned to pallet racks and the rest to box racks. For each SKU it will also be checked whether it is ordered in pallet sizes or carton sizes. If an SKU is assigned to box racks but is ordered in pallet sizes because the supplier delivers the SKUs on pallets and does not fit in box racks, the SKU is manually assigned to pallet racks. The same approach is applied vice versa for SKUs assigned to pallet racks, Although this approach is not very scientific, it should be mentioned that there is no right answer to the right type of storage medium that should be used because so many factors influence it (Richards, 2011). If in practice some assignments do not make sense they could be assigned otherwise easily. The following results are obtained:

SKUs assigned to pallet racks	102
SKUs assigned to box racks	294

Table 7 - Box rack and pallet racks assignment

5.3 Assigning SKUs to the fast pick area

At this point in the thesis, both the space required and storage medium per SKU are known. However, since PoolPlaza has both a fast pick area and a reserve area it should also be determined which SKUs are assigned to the fast pick area partially or completely. This refers to step 2c of the stepwise approach.

To determine which SKUs are assigned to the fast pick area the results from the mathematical model in chapter 3 are used in combination with the picking frequency and the labour efficiency ratio. It should be mentioned that in section 5.1 the space allocation has been expressed in cubic meters with the fluid model and the labor efficiency heuristic is also based on the fluid model. The fluid model assumes that SKUs are not discrete but continuous in their volume. However, the answers provided in 5.1 and 5.3 are divided by the volume per SKU and rounded up to provide a sensible concrete answer to PoolPlaza.

For each SKU the labor efficiency is calculated and SKUs with less than 10 picking frequencies are excluded. The labor efficiency formula is as followed:

$$Labor\ efficiency: \frac{p_i}{\sqrt{f_i}}$$

p_i : number of pickings yearly of SKU i
f_i : yearly volume of units sold of SKU i

This boundary of a yearly picking frequency of 10 was based on the yearly pickings of 3901 and determined in cooperation with the management PoolPlaza. It is argued that less than 10 pickings yearly gains too little in the reduced travelling costs to assign such an item to the fast pick area. By excluding SKUs with less than 10 picking frequencies yearly 98 SKUs remain. From these 98 SKUs, 67 SKUs are also assigned to the fast pick area by chapter 3 and overall have a high labour efficiency ratio. For these reasons, these 67 SKUs are assigned to the fast pick area.

The remaining 31 SKUs that have more than 10 yearly pickings but are not assigned to the fast pick area by chapter 3 are shown in Appendix X. The six SKUs shown in green are large SKUs which implies that the number of unit loads on a pallet is low and therefore the replenishment costs per unit load are high if these were put in the fast pick area. Furthermore, the labour efficiency ratio is relatively low with an average labor efficiency ratio of 37.94. Because of these two reasons and because of the results of the mathematical model of chapter 3 these six SKUs are not assigned to the fast pick area.

The remaining 25 SKUs in Appendix X which are not marked green are small SKUs and their summed yearly volume is only 1.182 cubic meters with 669 pickings yearly. Since these SKUs are very small, the replenishment costs are also low and the amount of fast pick area they would occupy is also low. Next to that, these SKUs still account for 669 pickings, which is 17.15% of the total yearly pickings of 3901, which is a significant amount. Finally, the labour efficiency ratio of these 25 SKUs is mostly above the average of 37.94 and in some cases far above the average.

The reason why these SKUs were not assigned to the fast pick area in chapter 3 is because these SKUs have less than 0.1 cubic meters yearly sold volume. In chapter 3 this made sense because at that point only the size of the fast pick area was important and SKUs with low yearly volume were excluded due to their insignificance on the output and the speed of the computational time. This is also the reason why in this chapter the picking frequency and labor efficiency ratio are also considered.

Due to the reasons mentioned above, 25 SKUs are assigned to the fast pick area even though the results of chapter 3 say otherwise. In total, 92 SKUs are assigned to the fast pick area and 305 SKUs are assigned to the reserve area.

5.4 Allocating fast pick area space to SKUs

With 5.3 completed, the SKUs assigned to the fast pick area are now determined. However, it is not determined yet how many unit loads of each SKU are devoted to the fast pick area. This section of the thesis will address this problem and this refers to step 2d of the stepwise approach.

The formula to determine how much space each SKU is assigned in the fast pick area is as follows:

$$v_i = \frac{\sqrt{f_i}}{\sum_{j=1}^{n} \sqrt{f_i}} V$$

f_i = yearly volume of units sold of SKU i which is assigned to the fast pick area
v_i = fast pick area space assigned to SKU i
V = size of the fast pick area

However, if this method is applied with a fast pick area size of 85 m^2 and therefore 59.5 m^3 (considering space lost for movement and aisles), the number of unit loads that fit in each SKU's allocated space area is on average 97.82% of the yearly sales and therefore not realistic. This is because the future warehouse is much larger than the current sales require. To make a more realistic output, the volume of the fast pick area is reduced. In chapter 5.1 it was calculated that the peak volume was 129.13 m^3 and in chapter 3 it was found that with 90% time spend in the reserve area and 10% time spent in the fast pick area the costs would be minimal. So, the volume of the fast pick area in this section will be 0.1*129.13 = 12.9 m^3. One could argue that only 92 SKUs are assigned to the fast pick area instead of all SKUs and therefore this peak volume of 129.13 m^3 is not justified. However, to counter the statement, it could be argued that the 92 SKUs selected for the fast pick area account for most of the yearly volume which is why the SKUs were selected in the first place for the fast pick area and therefore 12.9 m^3 is representative for the size of the fast pick area.

The results show that with 12.9 m^3 the average assigned unit loads to the fast pick area compared to the yearly sales amounts to 25.6%. It could be stated that this should be reduced even further because SKUs spend 10% of their time in the fast pick area, however, the smaller SKUs and extensions below influence this average percentage significantly. Moreover, the results make sense with 12.9 m^3 according to the management of PoolPlaza.

There are four extensions in the book of Bartholdi and Hackman (2005) which are applicable for PoolPlaza.

1. The first extension considers the different replenishment costs per SKU since the base model assumes each replenishment is equal in costs, but this is not true in reality due to the size of SKUs. ''simply replace any appearance of f_i with the weighted flow = $f_i^{\wedge} = c_i * f_i$ and results describing the Optimal allocations still follow.'' (Bartholdi & Hackman, 2005) Next to a weighted yearly volume PoolPlaza also has different savings per pick per SKU, so each s is changed to s_i. The formula to determine how much space each SKU is assigned in the fast pick area changes to the following:

$$v_i = \frac{\sqrt{f_i^{\wedge}}}{\sum_{j=1}^{n} \sqrt{f_i^{\wedge}}} V$$

2. Secondly, there is an extension to prevent stockouts in the fast pick area by always making sure at least the lead time demand plus the safety stock is in the fast pick area. However, for

PoolPlaza this is not applicable since the company is relatively small and the person picking the products is also responsible for the restocking. When a stockout occurs in the fast pick area the person responsible can just perform the replenishment at that time.

3. Thirdly, an extension is presented to ensure a minimal amount is stored in the fast pick area. The formula for the net benefit of storing an SKU in the fast pick area is as follows:

$$s_i p_i - c_i \frac{\hat{f_i}}{v_i}$$

If this formula is set equal to 0 and solved for v_i the minimum sensible storage is shown in cubic meters per SKU. Any volume lower than this will result in a negative net benefit. This found volume rounded up and set as a minimum level. The formula for the minimal sensible storage is as follows:

$$\frac{c_i \hat{f_i}}{s_i p_i}$$

27 SKUs out of the 92 in total that are assigned to the fast pick area have a v_i below this minimum level and therefore the v_i is increased to this minimum level. In general, SKUs with a higher volume per unit load and therefore higher replenishment costs are influenced by this extension.

4. Fourthly, there is an extension that considers on-hand inventory levels. This extension determines which SKUs should be fully assigned to the fast pick area. ''There should be no separate reserve storage for any SKU in the fast pick area for which maximum on-hand inventory takes no more space than twice its minimum sensible storage amount.'' (Bartholdi & Hackman, 2005) This statement can be expressed by the formula below. If SKU i goes into the fast pick area and the maximum on-hand volume is not greater than twice the sensible storage the SKU goes into the fast pick area fully.

$$2\left(\frac{c_i \hat{f_i}}{s_i p_i}\right)$$

21 SKUs out of the 92 SKUs fall under this category and are therefore assigned a volume equal to their peak on-hand inventory levels. However, it should be mentioned that out of these 21 SKUs, 10 also hit the minimum sensible storage level and these are now fully in the fast pick area.

However, with all these extensions included there is still a problem that needs to be addressed. For smaller SKUs, the number of assigned units increases immensely with the square root formula provided at the beginning of this paragraph. However, an SKU can get not get more unit loads assigned in the fast pick area than its peak on-hand inventory level, so this is also set as a maximum value and if this maximum level is reached it automatically implies that this SKU is fully dedicated to the fast pick area. This latter limitation applies to 10 SKUs and it can be seen that this extension is only applied to SKUs with a lower volume per unit load.

To summarize further, 31 SKUs are fully dedicated to the fast pick area, 17 SKUs are set on their minimal sensible storage level and 44 SKUs are not influenced by any extension and are assigned the amount that was originally calculated with the weighted square root formula.

The amount of unit loads in the fast pick area is 2203 units with 19.3 m^3 assigned. This is higher than 12.9 m^3 because some SKUs were influenced by extensions as mentioned before but it still provides a realistic assignment of space. Furthermore, since the fast pick area is larger in reality, with 63 cubic metres, this outcome is more than acceptable. If all the picking frequencies are multiplied by the savings per pick from the fast pick area in total this would result in € 1289.83 in savings. If the restocking costs are subtracted, the net benefit of the current configuration amounts to € 828.93.

5.5 Space allocation conclusion

In total 123 SKUs are assigned to the R,s,S inventory policy, 186 SKUs to the R,S inventory policy and 87 SKUs to the R,s,Q inventory policy. The R,s,Q has so few SKUs even though it encompasses all the C classified SKUs because SKUs with zero demand are excluded from the thesis. Next, 102 SKUs are assigned to pallet racks and 294 SKUs to box racks based on their peak storage volume. To continue the space allocation SKUs are analysed on their labor efficiency and picking frequency to determine which SKUs to assign to the fast pick area. Finally, based on the fluid model and extensions of the fluid model it is determined how many unit loads of each SKU are stored in the fast pick area. In total, 92 SKUs are assigned to the fast pick area and 305 SKUs are assigned to the reserve area. Furthermore, in the fast pick area, 2203 unit loads (19.3 m^3) in total are stored.

6 Storage location allocation

At this point, it is known which SKUs are stored in the fast pick area or/and the reserve area, in what quantities they are stored, what their peak volume is and in which storage mediums they are stored. However, now specific storage locations or areas should be assigned to each SKU to achieve an efficient storage allocation to reduce travelling times by the warehouse personnel. This refers to step 3 from the stepwise approach.

In section 6.1 the storage method is chosen for the fast pick area and the reserve area. Based on this decision the storage allocation for the fast pick area is discussed in 6.2 and the storage allocation for the reserve area is discussed in 6.3

6.1 What storage methods should be used for the various SKUs?

To start the storage allocation process the storage policy needs to be determined in both the fast pick area and the reserve area. The requirement set by PoolPlaza is that they want an improved storage allocation compared to their current random storage assignment which will reduce the travelling distance of the pickers. However, there is a rather important constraint that implies that the ERP system of PoolPlaza cannot support routing strategies. Lastly, PoolPlaza has variants on various products which they prefer to keep together. In this fast pick area, this preference can be relaxed due to the smaller size of the area and the absence of variants since they might not be assigned to the fast pick area.

Basically, there are three storage policies according to the literature:

- Random
- Dedicated
- Class-based approach

For the reserve area, a dedicated storage policy would not suit PoolPlaza. This is because the company is relatively small, and no routing strategies have been defined. In this context, a routing strategy implies that the picker is told where to go. So, if a picker gets a packing slip and there would be specific locations mentioned the picker would have to know by heart how to walk.

Adding to that, as explained before, PoolPlaza has products, and some products have different variants. For example, a metal frame pool can be regarded as a product, but it has four different sizes and therefore variants. It would be even more complicated for the pickers to not only remember where products are stored but also where variants are stored.

Finally, because a fast pick area is used in the next PoolPlaza warehouse almost all the pickings will be executed from the fast pick area, so optimizing the reserve area with a dedicated storage policy will not bring a lot of reduction in total travelling time taking into account that a class-based storage policy has also been proven to bring a lot reduction of the total travelling time compared to the randomized and dedicated storage policies.

Together with the management of PoolPlaza, it was agreed upon that the cons outweighed the pros significantly and an ABC zoning policy is preferred at PoolPlaza. To sum up, because of the following reasons an ABC zoning policy will be used in the reserve area:

- The ERP system at PoolPlaza does not support routing strategies.
- At PoolPlaza it makes more sense to keep variants of a single type of product close to each such that these items are not spread all over the warehouse.

- The number of benefits gained from adopting a dedicated storage policy compared to an ABC zoning storage policy in the reserve area is small because most of the pickings are performed via the fast pick area.

It was possible that on the packing slip the zone of an SKU could be mentioned and the picker would only need to know which aisles or pallet rack blocks are assigned to which zones which would not take long to learn by heart. Inside the zones, a random storage policy would apply to the pickers.

For the fast pick area, it would be possible to apply a dedicated storage policy because it is much smaller with much fewer SKUs. This would make it relatively easy to ''learn'' where products are stored by heart by the order pickers. Also, because most pickings are done via the fast pick area there is a lot to be gained in terms of total travelling time by implementing a dedicated storage policy.

In the future, when the company grows, and routing strategies have been implemented an analysis could be done to make a fully dedicated storage policy across the whole warehouse with routing strategies implemented.

6.2 Storage allocation of SKUs in the fast pick area

With the storage methods selected for both the fast pick area and the reserve area, SKUs are assigned to the specific storage locations in the fast pick area in this section of the thesis. This refers to step 3b in the stepwise approach. In section 6.2.1. it is determined how many box racks and pallet racks are required in the fast pick area to accommodate the SKUs assigned to the fast pick area. In 6.2.2 the specific storage locations are assigned to each SKU.

6.2.1 Defining pallet and box rack requirements

As pointed out by Malmborg & Bhaskaran (1989) and Mantel, Schuur & Heragu (2007) the cube per order index is proven to provide the optimal solution under a single command transaction assumption which is the case at PoolPlaza. The COI formula is shown in the literature study section 2.4. To start, a separation between pallet items and storage rack items needs to be made.

Storage medium	Number of SKUs	Required storage (m^3)
Pallet Racks	40 (43%)	17.38 (87%)
Box racks	52 (57%)	2.64 (13%)

Table 8 - Box rack and pallet rack assignment for the fast pick area

With the layout provided in chapter 3, there are three columns with pallet racks in the fast pick area and the most left column is transformed into a box rack because the fast pick is enclosed by a wall on the left side. For a box rack column, this is perfect because not much space is required to store and retrieve SKUs in a box rack and therefore the box rack column can be placed close to the wall using the space in the fast pick area more efficiently. In Appendix Y a sketch is provided where the blue square represents the order picking area and the black boxes the order picking tables.

However, for the COI formula, the number of storage locations per SKU is required and therefore a definition of a storage location is to be defined for both the pallet racks and box racks. Since a dedicated storage policy is applied in the fast pick area mixing of products in storage locations should not be possible. Besides that, the management of PoolPlaza also shares the opinion that items should not share storage locations to prevent confusion and mistakes among the pickers.

For the definition of a pallet storage location, a single pallet can be chosen. The Fast pick area is two meters high so let's assume that a pallet storage location in terms of the COI formula is one meter high. This amounts to 0.96 cubic meters in storage volume. Out of the 40 SKUs assigned to pallet racks, 35 SKUs have less than 0.96 cubic meters assigned to them. This might seem like a lot and could imply lowering the storage location size. However, lower than 0.96 cubic meters is not realistic because if the height needs to be lowered further it becomes unrealistic according to PoolPlaza and if the width or length needs to be adjusted SKUs have to be mixed on pallets which is not preferred by PoolPlaza.

For the box racks, there is a standard warehouse bin used in box racks and this is the minimum storage an SKU receives at PoolPlaza. A picture of such a warehouse bin is shown in Appendix Z. The size of the bin is 500x300x200mm and the internal dimensions are 425x270x190mm which will be used as the minimal volume per storage bin. This accounts for 0.22 cubic meters in storage volume. Out of the 52 SKUs assigned to box racks, 17 SKUs have less than 0.22 cubic meters assigned and will therefore receive a single storage location. Other SKUs will receive storage locations in multiplications of 0.22 cubic meters.

Now that the number of storage locations per SKU is known the COI index can be calculated. In total 148 bin locations are required, and 45 pallet spaces are required. In a single box rack, there are four levels with on each level the possibility of four storage bins which means a single storage rack can hold 16 storage bins. In total this would require 10 box racks. In a single pallet rack in the fast pick, there are two levels with each level three pallet locations which would imply in total eight pallet racks are required.

6.2.2 Python algorithm to assign SKUs to storage locations

To perform the storage allocation algorithm python code will be used. To solve this in phyton only the levels are required as input. Below the algorithm to assign SKUs to storage locations based on their COI index is provided in the form of pseudo-code. The actual program is written in python and the code is provided in Appendix AA. In the actual code, there is also a third section where the travelling distance is compared.

- Import the SKU data from excel (SKU ID, Article number, Number of storage locations required, COI index and picking frequency)
- Create a grid with dimensions x = 20, y = 2 and z = 4. This amounts to 10 box racks.
- Calculate distances for each storage location. Height is not considered since the fast pick area is two meters high so everything can be reached rather easily.
- Sort the SKUs on their COI index from small to large in “sorted unassigned”

```
For i is 1 to n
        Select the first SKU in the “sorted unassigned”
        Find the best available storage location in terms of travelling distance
        For j is 1 to “number of storage locations required for SKU i”
                If j = 1 then
                        • Place the SKU in the best available storage location
                        • Mark the storage locations as unavailable
                        • Fill in the SKU number at the storage location
                Else
                        • Place the SKU in the available storage locations adjacent to the first selected
                          storage location of the SKU.
                        • Mark the storage locations as unavailable
                        • Fill in the SKU number at the storage location
        Next j
Next i
```

From the results, indeed 12 box racks storage locations are empty which is to be expected because 148 storage locations were required and 160 were provided because each box rack is 16 which implies the available storage locations are always a product of 16. The same applies to the pallet racks where three storage locations remain empty. There are eight pallet racks with each six pallet locations which totals 48 available pallet storage locations and in total 45 locations were required. The same algorithm is used for both box racks and pallet racks. The only thing that for the pallet racks is the dimensions of the grid which are x = 6, y = 4 and z = 2 and the input data is retrieved from another excel file.

To benchmark the solution a random assignment algorithm was also constructed and in both the randomized and COI index assignment algorithms the travelling distance was calculated. It should be noted that the travelling distance is expressed in the storage bin sizes which differ for the box rack assignment algorithm and the pallet rack assignment algorithm. However, this is not a problem since the total distance travelled is merely used to express the relative improvement in distance travelled between the COI index assignment algorithm and the random assignment. In Table 9 below these distances travelled are presented. As can be seen, by adapting a COI based assignment policy in the fast pick area significant improvements in travelling time can be gained. Furthermore, as explained previously in this thesis, if a single command policy is applied at PoolPlaza the COI will grant the optimal solution.

However, since SKUs are constrained to always be placed adjacent to one another the COI approach is not fully implemented and therefore the optimal solution is not presented. A small adjustment was done to the COI algorithm that relaxes this placement constraint and is indicated with the * in Table 9 below. Of course, it is not logical to place SKUs all over the fast pick area and therefore this solution is not accepted however it does indicate the optimality gap. As can be seen below, for the box racks this is 14% and for the pallet racks 1% which is acceptable with a total reduction of only 3% and indicates that the performance of the COI assignment with placement constraints is outstanding. Also, a total distance column has been added where the box storage distance has a weight of 0.156 since the square meters of the box storage bin is 15.6% of the size of the square meters of a pallet storage bin. This is done with square meters instead of cubic meters since the distances travelled vertically are not measured.

	Box storage location assignment	**Pallet storage location assignment**	**Total weighted distance**
Random assignment	18546	10506	13399
COI assignment	8651	6483	7833
Relative improvement	53%	38%	42%
COI assignment*	7445	6399	7560
Relative improvement	14%	1%	3%

*Table 9 - Travelling times of various storage allocation algorithms. * = Relaxed algorithm where SKUs are not constrained to be placed adjacent to one another.*

6.3 Storage allocation of SKUs in the reserve area

As discussed in paragraph 6.1 an ABC zoning policy is adapted in the reserve area of the warehouse. In Appendix T the final layout of the warehouse and the pallet rack placements in the reserve area are presented. With this information, a grid can be easily constructed, and the distances travelled to each location can be calculated with the receiving I/O point on the right side and the fast pick area/order pick area on the left side.

However, the distance from the receiving area to the storage location to the fast pick area cannot simply be measured by the amounts of steps taken through the grid. By analysing the average order size per SKU determined in chapter 4 and the number of units dedicated to the fast pick area per SKU the ratio can be determined between the number of replenishments and goods received. It was found that the demand weighted replenishment/receive ratio is 3.46. This would imply that replenishments occur 3.46 times as much as the receiving of goods. Of course, this is only a rough estimate because there are also SKUs that are only in the reserve area, but it gives a rough estimate. However, this latter statement can once again be countered by the fact that the SKUs in the fast pick area are responsible for most of the picking frequencies and therefore the SKUs in the reserve area can be ignored to gain a rough estimate.

That being said, with the ratio now determined it can be used to create a weighted distance grid matrix. The distance from a storage location to the fast pick area counts 3.46 times as heavy as the distance from the storage location to the receiving area. The distance grid is shown in Appendix AB. With the colour scales, the storage locations with lower distances are illustrated. In total there are 76 pallet rack blocks which leads to the following distribution of pallet rack blocks among the zones:

- Zone A (20%) = 15 pallet rack blocks
- Zone B (30%) = 23 pallet rack blocks
- Zone C (50%) = 38 pallet rack blocks

However, with determining zones it is also considered what makes sense. This means that sections of aisles areas are chosen which is convenient thus making the amount of pallet rack blocks per zone more like guidelines. Below, the different zones are presented with green for zone A, orange for zone B and red for zone C. The numbers represented the weighted distances.

Figure 14 - ABC zoning of the reserve area

The final amount of pallet blocks per zone is as followed which are close to the amounts defined above:

- Zone A (20%) = 18 pallet rack blocks
- Zone B (30%) = 22 pallet rack blocks
- Zone C (50%) = 36 pallet rack blocks

On a final note, there are no box racks placed in the reserve area. This is because the fast pick area is only two meters high and PoolPlaza intends to create a Mezzanine above the fast pick area to create the reserve stock area for box rack SKUs.

6.4 Storage location allocation conclusion

In the fast pick area, a fully dedicated storage policy is chosen with the COI approach to assign storage locations to SKUs to achieve the most reduction in the travelling distances of the pickers. In the reserve area, an ABC zoning storage policy is chosen to still achieve a reduction in travelling times but also be compatible with the size of PoolPlaza and the capabilities of their ERP system. Compared to a random storage assignment, which is currently implemented at PoolPlaza, the COI storage allocation in the fast pick area results in a 42% reduction in travelling times. For the reserve area, this cannot be benchmarked easily however a floor plan is provided indicating the various pickings zones.

7 Discussion

In this chapter of the thesis, the choices made on the various models used will be reflected upon. What were the limitations of the research done? What is left to research in the future and what course of action should be taken by the company in the future?

Layout

To start, the dimensions of the various functional areas are a rough estimation of the required square meters. When the actual plans of the warehouse are worked out more in detail it will probably become clearer what will be the exact square meters of the office area, shop area and other areas. Once the exact dimensions of the functional areas are known the LP model can be executed again with the right input to determine the fast pick area and reserve area sizes. It could also be possible to further investigate the holding costs and storage costs more precisely through timing actual warehouse operations. This is time-consuming but could improve the input of the model and therefore make the output more accurate.

Inventory policy parameters

For the space allocation inventory policies were used per SKU to determine re-order levels, order sizes, average stock levels and peak stock levels. However, usually one year of data can be used to ”train” the models which provide the parameters and another year or more data can be used to ‘’test’’ these parameters. However, due to the lack of data and time constraints the testing was left out of the research. PoolPlaza has only one year of data available due to the implementation of the new ERP system in the middle of 2020. Once the warehouse is finished (two to three years), there will be more data available and then the parameters could be tested and tuned if necessary. It could also be possible to use one of these three years to train the parameters again and use the remaining two years to test the parameters. With more data, the inventory policies will become more accurate.

Optimal storage allocation

With regards to the storage allocation of products, Malmborg (1995) mentions that multiple aisles do not present a problem to the COI approach under the condition that the same SKU can be located in multiple aisles. However, as discussed in chapter 5, PoolPlaza prefers that the same SKU should always be located together. In chapter 5, it was found that if this constraint is relaxed the solution can be improved by 3%. Future research could try to find a better storage allocation by using a simulated annealing algorithm as proposed by Malmborg (1995). However, due to the optimality gap of only 3% and time constraints, this was not included in this thesis.

Contribution to science and practice

In terms of a contribution to science this thesis does provide a suggestion on how to improve the mathematical model provided by Heragu, Du, Mantel & Schuur will be used (2005). In this thesis, the gamma and beta are used in the objective function to influence the handling costs in the fast pick area and reserve area. For the specific scenario of PoolPlaza, this modified model performed well. However, in the future, research could be conducted to analyse whether this new model indeed provides better results in various scenarios and whether this also works with larger problems.

With regards to a contribution to practice, this thesis provides a good framework and stepwise approach for the warehouse design of PoolPlaza. As mentioned above, after two or three years, when more data is collected on demand, handling and storage costs, the models could be run again resulting in better results. For as of now, it provides good insights for PoolPlaza for the planning phase of the design of the warehouse.

Another contribution to practice and science could be that this thesis provides a good framework for smaller companies in designing their warehouse. As mentioned before in the literature study, Rouwenhorst et al. (2000) conclude that most papers are concerned with mostly automated and large warehousing systems. Since this thesis focuses on warehousing systems for smaller companies, the framework provided could be extended and improved upon by other companies or academics.

8 Conclusion and recommendations

During the last few years, PoolPlaza has grown significantly which gave rise to the need for a new and larger warehouse. This thesis provides PoolPlaza with a framework to design its future warehouse.

The layout of the warehouse

Starting at the strategic level the various functional areas are identified, dimensioned and their relative position to each other in the layout was determined. From the 1200 m^2 available building space each functional area was assigned to the following square meters:

Functional area	**Assigned space**	**Functional area**	**Assigned space**
Receiving area	60 m^2	Order picking area	40 m^2
Shipping area	60 m^2	Fast pick area	85 m^2
Offices	100 m^2	Reserve area	605 m^2
Shop	100 m^2	Internal transport system	10 m^2
Value-adding service Area	100 m^2		

Table 10 - Functional area space assignment

An initial layout of the warehouse was constructed based on a U-shaped warehouse principle and PoolPlaza's insights into the flow of materials and personnel between various functional areas. With a Systematic Layout Planning (SLP) approach specific employees of PoolPlaza were asked to assign closeness ratings between functional areas with which the initial layout was improved.

Space allocation

After designing the strategic level of the warehouse, the thesis focuses on a more tactical level design phase. The SKUs of PoolPlaza are analysed and inventory policies are assigned to each SKU along with a fill rate based on their ABC-XYZ classification. With each SKU having an inventory policy assigned the parameters of that policy are determined from which the average and peak stock level can be determined. This in turn also helps with determining a storage medium for each SKU. It was found, that based on the current demand, the peak inventory stock level encompasses 8272 unit loads overall SKUs which can also be expressed as 129.13 cubic meters in volume. With regards to the storage mediums, it was found that 102 SKUs are assigned to pallet racks and 294 SKUs are assigned to box racks. Also, with the inventory policies determined, PoolPlaza can now automate the purchasing process with order levels, order up to levels and order quantities per SKU. On a side note, it should be mentioned that in the beginning these purchasing orders have to be carefully monitored and the parameters tuned if required.

As a final step of the space allocation, it was determined how many SKUs were assigned to the fast pick area and how many unit loads of each SKU should be allocated to the fast pick area. It was found that 31 SKUs are fully stored in the fast pick area, 61 SKUs are assigned to both the fast pick area and the reserve area, and 305 SKUs were assigned to the reserve area alone. In total 2203 unit loads are assigned to the fast pick area which amounts to 19.3 cubic meters.

Storage allocation

To finalize the layout of the warehouse the allocation of SKUs to storage locations was analysed. For the fast pick area, a fully dedicated storage policy was implemented and according to the COI approach, SKUs were assigned to storage locations. For the reserve area, an ABC zoning policy is advised to PoolPlaza for the storage of SKUs. Compared to the current random storage policy of PoolPlaza an improvement of 42% in travelling distance can be achieved with the COI approach.

It can be concluded that with this thesis PoolPlaza is provided with a strategic and tactical layout for their new warehouse. Further down the road, PoolPlaza could also investigate more detailed operational layout aspects when the warehouse is about to be finished in two to three years. It is also easier to implement changes in operational aspects compared to strategical and tactical aspects. Just before the functional areas are constructed the models in this thesis can be run again with more demand data and this might provide more accurate results.

Recommendations

As mentioned in the discussion it is recommended to go through the complete stepwise approach again when the warehouse is almost finished because more data will be available and the results will be more accurate. Specifically, the inventory policies determined in chapter 5 could be analysed to see whether the determined parameters can maintain the assigned fill rates and what adjustments could be made if the fill rates are not achieved.

Also, if the growth of PoolPlaza continues its current trend it would be recommended to investigate how the ERP system could support routing strategies in the future. Or maybe other ERP systems could be investigated, but that would take a lot more effort in all areas of the company and would require more investment and time. But the main takeaway is that if PoolPlaza grows further, routing strategies could reduce the travelling times even more if there are more pickers and pickings in the warehouse.

However, since in its current state PoolPlaza's ERP system cannot support routing strategies and locations have to be learned by heart it might be useful to colourize the pallet racks or areas in the reserve area, and for the fast pick area, it could be helpful to give each storage bin a plasticized card with a picture of the SKU, the SKU number and the SKU name. Currently, this is already implemented at PoolPlaza for their Kanban items and this could be expanded to all the SKUs in the fast pick area.

To further extend upon the size of PoolPlaza, with the current demand data the warehouse is too large for PoolPlaza. Under the current situation, it is recommended that Poolplaza splits the initial warehouse of 1200 m^2 to 300 m^2 and 900 m^2. The first 300 m^2 could be rented out to an external party and the latter 900 m^2 could be used for PoolPlaza's operations. This would imply that the rent can support the loan of the warehouse partially and therefore the monthly costs of PoolPlaza will be reduced which leads to more liquidity and more possibility for PoolPlaza to grow with that extra liquidity.

Finally, all the inventory policy parameters and fast pick area assignments are purely based on historical data and theoretical analysis but as is often the case, reality can be different from theory. It is recommended that PoolPlaza maintains good communications with the pickers in the warehouse and sales personnel. If a warehouse picker feels an SKU should be in the fast pick area this should be investigated. The same goes for sales personnel, if the sales department feels that some SKUs are out of stock often it should be communicated within the company to change the inventory parameters.

Appendices

Appendix A – Number of orders per day over 365 days

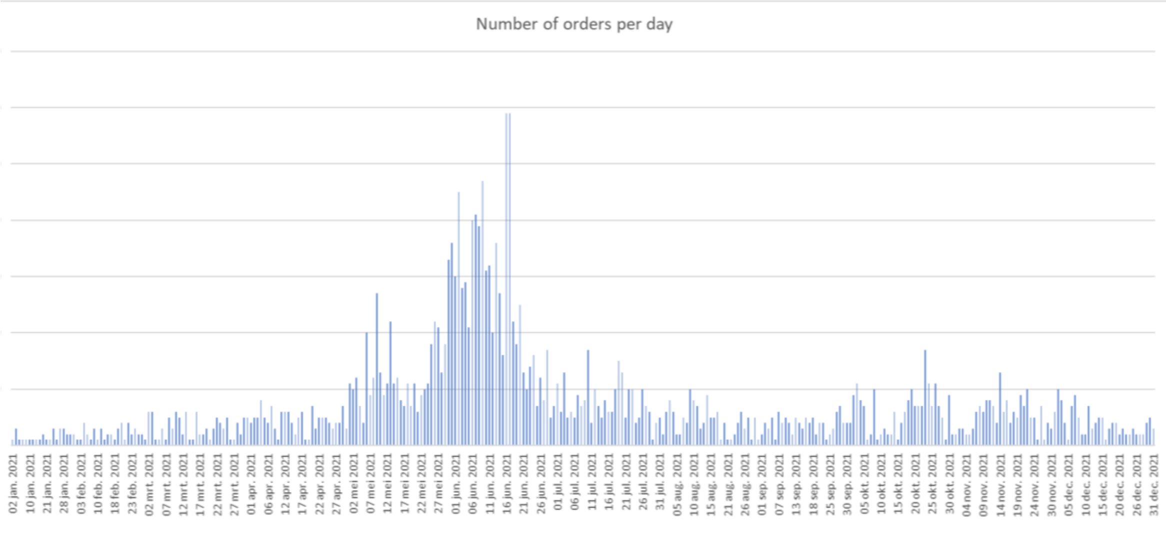


Figure 15 - Number of orders per day within one year.

Appendix B – Revenue ABC analysis over all SKUs

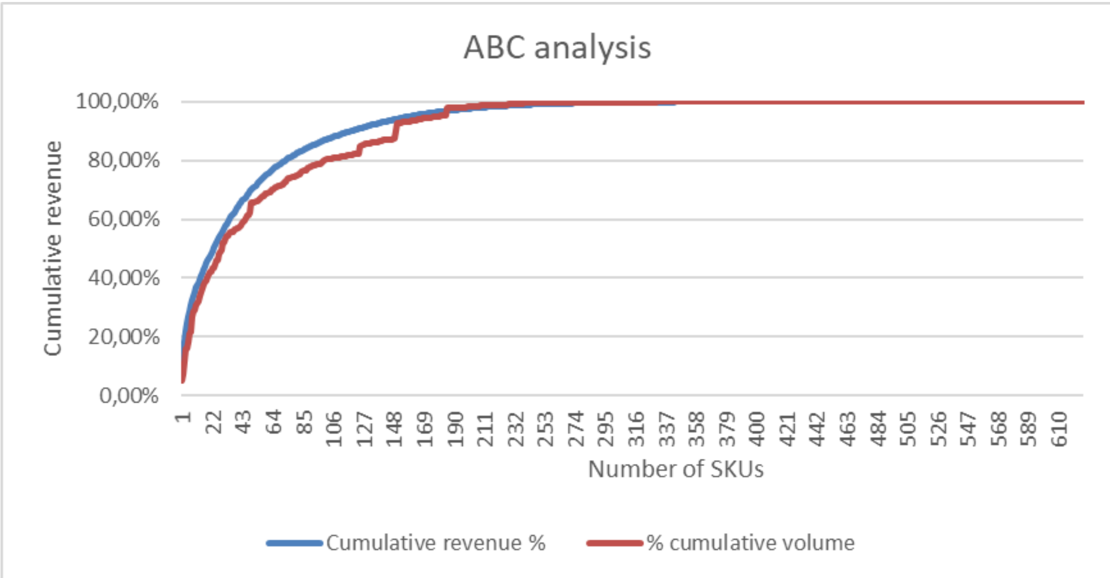


Figure 16 - Revenue ABC analysis over all SKUs with one year.

Appendix C – Top ten SKUs ABC analysis

SKU i	Picking frequency	Volume/year %	Revenue %	Cumulative revenue %
1	71	5,20%	8,15%	8,15%
2	12	1,89%	7,03%	15,18%
3	49	8,78%	7,01%	22,18%
4	6	0,09%	2,61%	24,79%
5	18	2,09%	2,09%	26,88%
6	91	2,99%	1,87%	28,75%
7	20	0,66%	1,86%	30,61%
8	32	5,03%	1,80%	32,41%
9	6	1,70%	1,49%	33,90%
10	7	0,48%	1,47%	35,37%

Table 11 - Top ten SKUs in terms of revenue analysed within one year.

Appendix D – ABC analysis with picking frequency

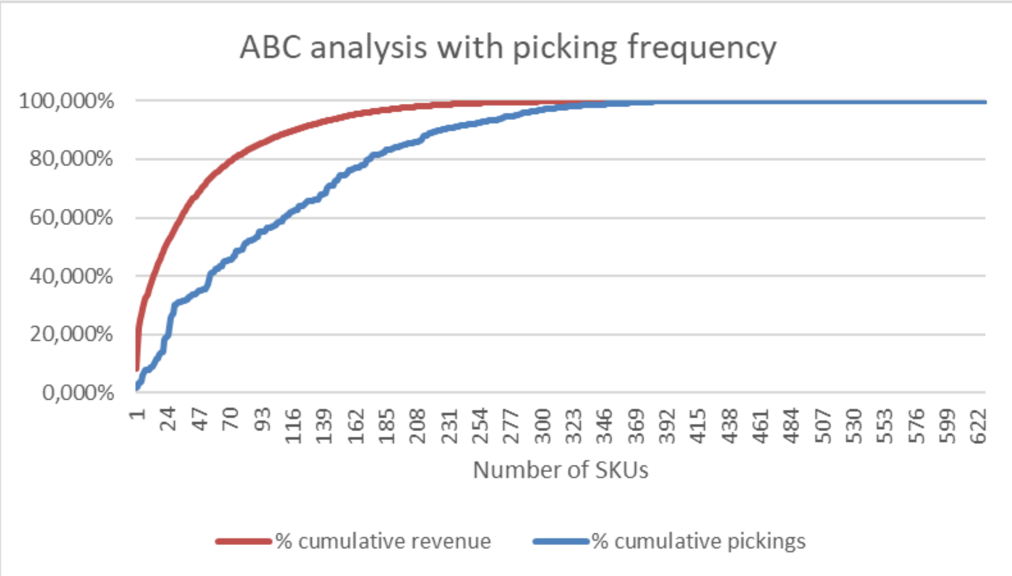


Figure 17 - Revenue ABC analysis and picking frequency analysis over all SKUs and one year time period. Sorted on best revenue-generating SKUs.

Appendix E – ABC analysis with picking frequency sorted

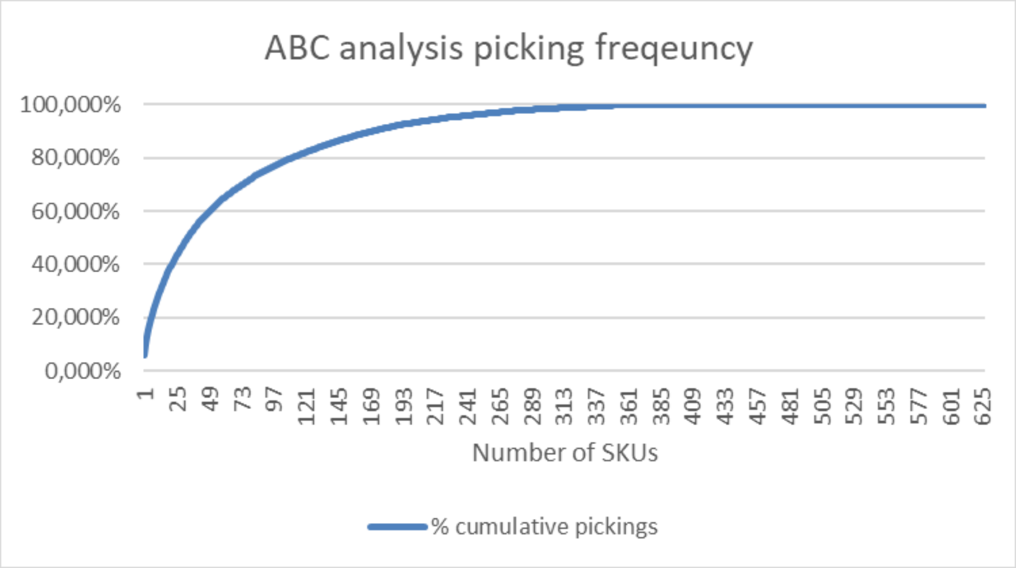


Figure 18 - Revenue ABC analysis and picking frequency analysis over all SKUs and one year time period. Sorted on highest picking frequency SKUs.

Appendix F – Order lines and order picking

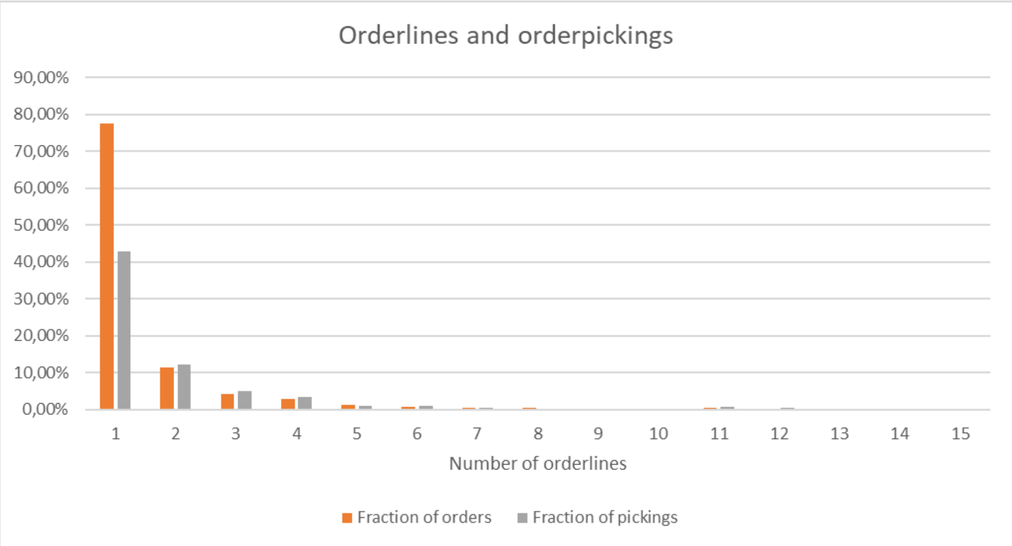


Figure 19 - Number of order lines and order pickings over all SKUs within one year.

Appendix G – Sketch of office functional area

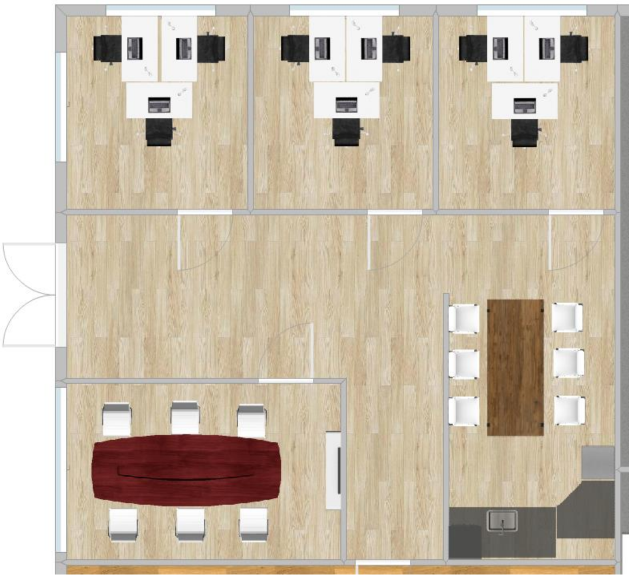


Figure 20 - Sketch of office functional area

Appendix H – Sketch of receiving area functional area

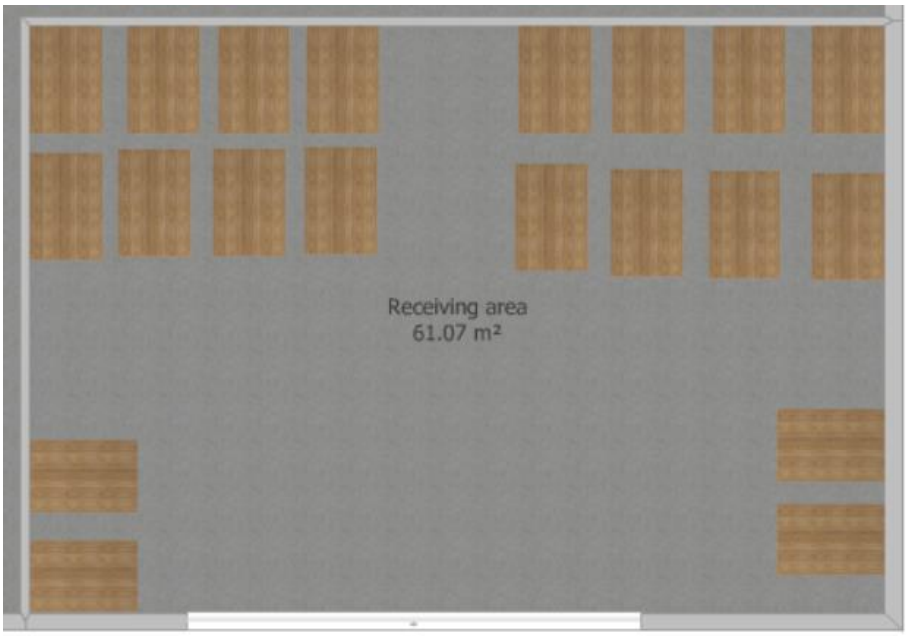


Figure 21 - Sketch of receiving area functional area

Appendix I – Sketch of shipping area functional area

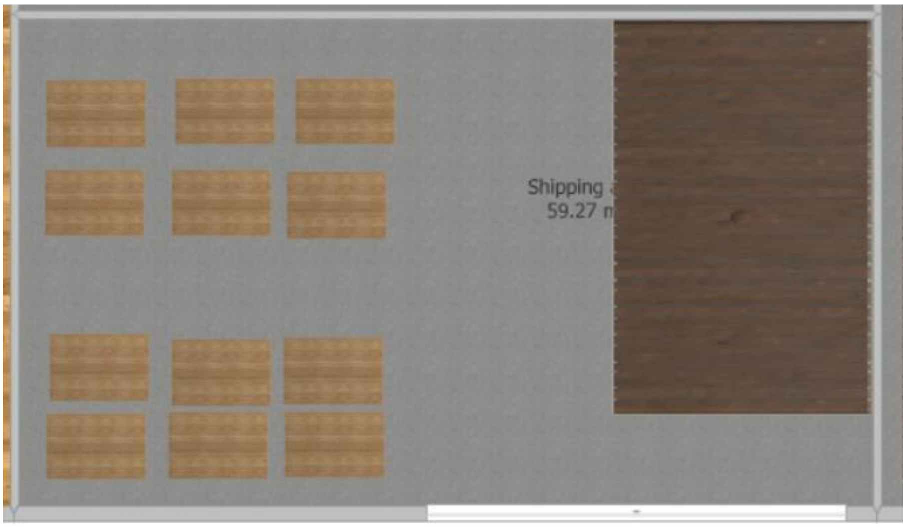


Figure 22 - Sketch of shipping area functional area

Appendix J – Sketch of internal transport system functional area

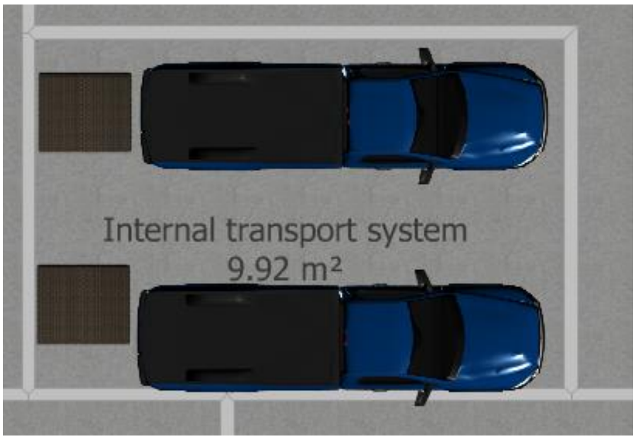


Figure 23 - Sketch of internal transport system functional area

Appendix K – Sketch of VAS functional area with shipping area

Figure 24 - Sketch of VAS functional area with shipping area

Appendix L – Sketch of VAS functional area

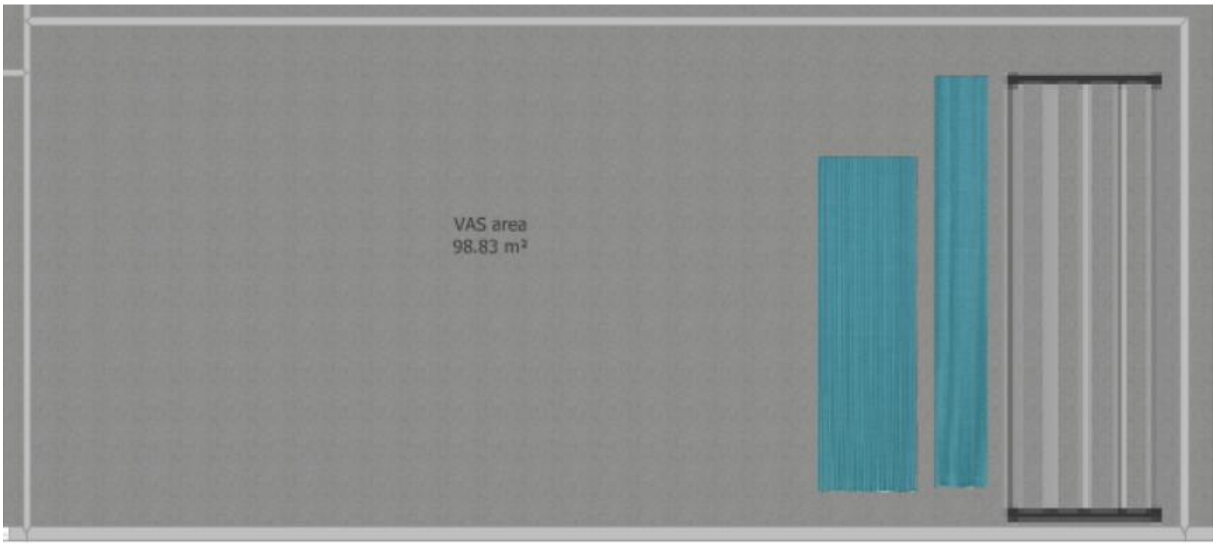


Figure 25 - Sketch of VAS functional area

Appendix M – Sketch of order picking area functional area

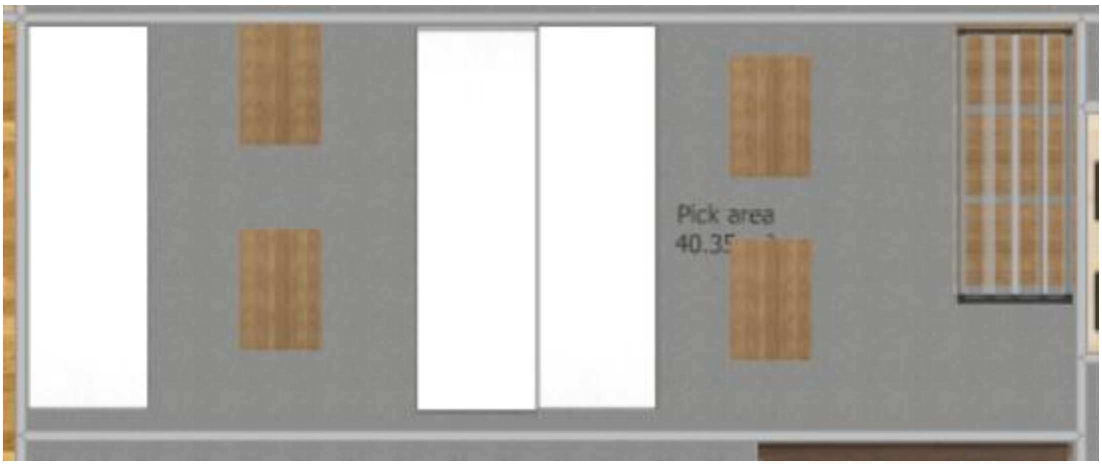


Figure 26 - Sketch of order picking area functional area

Appendix N – Modified nonlinear objective function

$$\min: 2 * \left(\sum_{i=1}^{n} \left(\frac{\beta}{0,8} * RTTR + (1 - RTTR) \right) H_{i,1} \lambda_i X_{i,1} + \sum_{i=1}^{n} \left(\left(\frac{\gamma}{0,2} * RTTF + (1 - RTTF) \right) H_{i,3} + \frac{\left(\left(\frac{\gamma}{0,2} * RTTF + (1 - RTTF) \right) H_{i,3} + \left(\frac{\beta}{0,8} * RTTR + (1 - RTTR) \right) H_{i,1} \right)}{d_i} \right) \lambda_i X_{i,2} + \sum_{i=1}^{n} \left(\frac{\gamma}{0,2} * RTTF + (1 - RTTF) \right) H_{i,3} \lambda_i X_{i,3} \right) + \sum_{i=1}^{n} \sum_{j=1}^{3} (C_{i,j} Q_i X_{i,j} / 2)$$

Appendix O – SLP survey

You as an employee of PoolPlaza are asked to give closeness ratings to the functional areas of PoolPlaza in the new warehouse. A closeness rating determines how desirable it is to place certain facilities close to each other. Below there are two tables shown, the first table represents the closeness ratings with A being the most favourable giving 4 points and U being the least favourable giving 0 points. Below the closeness rating table, there is also a table with various reasons why a certain closeness rating is given.

Closeness rating	Definition	Points
A	Absolutely necessary	4
E	Especially important	3
I	Important	2
O	Ordinary/closness okay	1
U	Unimportant	0

Table 12 - Closeness ratings SLP

Code	Reason
1	Quantity of flow
2	Cost of material handling
3	Equipment used in MH
4	Communication needed
5	Personnel needed
6	Separation needed

Table 13 - Reasons for closeness ratings SLP

So, for example, if we take the receiving area and the reserve area a score of A could be given because goods that are received go to the reserve area after being processed in the receiving area. So, reason 1 is assigned due to the quantity of flow and code 5 is given since personnel that operates in the receiving area also operates in the reserve area and therefore between these two departments there is a need for personnel.

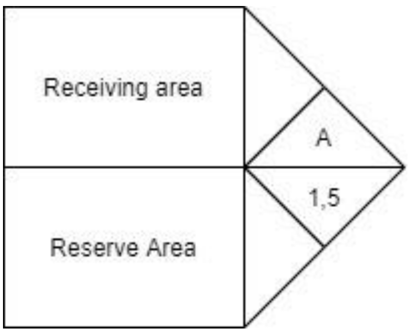


Figure 27 - Small example of SLP input form

Further down below is the full table with all the functional areas defined. Please fill out the form to the best of your abilities and if questions arise these can of course be asked and answered.

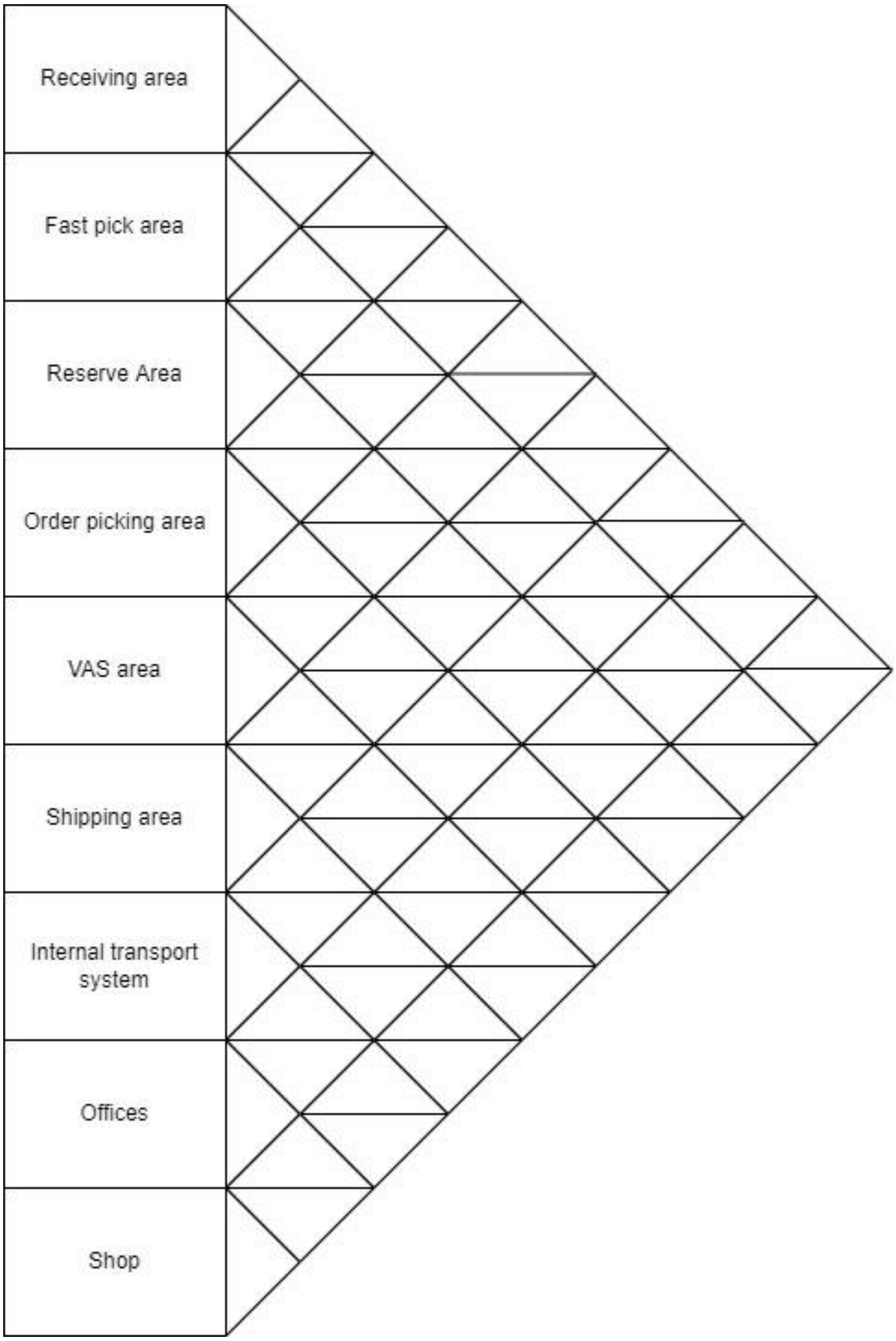


Figure 28 - SLP input form

Figure 29 - Survey results – interviewee 1

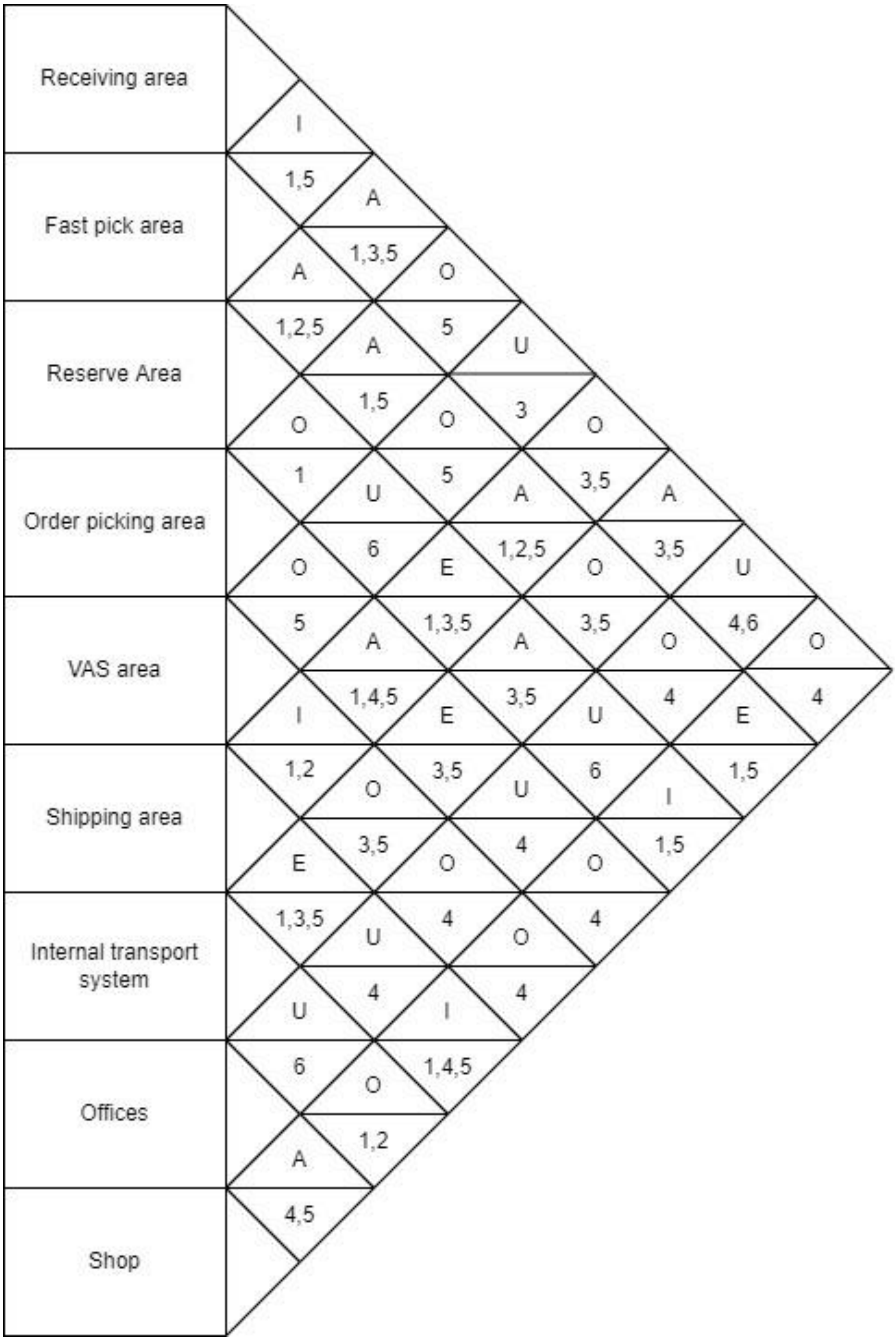


Figure 30 - Survey results – interviewee 2

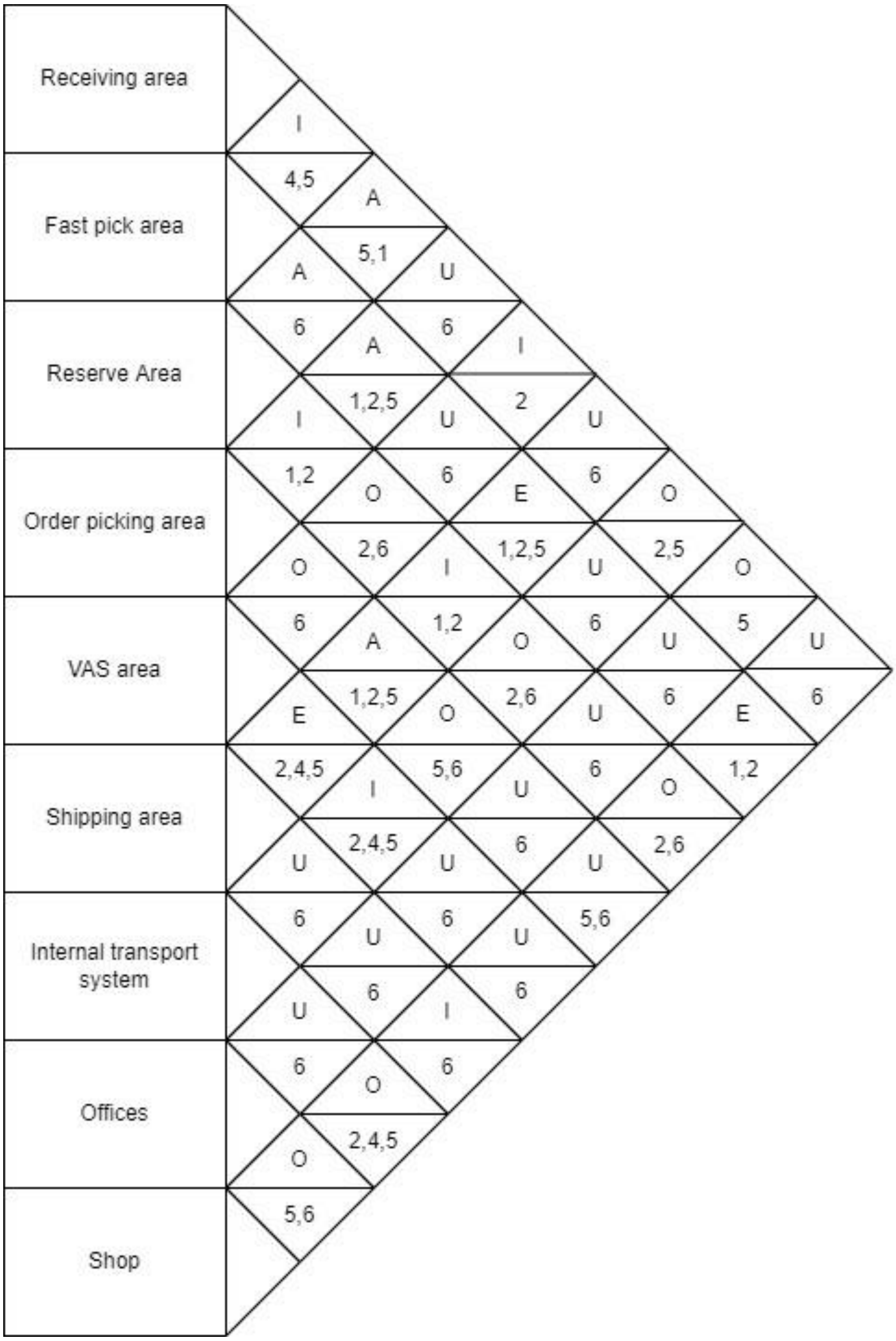


Figure 31 - Survey results – interviewee 3

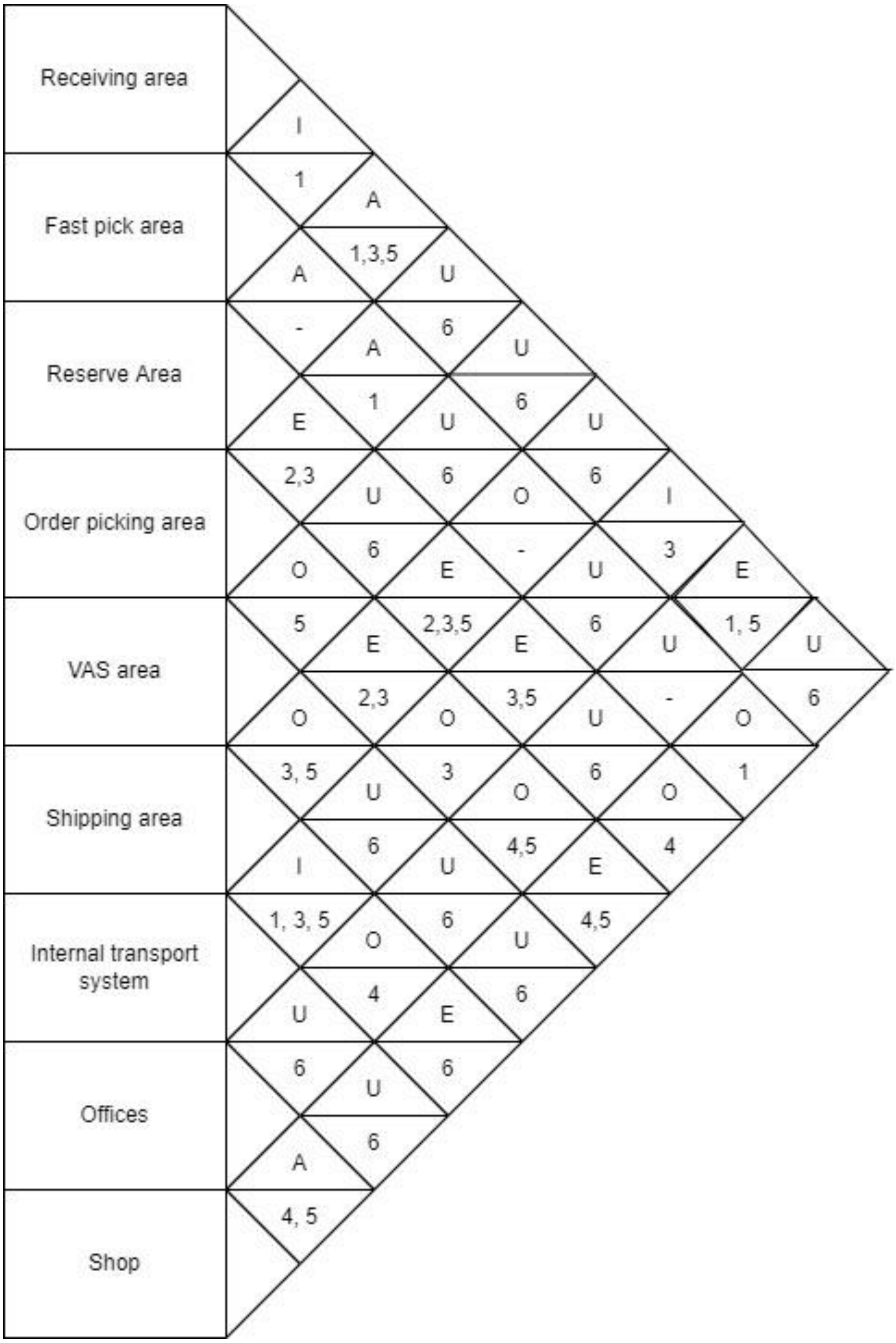


Figure 32 - Survey results – interviewee 4

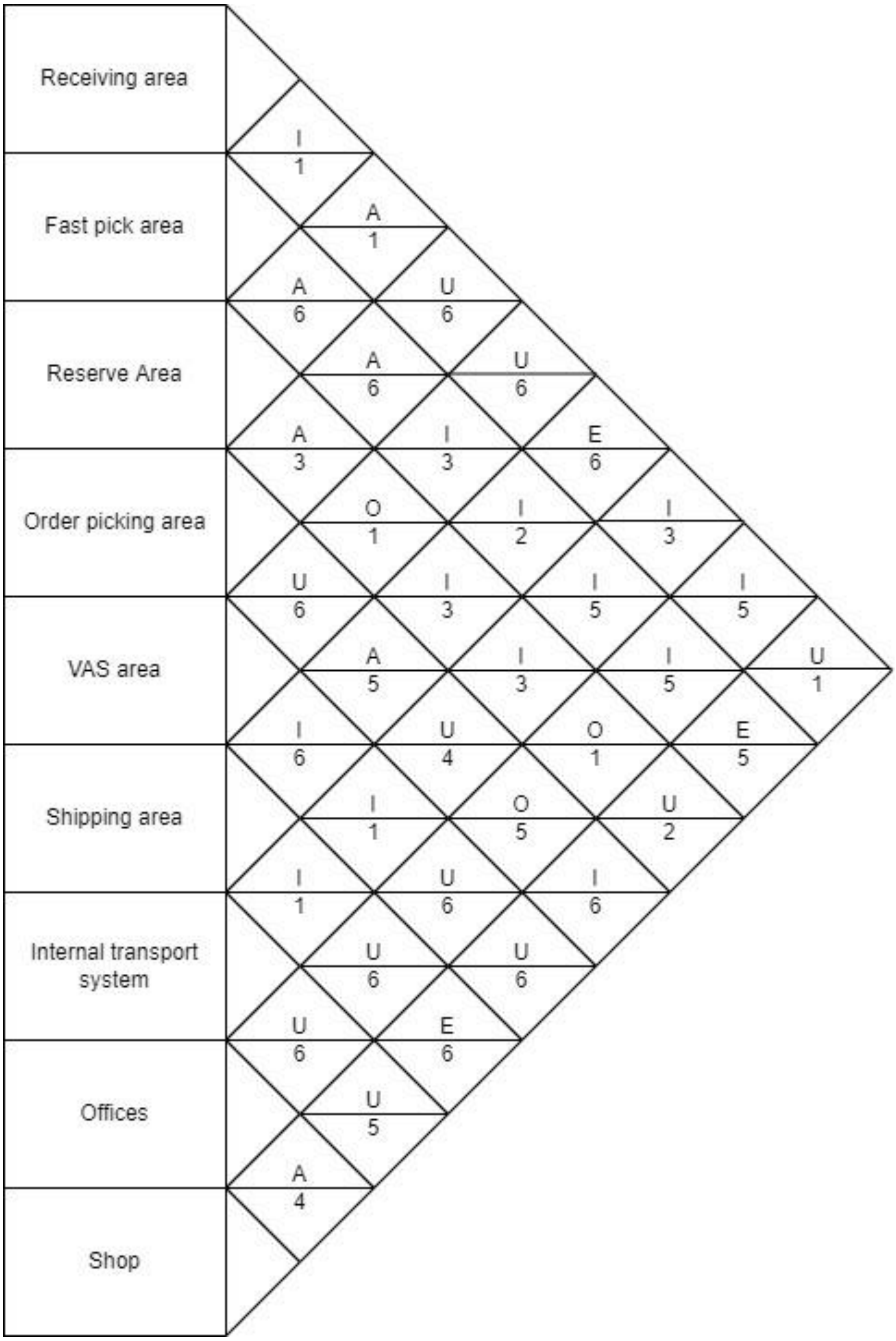
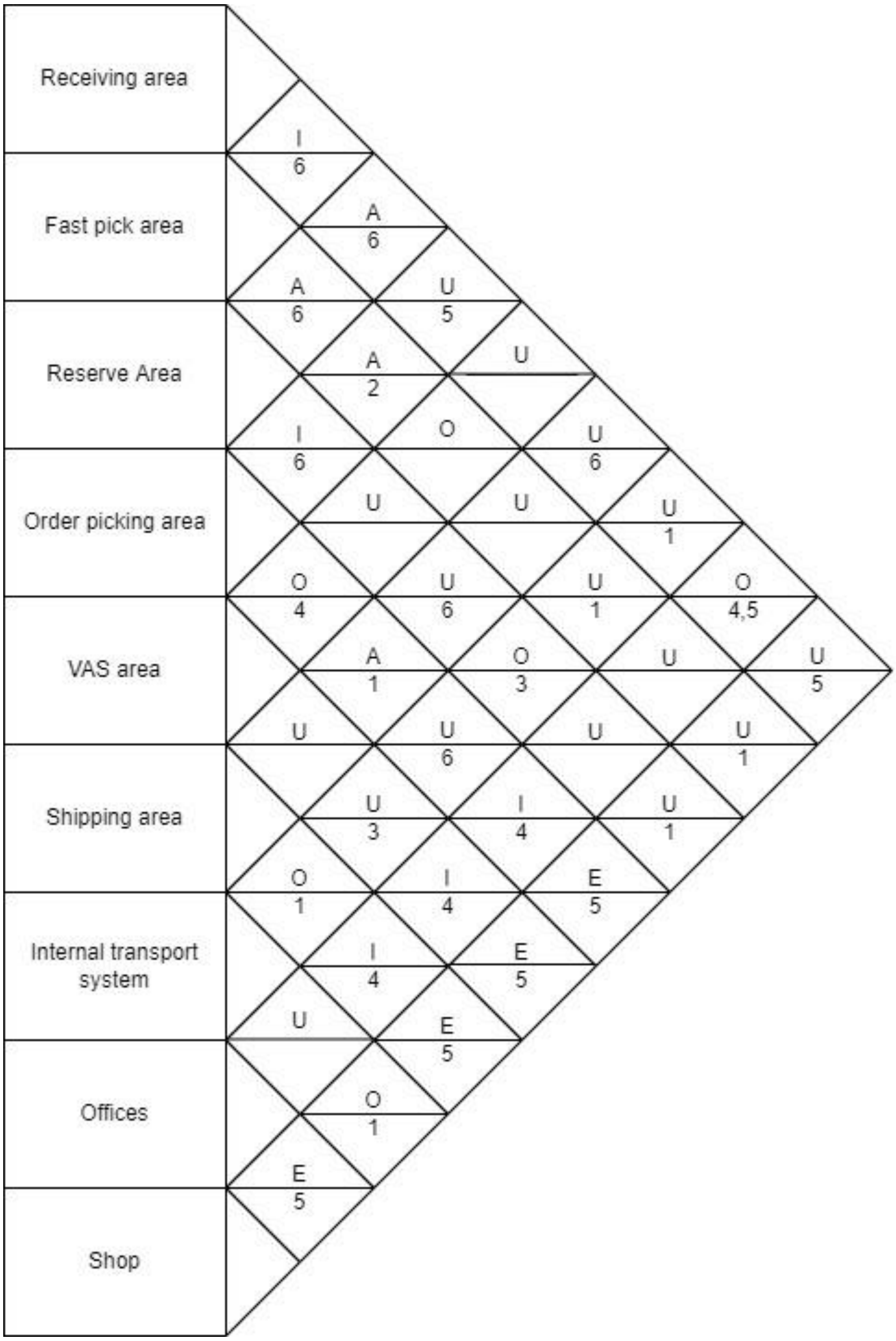


Figure 33 - Survey results – interviewee 5



Appendix P – The comprehensive diagram and the activity relationship diagram from the surveys

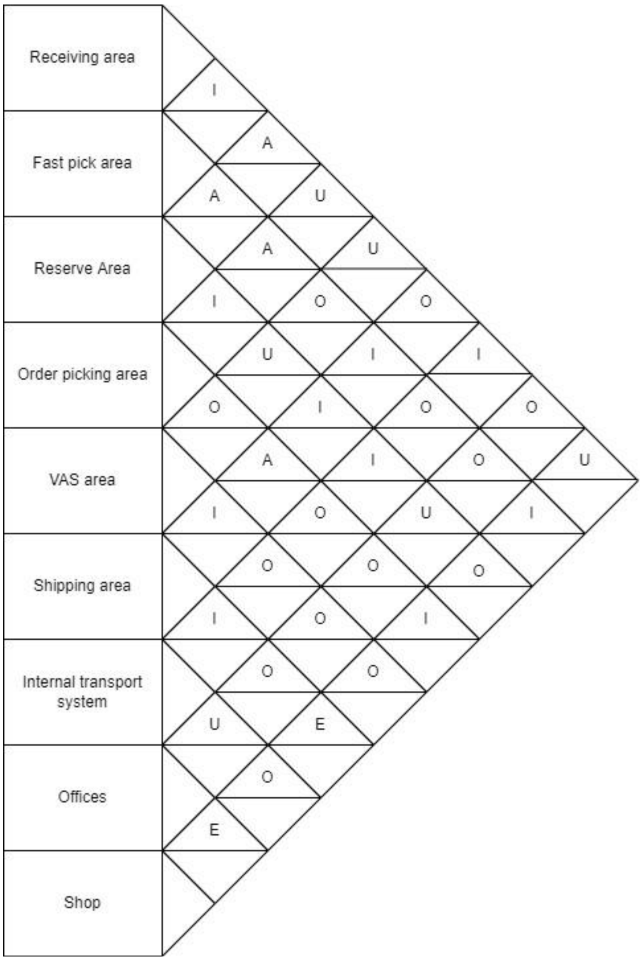


Figure 35 - Comprehensive diagram of SLP

	Receiving area	Fast pick area	Reserve area	Order picking area	VAS area	Shipping area	Internal transport system	Offices	Shop
Receiving area	-	I	A			O	I	O	
Fast pick area		-	A	A	O	I	O	O	I
Reserve area			-	I		I	I		O
Order picking area				-	O	A	O	O	I
VAS area					-	I	O	O	O
Shipping area						-	I	O	E
Internal transport system							-		O
Offices								-	E
Shop									-

Figure 34 - Activity relationship diagram

Appendix Q – First block layout from SLP

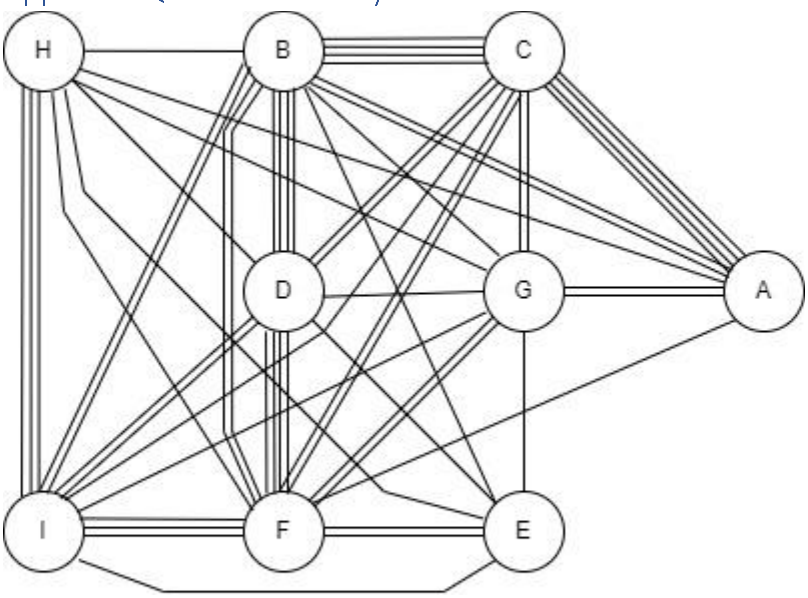


Figure 36 - First block layout from SLP

Appendix R – First block layout from SLP with downscaled survey results – 4 conflicts

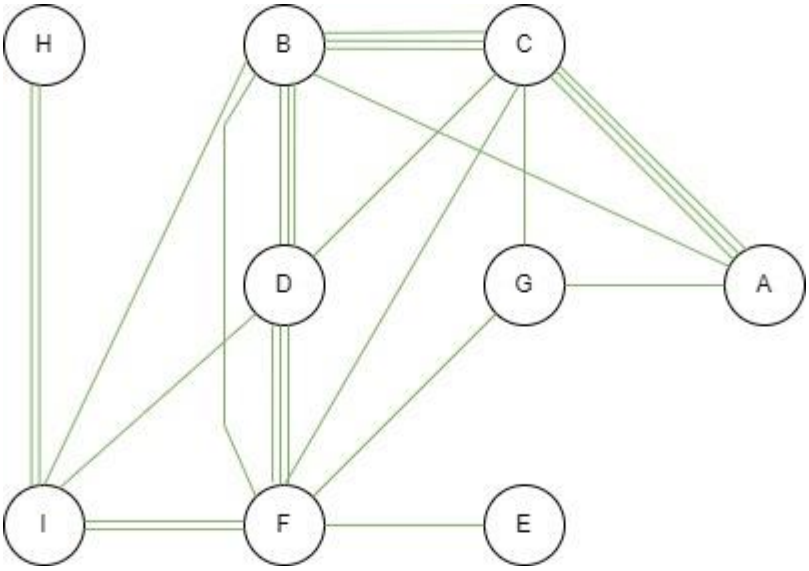


Figure 37 - First block layout from SLP with downscaled survey results – 4 conflicts

Appendix S – Alternative block layouts

Figure 38 - Alternative 1 – 6 conflicts

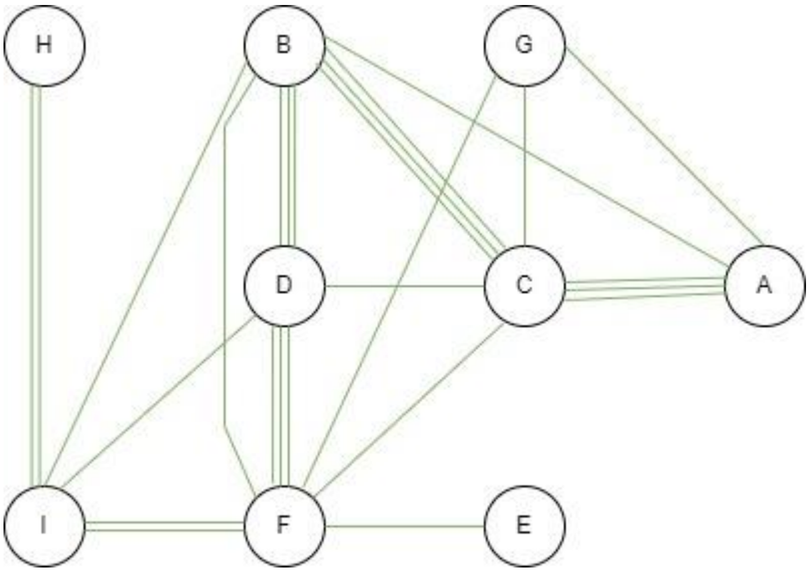


Figure 39 - Alternative 2 – 6 conflicts

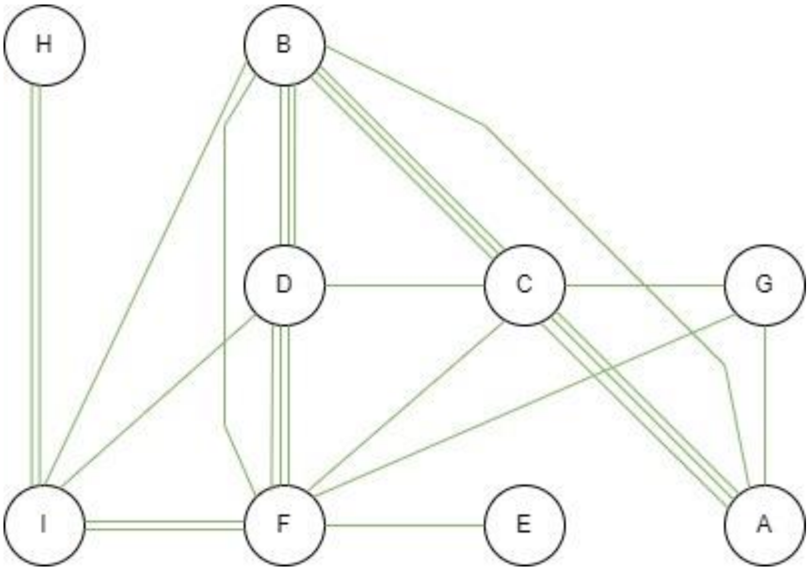


Figure 40 - Alternative 3 – 1 conflict

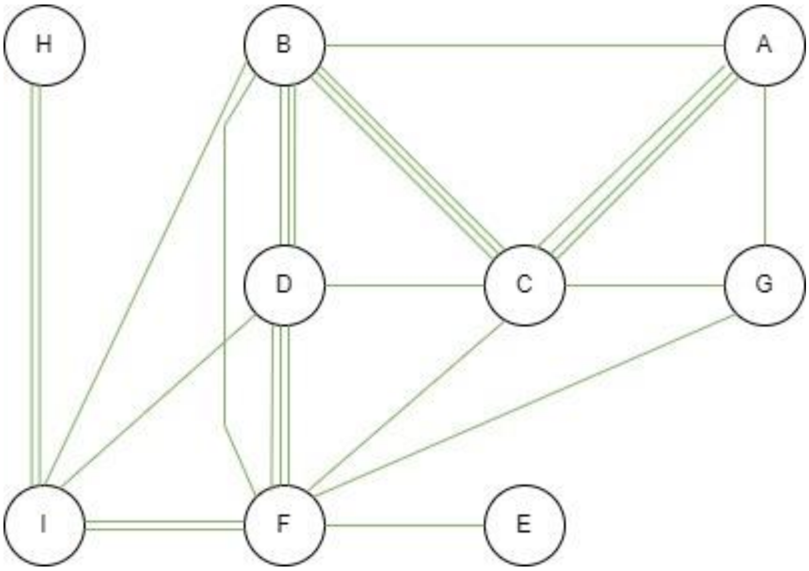
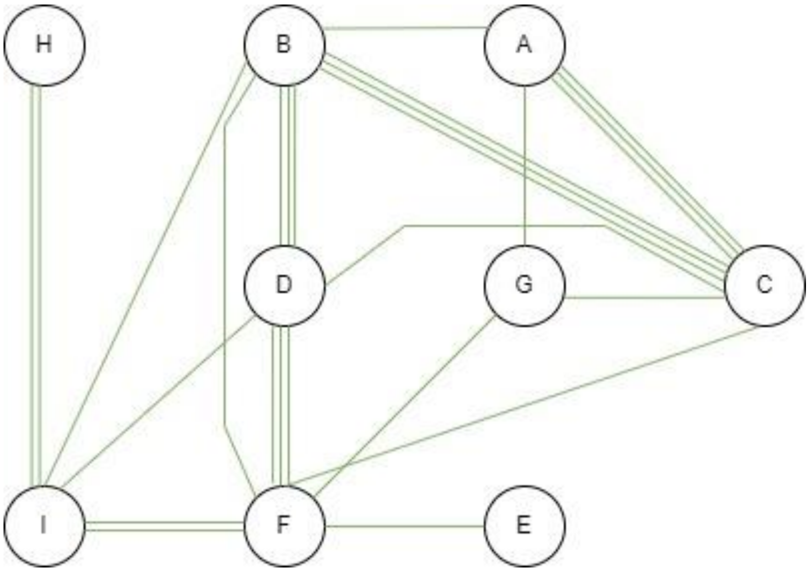


Figure 41 - Alternative 4 – 5 conflicts



Appendix T – Final warehouse layout

Figure 42 - Final warehouse layout

Appendix U – Formulas R,s,S inventory policy

$$E[z] = \frac{\sigma_R^2 + D_R^2}{2D_R}$$

$$Q = S - s + E[z]$$

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

$$Q = \sqrt{\frac{2DC}{hP}}$$

$$\sigma_{R+L}^2 J(k) = 2(1 - P_2)X_R \left[S - s + \frac{\sigma_R^2 + D_R^2}{2D_R}\right]$$

Which can be rewritten as:

$$J(k) = \frac{2(1 - P_2)X_R \left[Q + \frac{\sigma_R^2 + D_R^2}{2D_R}\right]}{\sigma_{R+L}^2}$$

For this approach, to determine k a very accurate approximation is provided in Appendix III of the book which can be easily implemented by Excel (Silver, Pyke, & Thomas, 2016):

$$k = \frac{a_0 + a_1 z + a_2 z^2 + a_3 z^3}{b_0 + b_1 z + b_2 z^2 + b_3 z^3}$$

Where for 0 ≤ J(k) ≤ 0,5

$z = \sqrt{\ln\left(\frac{1}{J(k)}\right)^2}$

$a_0 = -4.18884136 \times 10^{-1}$

$a_1 = -2.5546970 \times 10^{-1}$

$a_2 = 5.1891032 \times 10^{-1}$

$a_3 = 0$

$b_0 = 1$

$b_1 = 2.1340807 \times 10^{-1}$

$b_2 = 4.4399342 \times 10^{-2}$

$b_3 = -2.6397875 \times 10^{-3}$

While for J(k) > 0,5

$z = J(k)$

$a_0 = 1.1259464$

$a_1 = -1.3190021$

$a_2 = -1.8096435$

$a_3 = -1.1650097 \times 10^{-1}$

$b_0 = 1$

$b_1 = 2.8367383$

$b_2 = 6.5593780 \times 10^{-1}$

$b_3 = 8.2204352 \times 10^{-3}$

Definitions

$E[z]$ = Expected undershoot

$E[US]$ = Expected units short

Required data

σ_R^2 = Standard deviation over demand during the review period

D_R^2 = Demand during the review period

$2X_R$ = Demand during the review period

X_{R+L} = Demand during the review period and Lead time

σ_{R+L} = Standard deviation over demand during the review period and Lead time

k = safety factor (automatically chosen with P_2)

P_2 = Percentage of demand fulfilled from stock, A.K.A. item fill rate

Appendix V – Formulas R,S inventory policy

$$s = X_L + k * \sigma_L$$

$$G(k) = \frac{Q(1 - P_2)}{\sigma_L}$$

To transform the formulas to an (R,S) system the following parameters must be substituted:

- s → S
- Q → D_r
- L → L + R

This will result in the following formulas:

$$S = X_{L+R} + k * \sigma_{L+R}$$

$$G(k) = \frac{D_r(1 - P_2)}{\sigma_L}$$

For this approach, to determine k a very accurate approximation is provided in Appendix III of the book which can be easily implemented by Excel (Silver, Pyke, & Thomas, 2016):

$$k = \frac{a_0 + a_1 z + a_2 z^2 + a_3 z^3}{b_0 + b_1 z + b_2 z^2 + b_3 z^3 + b_4 z^4}$$

Where

$z = \sqrt{\ln\left(\frac{25}{G(k)}\right)^2}$	$b_0 = 1$
$a_0 = -5.3925569$	$b_1 = -7.2496485 \times 10^{-1}$
$a_1 = 5.6211054$	$b_2 = 5.07326622 \times 10^{-1}$
$a_2 = -3.8836830$	$b_3 = 6.69136868 \times 10^{-2}$
$a_3 = 1.0897299$	$b_4 = -3.29129114 \times 10^{-3}$

Appendix W – Formulas R,s,Q inventory policy

For R,s,Q it is the same as R,s,S but only S is not calculated but Q is kept. The following equation of Silver, Pyke and Thomas are provided (2016):

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

$$k = \Phi^{-1}\left(1 - \frac{D_R}{TBS}\right)$$

$$Q = \sqrt{\frac{2DC}{hP}}$$

D_r = Demand during review period
C = ordering cost
h = inventory carrying cost rate
D = yearly demand
P = SKU value

Appendix X - 31 SKUs that have more than 10 yearly pickings but are not assigned to the fast pick area by chapter 3

m3	Yearly volume (m3	Picking frequency (Odoo)	Picking frequency (Bol)	Total picking frequency	Labor efficiency	Chapter 3
0,0001	0,007	44	4	48	589,06	Reserve area
0,0002	0,020	24	52	76	537,40	Reserve area
0,0000	0,009	34	6	40	423,76	Reserve area
0,0002	0,016	25	26	51	401,19	Reserve area
0,0000	0,006	19	11	30	378,57	Reserve area
0,0003	0,045	48	3	51	240,20	Reserve area
0,0009	0,067	23	29	52	201,50	Reserve area
0,0005	0,032	33		33	184,59	Reserve area
0,0003	0,006	14		14	177,66	Reserve area
0,0003	0,044	24	12	36	171,94	Reserve area
0,0005	0,045	15	20	35	164,99	Reserve area
0,0002	0,010	7	6	13	129,48	Reserve area
0,0005	0,009	12		12	129,10	Reserve area
0,0006	0,013	11		11	95,74	Reserve area
0,0026	0,047	18		18	83,21	Reserve area
0,0026	0,081	16	7	23	81,01	Reserve area
0,0001	0,023	12		12	78,36	Reserve area
0,0016	0,040	15		15	75,00	Reserve area
0,0020	0,074	19		19	69,67	Reserve area
0,0011	0,025	10		10	63,45	Reserve area
0,0033	0,066	15		15	58,48	Reserve area
0,0013	0,038	11		11	56,22	Reserve area
0,0024	0,073	13		13	48,05	Reserve area
0,0085	0,085	10		10	34,36	Reserve area
0,0038	0,096	10		10	32,32	Reserve area
0,0171	0,206	11		11	24,25	Reserve area
0,1029	1,955	14		14	10,01	Reserve area
0,2025	3,240	15		15	8,33	Reserve area
0,1629	1,629	10		10	7,84	Reserve area
0,4106	4,928	12		12	5,41	Reserve area
0,2940	3,822	9	1	10	5,12	Reserve area

Figure 43 - 31 SKUs that have more than 10 yearly pickings but are not assigned to the fast pick area by chapter 3.

Appendix Y - Sketch of box racks and pallet racks in the fast pick area

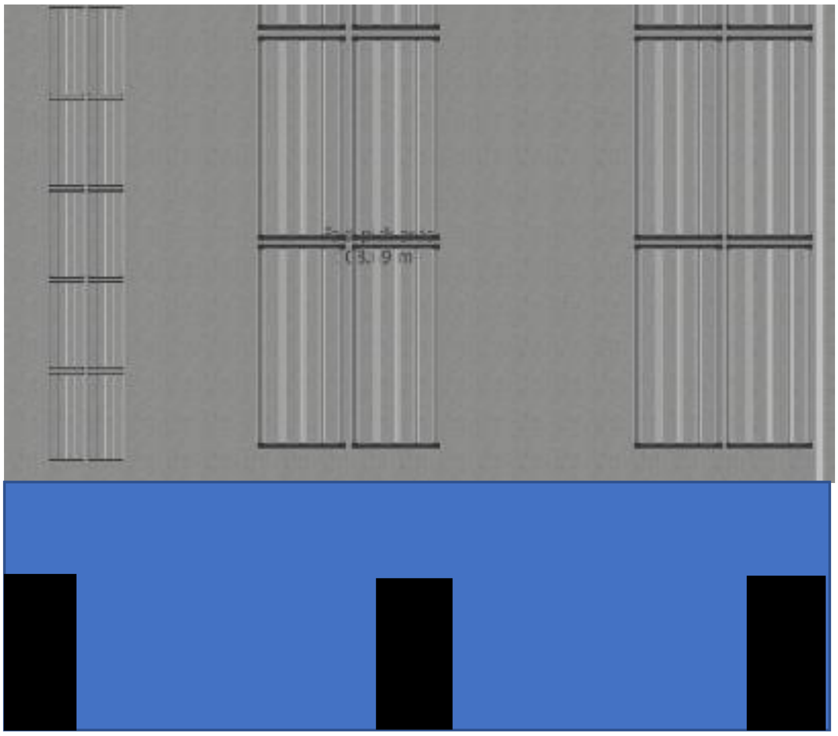


Figure 44 - Sketch of box racks and pallet racks in the fast pick area

Appendix Z - Warehouse storage bin

Figure 45 - Warehouse storage bin

Appendix AA – Algorithm to assign storage locations based on COI index

```
import pandas as pd
import numpy as np

SKUSortedonCOI = pd.read_excel("Input box racks storage allocation.xlsx")
print(SKUSortedonCOI)

LengthGrid = 20
WidthGrid = 2
HeightGrid = 4
NumberofSKUs = 52
DistanceArray = []
AssignmentArray = []

#set dimensions for 3D array
for x in range(LengthGrid):
    #breakpoint()
    if x == 0:
        DistanceArray.append([])
    DistanceArray.append([[]])
    DistanceArray[x] = [0 for i in range(WidthGrid)]
    for y in range(WidthGrid):
        DistanceArray[x][y] = [0 for i in range(HeightGrid)]
del DistanceArray[-1:]

#fill 3D array with distances
for x in range(len(DistanceArray)):
    for y in range(len(DistanceArray[x])):
        for z in range(len(DistanceArray[x][y])):
            if y == 0:
                DistanceArray[x][y][z] = x + y + 1 #always plus one for walking in the aisle
            elif y == 1:
                DistanceArray[x][y][z] = x + y + 3 #always plus three for walking in the aisle and across the aisle

#create an array wether storage locations are assinged or not
for x in range(LengthGrid):
    if x == 0:
        AssignmentArray.append([])
    AssignmentArray.append([[]])
    AssignmentArray[x] = [0 for i in range(WidthGrid)]
    for y in range(WidthGrid):
        AssignmentArray[x][y] = [0 for i in range(HeightGrid)]
del AssignmentArray[-1:]
```

Figure 46 - Algorithm to assign storage locations based on COI index part 1

```python
#init variables
NumberOfLocationstoAssign = 0

#loop through the SKU array and assign locations
for SKU_ID in range(NumberofSKUs):
    NumberOfLocationstoAssign = SKUSortedonCOI['Number of storage locations'].values[SKU_ID]
    MinDistanceFound = 100
    for x in range(len(DistanceArray)):
        for y in range(len(DistanceArray[x])):
            for z in range(len(DistanceArray[x][y])):
                if DistanceArray[x][y][z] <= MinDistanceFound and AssignmentArray[x][y][z] == 0: #check if there is a loca
                    MinDistanceFound = DistanceArray[x][y][z]
                    Xfound = x
                    Yfound = y
                    Zfound = z

    for LocationNumber in range(NumberOfLocationstoAssign):
        if LocationNumber == 0:
            AssignmentArray[Xfound][Yfound][Zfound] = SKUSortedonCOI['Interne referentie'].values[SKU_ID]
        else: #if we need to assign multiple storage locations we need to assign adjacent locations
            #the previous location found is NOT at the bottom floor location --> the storage location underneath is select
            if Zfound != 0:
                Zfound = Zfound - 1
                AssignmentArray[Xfound][Yfound][Zfound] = SKUSortedonCOI['Interne referentie'].values[SKU_ID]
            # the previous location found is at the bottom and NOT at the end of the aisle --> move up one location down t
            elif Xfound != LengthGrid - 1:
                Xfound = Xfound + 1
                Zfound = 3
                AssignmentArray[Xfound][Yfound][Zfound] = SKUSortedonCOI['Interne referentie'].values[SKU_ID]
            # the previous location found is at the bottom floor AND is in the last location down an aisle --> go to next
            else:
                #find first open spot in next aisle
                Yfound = Yfound + 1
                BreakOutOfXloopToo = False
                for x in range(len(DistanceArray)):
                    for z in reversed(range(len(DistanceArray[x][Yfound]))): #reverse loop required because always fill f
                        if AssignmentArray[x][Yfound][z] == 0:
                            # we have to set Xfound and Zfound if there is another loop to be done.
                            Xfound = x
                            Zfound = z
                            AssignmentArray[Xfound][Yfound][Zfound] = SKUSortedonCOI['Interne referentie'].values[SKU_ID]
                            BreakOutOfXloopToo = True
                            break
                    if BreakOutOfXloopToo == True:
                        break
print(AssignmentArray)
```

Figure 47 - Algorithm to assign storage locations based on COI index part 2

```python
#Calculate distance travelled
TotalDistanceTravelled = 0
for SKU_ID in range(NumberofSKUs):
    AverageDistanceSKU = 0
    SKUnumber = SKUSortedonCOI['Interne referentie'].values[SKU_ID]
    NumberOfLocations = SKUSortedonCOI['Number of storage locations'].values[SKU_ID]
    PickingFrequency = SKUSortedonCOI['Picking frequency'].values[SKU_ID]
    #find the storage locations in the assignment array
    for x in range(len(AssignmentArray)):
            for y in range(len(AssignmentArray[x])):
                for z in range(len(AssignmentArray[x][y])):
                    if AssignmentArray[x][y][z] == SKUnumber:
                        AverageDistanceSKU = AverageDistanceSKU + DistanceArray[x][y][z]
    AverageDistanceSKU = AverageDistanceSKU / NumberOfLocations
    TotalDistanceTravelled = TotalDistanceTravelled + AverageDistanceSKU * PickingFrequency

print("The total distance travelled is " + str(TotalDistanceTravelled))
```

Figure 48 - Algorithm to assign storage locations based on COI index part 3

Appendix AB - Distance grid for ABC zoning

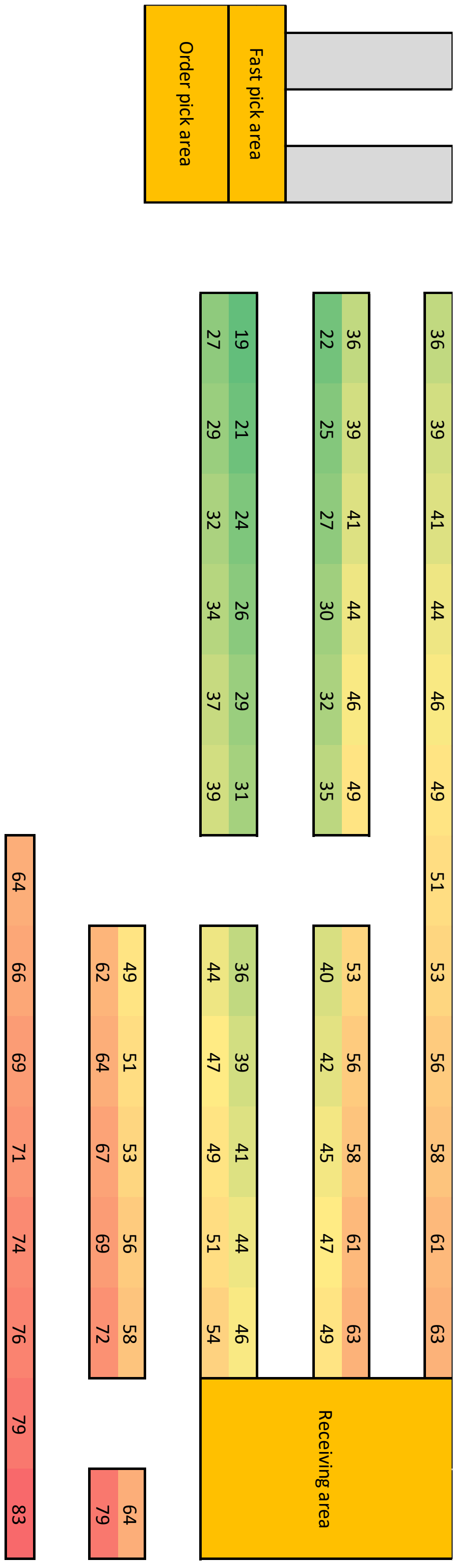


Figure 49 - Distance grid for ABC zoning

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