Improving the storage capacity of Twence’s central warehouse by testing alternative layouts

Bachelor Thesis

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Bachelor of Industrial Engineering and Management
10^{th} of March 2023

Bachelor thesis Industrial Engineering and Management

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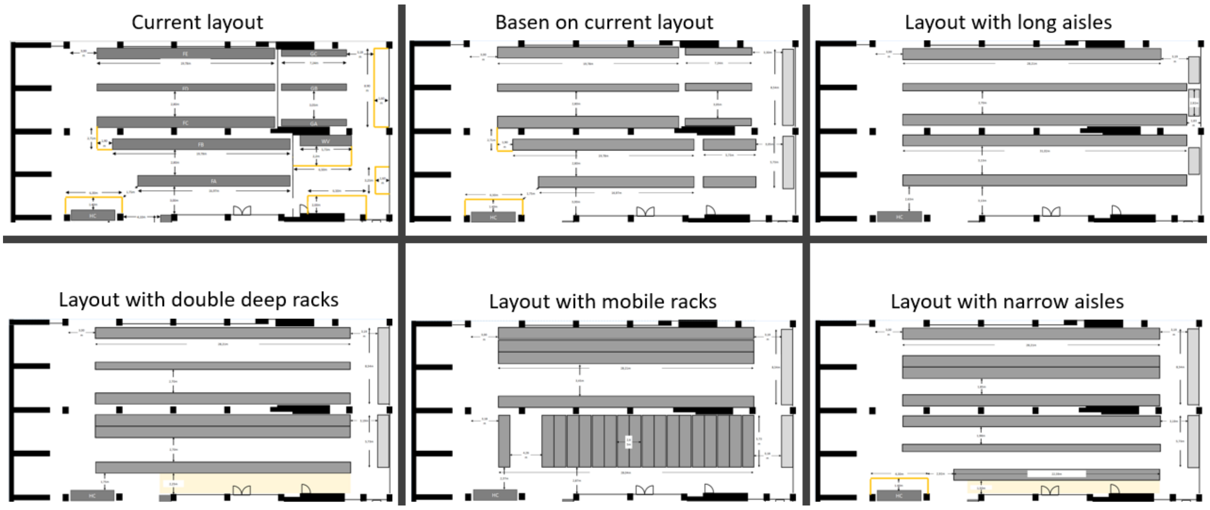
Management summary

Twence does not have enough storage space for the pallet loads in their central warehouse, resulting in sub-warehouses scattered on their site. This lowers the overview of the inventory locations. To improve the situation, this research answers the following action problem: *"How can the storage capacity of Twence's central warehouse be improved by at least 10% by testing alternative layouts?"*

To improve storage capacity and efficiency at the central warehouse, solutions were found through a comprehensive process that included mapping the current situation, analysing the layout, collecting data, and conducting a literature review. The alternatives were presented in Microsoft Publisher (see figure I) and their impact on key performance indicators (KPIs) such as storage capacity (in Euro pallet places), warehouse efficiency (as measured by average longest retrieval time, longest possible retrieval time, and accessibility), and costs were quantified using Microsoft Excel. Additionally, the storage allocation policy was also analysed to determine the most effective way to optimize storage capacity and improve warehouse efficiency.

Figure I: Overview of all the layouts



The KPIs are applied to five alternative layouts (see figure I). Each KPI has a weight, so a total score per layout can be given, these weights are stated together with the asset management team and the warehouse operators. The storage capacity weighs 0.5, the average longest retrieval time 0.1, the longest possible retrieval time 0.1, the accessibility 0.2 and the costs 0.1. Table I shows the impact of the layouts on the different KPIs.

Table I: Impact of the layouts on the stated KPIs

KPI	Current layout	Based on current layout	Long aisles	Double deep racks	Mobile racks	Narrow aisles
Number of pallet locations	824	885	1021	1159	1507	1312
Average longest retrieval time (minutes)	1.76	1.39	1.59	1.45	1.36	1.38
Longest possible retrieval time (minutes)	2.37	1.64	1.84	1.63	1.51	1.62
Accessibility (% of pallet locations that are directly accessible)	100%	100%	100%	88.09%	37.89%	100%
Costs	€ 0.00	€ 3,050.-	€47,100.-	€54,000.-	€292,740.-	€61,200.-

The explanation of the layouts and their influence on the KPIs are further elaborated below, and the main trade-offs are evaluated. The comparison of the KPIs is made by determining the percentual difference from the current layout:

- *Layout based on the current situation*
  The first solution involves the removal of roll-up doors in the warehouse to decrease the average retrieval time by 20.59%. Additionally, some ground storage areas are replaced with pallet racks, leading to a 7.40% improvement in storage capacity. This solution is the easiest and cheapest to implement as the existing racks can remain unchanged. The solution scores a total of 38.77%.
- *Layout with long aisles*
  This solution trades warehouse efficiency for increased storage capacity by extending the storage aisles and limiting access to one side. This results in a 23.91% improvement in storage capacity and a 9.65% decrease in the average longest retrieval time. The solution scores a total of 43.54%.
- *Layout with double deep racks*
  Double deep racks store inventory directly behind each other, resulting in the need for fewer aisles and thus better use of space. This solution improves the storage capacity by 40.66% and the longest average retrieval time by 17.49%. The overall weighted score is 50.31%.
- *Layout with mobile racks*
  Mobile racks are storage systems that move along tracks, allowing for compact storage and efficient use of space. It provides the most storage capacity, with an improvement of 82.89%. It also scores best for the longest average retrieval time, improving by 22.59%. The downsides are the poor accessibility of 38.89% and the high costs of approximately €292,740, resulting in a total score of 54.92%.
- *Layout with narrow aisles*
  This narrow aisles storage method has narrower than standard aisles, enabling high storage capacity in limited space. It requires specialized handling equipment such as very narrow aisle lift trucks to access stored pallets. This solution improves storage capacity by 59.22% and average longest retrieval time by 21.31%, achieving the highest overall score of 62.81% compared to all other solutions.

A summary of all the KPIs measured in percentage terms relative to the current layout is presented in Table II. It is important to note that cost efficiency is measured using a "cheapness score." The higher the score, the more cost-effective the solution is considered to be.

Table II: Percentual change of KPIs compared to the current layout

Layout	**Based on current layout**	**Long aisles**	**Double deep racks**	**Mobile racks (0.2)**	**Narrow aisles (0.1)**
Pallet locations (0.5)	7.40%	23.91%	40.66%	82.89%	59.22%
Average longest retrieval time (0.1)	20.59%	9.65%	17.49%	22.59%	21.31%
Longest possible retrieval time (0.1)	30.77%	22.27%	31.17%	36.44%	31.58%
Accessibility (0.2)	100.00%	100.00%	88.09%	37.89%	100.00%
Cheapness cost score (0.1)	98.96%	83.91%	81.55%	0.00%	79.09%
Weighted score	**38.77%**	**43.54%**	**50.97%**	**54.92%**	**62.81%**

To conclude, the narrow aisle layout (see figure II) achieved the highest overall score of 62.81% on the KPIs. This solution is recommended for Twence, but they should carefully consider their storage capacity requirements to ensure that this option meets their needs, or if another solution might be more suitable.

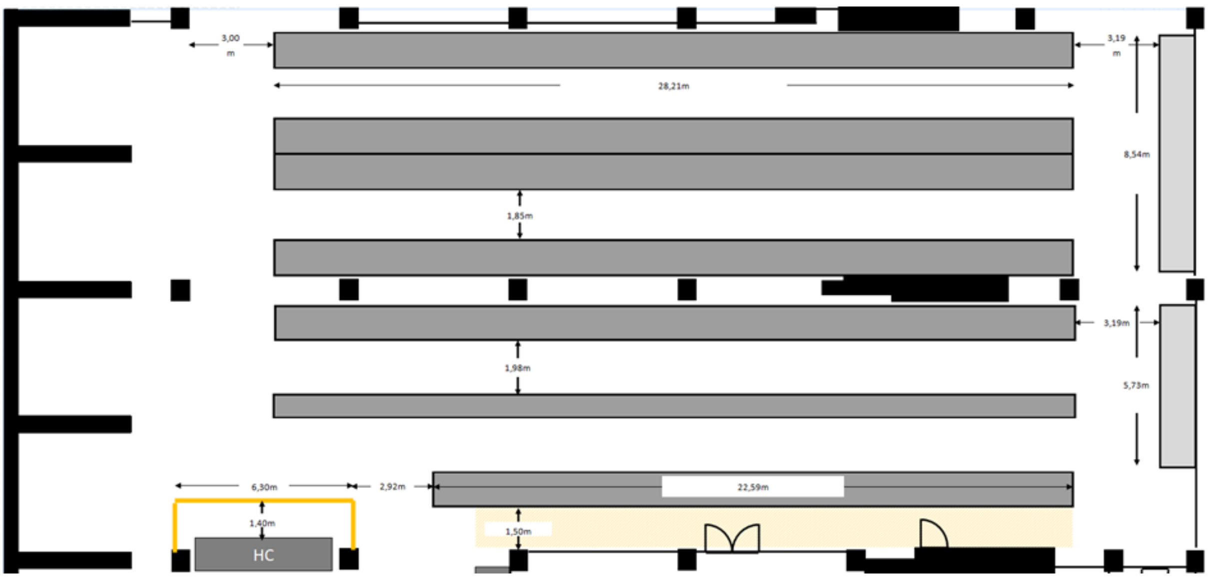


Figure II: Layout with narrow aisles

Besides recommending the warehouse with narrow aisles there are recommendations regarding the activities to be done after this research. The roadmap in table III is created to show the activities with their priority and responsible actors. High-priority activities are essential to the implementation of the solution, and without their completion, a new layout cannot be built. Medium-priority activities can be carried out after the best layout has been installed, and low-priority activities are optional improvements that can be made to the warehouse operation.

Table III: Roadmap for Twence to implement the solutions

Priority	Activity	Actors
High	Assess expected growth in required storage capacity for the next 5 years.	• Researcher (student or assigned employee) • Logistic company (e.g. Gordian)
High	Find the allowable costs and come up with an investment plan.	• Asset management • Board of Twence • Researcher (student or assigned employee)
High	Design and install the final layout.	• Asset management • Storage system company (e.g. STILL or Polypal)
High	Remove roll-up doors.	• Facility management • Asset management
Medium	In the case of a new lift truck, find a new lift truck and obtain the necessary certification to operate the truck.	• Warehouse operators
Medium	Find out which materials need special care or placement.	• Factory employees • Warehouse operators • Researcher (student or assigned employee)
Low	Apply the most suitable storage allocation policy.	• Warehouse operators
Low	Redesign the WMS to improve inventory location accuracy.	• IT department • Warehouse operators • Asset management • Logistic company (e.g. Gordian)

Preface

Dear reader,

Before you lies the bachelor thesis "Improving the storage capacity of Twence's central warehouse by testing alternative layouts". This thesis is written to finish the bachelor of Industrial Engineering and Management at the University of Twente. I was researching and writing my thesis from September 2022 till March 2023.

I recently undertook my first independent academic research project, which presented challenges but also allowed me to gain valuable experiences in research methodology, initiative, adaptability, and responsibility. I learned a lot at Twence and enjoyed working there. I am glad I challenged myself in this bachelor thesis with subjects I was not familiar with before.

I would like to thank Peter Schuur, Ipek Seyran Topan and Joris ter Heijne for their trust and guidance. Graduating at Twence was a great experience and I would like to thank all my colleagues there, who kept me motivated during my bachelor's thesis. A special thanks goes to the warehouse operators, who were always willing to help me and provide me with the needed information.

Stijn Jensema

Enschede, March 2023

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Acronyms

APR	Adjustable Pallet Racks
AS/RS	Automated Storage/Retrieval System
CO2	Carbon Dioxide
FIFO	First In First Out
KPI	Key Performance Indicator
LIFO	Last In First Out
MPSM	Managerial Problem-Solving Method
SKU	Stock Keeping Unit
SLAP	Storage Location Assignment Problem
SLAP/PI	Storage Location Assignment Problem/Product Information
VBA	Visual Basic Analysis
WMS	Warehouse Management System

1 Introduction

This thesis is written at Twence, a sustainable energy provider. Section 1.1 elaborates more on the company. The problem central to this research is identified in section 1.2 and eventually, the problem-solving approach is set up in section 1.3.

1.1 Company description

Twence is a sustainable energy company in Hengelo, The Netherlands, that generates energy from the sun, waste and biomass to power 138,000 households. They focus on making the energy production process as sustainable as possible through methods like filtering smoke to produce steam and capturing emitted carbon dioxide (CO2).

1.2 Problem identification

This section identifies the problem that Twence is facing. The problem and its context are stated in section 1.2.1. Here the core problem is found by making an overview of all the problems that Twence is currently facing. With the core problem, an action problem is formulated in section 1.2.2. The action problem is the question central to this research that measures the norm and reality.

1.2.1 Problem statement

To describe the problem central to this research (the core problem), the problem cluster in Figure 1 is designed.

To generate sustainable energy, the plant of Twence has large machines and installations. Therefore, the inventory mainly consists of spare and maintenance parts. These parts can weigh a few grams (e.g. screws) and thousands of kilograms (e.g. electromotors). Twence has been growing and innovating at a rapid pace, but its warehouses have not kept up with this growth.

Twence has a central warehouse and six sub-warehouses that have become insufficient due to the company's growth. The scattered storage locations, not designed for warehousing, have resulted in safety hazards, such as increased traffic and ineffective inventory management. Warehouse employees have also reported a lack of space for pallet loads. The root cause of these problems is the outdated warehouse design and increasing inventory demands.

In this research, "warehouse design" refers to the physical layout and storage policy of the warehouses. Currently, there is no plan for either aspect. The layout only uses basic "Adjustable Pallet Racking" (APR, see section 3.2.1) and alternatives have hardly been explored. The same applies to the storage policy. The random placement of tools fails to optimize storage capacity and efficiency. The outdated design results in inadequate storage space, multiple warehouses, and a lack of inventory control leading to energy production disruptions and missed revenue in case of machine breakdowns caused by difficulty in finding necessary tools.

Three core problems are described. The plans for which Twence needs extra tools are plans to grow and thus generate more sustainable energy. This is the main goal of Twence and therefore it is not possible to cancel these plans. Thus, the main core problem of the research must be one of the other two. Since the layout and storage policy can both be influenced and have a big impact on the warehouse, they are combined in the main core problem. Therefore, the main core problem of this research is:

"Twence has an outdated warehouse design"

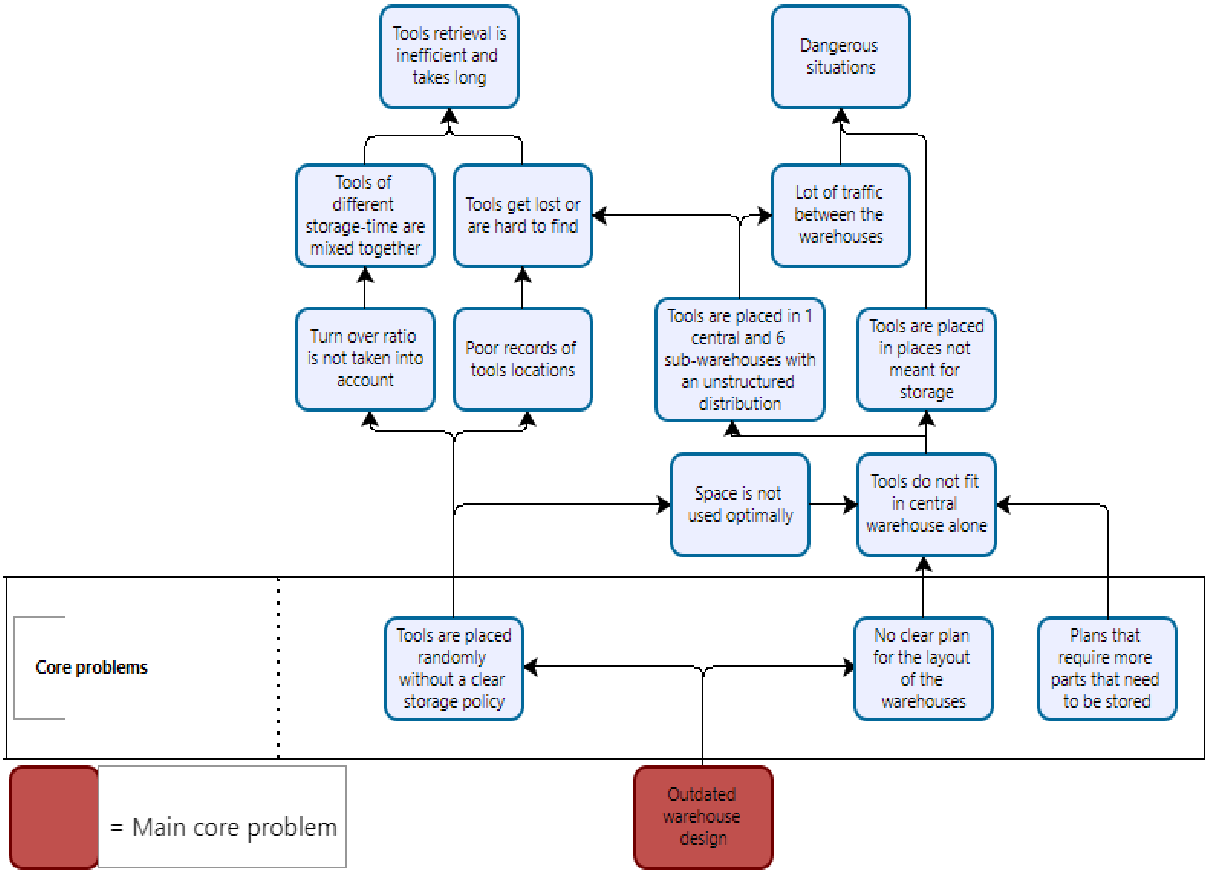

Figure 1: Problem cluster (the arrows show the relationships between problems, and the direction indicates which problem causes the other problem).

1.2.2 Action problem

With the core problem, the action problem can be derived. The action problem consists of a measurement between norm and reality that is about comparing the current situation to the desired situation. The difference between both situations is called the gap (Heerkens & van Winden, 2017). This gap must be bridged to meet Twence's desires. This section states this gap and combined with the core problem, aim and scope of this research the action problem is stated.

The reality is that Twence is starting to run low on storage space for pallet loads. This is a longer known problem and they tried to solve it by making "temporary" sub-warehouses which became permanent. There are now six sub-warehouses and one central, and this scattering of warehouses causes a loss of overview.

The desired situation, or norm, for Twence, is to improve its central warehouses' storage capacity by 10% while ensuring inventory retrieval efficiency. The more inventory is stored in warehouses close to the central warehouse, the easier it is for the warehouse employees to keep an overview.

The research will focus on identifying ways to improve the warehouse design at Twence, specifically targeting the central warehouse and its storage capacity for pallet loads. The storage and inventory allocation processes will be the primary focus of the research, as they are the most relevant to Twence's slow-moving inventory. The central warehouse has been chosen as the main area of focus due to its larger storage space and better inventory visibility.

This results in the following action problem: *"How can the storage capacity of Twence's central warehouse be improved by at least 10% by testing alternative layouts?"*

The deliverable is a helpful tool made in Microsoft Excel to test the impact of layout decisions on the central warehouse. Its main key performance indicator (KPI) is storage capacity. Other relevant KPIs and their importance are discussed in section 3.4 and stated in chapter 4. Finally, there will be advice on how Twence can use the taken steps to improve its central warehouse.

1.3 Problem-solving approach

To answer the action problem, the Managerial Problem Solving Method (MPSM) (Heerkens & van Winden, 2017) is used. The MPSM is a problem-solving method that can be used in most subject areas. It is designed for researchers who want to solve complex practical problems and use their creativity. The MPSM focuses on analyzing the problem, finding the solution that fits best and implementing the solution. Since this corresponds to the purpose of the research, the MPSM is used. The phases of the research are:

1. Defining the problem (Chapter 1, Introduction)
2. Formulating the problem (Chapter 1, Introduction)
3. Analysing the problem (Chapter 2, Current situation)
4. Formulating (alternative) solutions (Chapters 3 and 4, Literature review and Formulating alternative layouts)
5. Choosing a solution (Chapter 4, Formulating alternative layouts)
6. Implementing the solution (Chapter 5, Conclusion and recommendations)
7. Evaluating the solution (Chapter 6, Discussions)

Each of these phases describes activities and sub-research questions that should be answered to find the solution to the action problem. The problem-solving phases are linked to the chapters of this research.

Current situation
After chapter 1, the introduction, the current warehouse situation of Twence is discussed. The aim is to discover better what the problem is and how the warehouse is currently operated. This chapter involved interviews with employees at Twence, making observations and analysing the existing data. A good overview of the current situation is of great value when attempting to improve the situation. Making a floor plan in Microsoft Publisher gave an overview of the current layout. This served as a basis to test other layouts in Chapter 4, Formulating solutions.

Chapter 2 focuses on answering the following questions:

- *How is the current situation of the warehouses set up at Twence?*
    - *What are the characteristics of the inventory?*
    - *What is the current layout of the central warehouse?*
    - *What is the current storage allocation policy?*
    - *What is the current capacity of its central warehouse?*

Literature review
After the current situation, there is looked at what is known in the literature in chapter 3. This literature review investigates previous research to find out how similar problems are handled and solved by other researchers. The goal was to gain knowledge about optimizing the warehouse layout and storage policy to improve storage capacity. For the layout, hardware materials are looked at in the warehouse, such as forklifts, types of racks and the aisle width between these racks. Finally, different KPIs are discussed to measure the success of the layouts.

Chapter 3 focuses on answering the following questions:

- *Which methods and theories exist in the scientific literature about warehouse design to improve storage capacity?*
    - *What are the basic principles of a warehouse?*
    - *Which methods and theories exist about the internal layout of a warehouse?*
    - *Which methods and theories exist about storage policies in warehouses?*
    - *Which interesting KPIs are there for warehouse design?*

Formulating alternative layouts

In chapter 4, a model is developed based on the methods found in the literature review, aimed at testing ways to improve storage capacity. This model is created using Microsoft Excel and simulates a brownfield warehouse, where only the interior can be changed and not the exterior structure such as supporting walls. The model allows for different warehouse layouts to be tested and the impact on KPIs to be measured, providing Twence with a more informed decision-making process regarding its warehouse design.

Chapter 4 focuses on answering the following questions:

- *How can the found theories be applied to the central warehouse?*
    - *What are possible layouts to improve the warehouse design?*
    - *What KPIs could be measured?*
    - *What is the impact of the different layouts on the chosen KPIs?*
    - *How do the different layouts score overall?*

Discussions

Chapter 5 is dedicated to discussions. Here the validity and limitations are discussed.

Conclusion and recommendations

Chapter 6 summarizes the findings in the conclusion and provides recommendations for selecting the optimal solution and implementing it. It addresses the sub-research questions to answer the action problem. It will also shed a light on how to implement the solutions, the contribution of this research to practice and theory and what future research is required.

2 Current situation

Chapter 2 focuses on the current inventory management and storage practices within Twence. Section 2.1 describes the various categories of inventory and their respective storage locations on the site of Twence, as well as examining the characteristics of each type of inventory and how they are stored. Section 2.2 provides an overview of the current layout and describes the sizes of the building and the racks. Section 2.3 elaborates on this by discussing the current storage capacity. The storage allocation policy and distribution of SKUs based on their demand are shown in section 2.4. Section 2.5 states what aspects will be used further in the research.

2.1 Types of inventories

This section focuses on the characteristics of the inventory Twence is storing. It first examines the different types of warehouses scattered around the site and what type of inventory they store. Then it is stated what unit loads are used to store the inventory central to this research.

2.1.1 The different warehouses

The inventory in the warehouses mainly consists of spare parts to maintain the machines. All inventory is to keep the machines and thus the factory running. There are different kinds of inventory, and these are stored in different locations on the site of Twence. Table 1 shows the kind of inventory and in which warehouse department it is stored.

Table 1: Inventory type and their locations

Inventory type	**Warehouse location**
Grab stock	A (central warehouse)
Order parts	B (central warehouse)
Tools	C (central warehouse)
Mechanical parts	D (central warehouse)
Electrical parts	E (central warehouse)
Pallet loads	F, G, H, Z, Stop (central warehouse) and K, L (sub-warehouses)
Oil & grease	I (central warehouse)
Gas	J (sub-warehouse)
Plates & pipes	K, L (sub-warehouses)

Figure 2 shows the locations of the warehouse departments and sub-warehouses. Departments A up to H, Z and STOP connect and are called the central warehouse. There are also other smaller sub-warehouses which do not have an official name, these are marked with a colour. Section 2.2 further elaborates on the central warehouse, including the various types of inventory that are stored there.

Figure 2: Distribution of warehouses

This research focuses solely on the pallet load storage facilities F, G, H, and Stop, as they present the most significant challenges and Twence is looking to centralize storage more. Warehouses A to E, which store smaller items and have sufficient storage capacity, are not part of the study. Warehouses I and J, which store oil, grease, and gasses and require special storage conditions, are also excluded from the research. Warehouse Z, which is used for shredding waste and has limited storage space with no scope for improvement, is not part of the research.

2.1.2 Types of unit loads

In the warehouse departments handling pallet load inventory, there is a diverse range of item sizes and weights. Pallet loads refer to items stored on pallets, which can include multiple smaller items. Due to the variety of inventory types stored in the central warehouse, this section focuses on their key characteristics.

Pallets

Most stock-keeping units (SKUs) are stored on pallets (see Figure 3). These pallets differ in size. There are euro (1200mm x 800 mm) and block (1200mm x 1200mm)[1] pallets. Inventory stored on these pallets is mainly medium-sized. Therefore, there is usually only one item per pallet. Items often stored on pallets are smaller electro-motors, cables, and square-shaped boxes.

Figure 3: Pallet storage

[1] All measurements are stated in this report in the order of length x depth x height.

Boxes
Figure 4 shows storage boxes. It is a Euro pallet, where the sides are added. The height of the side is 0.32m and they can be stacked on top of each other to increase the height. To increase storage space utilization, it is possible to place another pallet on a box, as shown on the right in Figure 4. These boxes are convenient for small items which have a high quantity.

Figure 4: Box storage

Non-standard-sized inventory
In addition to standard pallets, there is also inventory that cannot be stored on standard pallets, referred to as non-standard-sized inventory. In the central warehouse for large inventory, there are plates and pipes (Figure 5) and inventory that is stored on larger pallets (figure 6) or exceeds the borders of normal pallets. The plates and pipes, which are long items, are stored on cantilever racks and are used for repairing isolation and replacing old or broken pipelines. The larger pallets or items that exceed the borders of normal pallets are mainly big rolls or electro motors.

Figure 5: Plates and pipes

Figure 6: Non-standard-sized pallet

Ground storage

When factory employees need items for immediate use, these items are often temporarily stored on the ground for easy access (see Figure 7). However, this leads to poor space utilization as items are only stored one level high. To improve space utilization, Twence should remove all ground storage and replace it with pallet racks. The first layer could still function as ground storage, but with the added advantage of storing heavier items and using the space above.

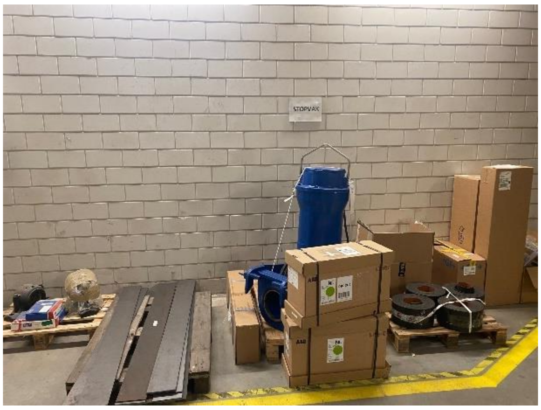

Figure 7: Ground storage

2.2 Current layout

Warehouse departments F, G, H and Stop form the central warehouse for pallet loads and pipes and are connected. These departments and their current layouts are depicted in Figure 8. The layout refers to where there is space for storage, where the office is located and where tools such as forklifts are placed.

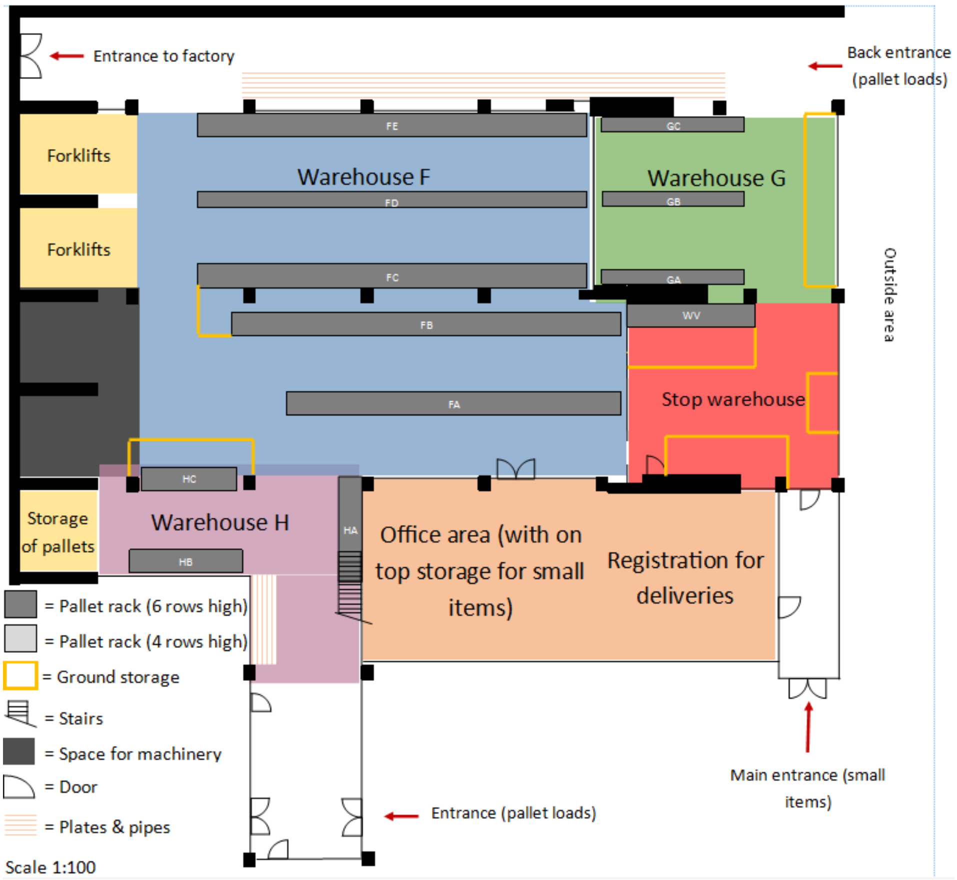

Figure 8: Current layout of the central warehouse

Deliveries are registered at the main entrance of the building. Smaller orders are carried in, while larger orders on pallets enter through a designated pallet entrance. Orders for immediate use and inventory for planned maintenance are temporarily stored in the Stop warehouse. Most orders, spare parts, are stored in warehouses F, G or H, but the current storage and retrieval process is not efficient. Roll-up doors (Appendix B, Roll-up doors) prevent warehouse operators from crossing between the racks between warehouses F, G and Stop to store or retrieve items.

Since most SKUs are stored on pallets, the pallet racks are the part where this research mainly focuses on. Currently, the sizes of the racks differ from each other. Racks FA, FB, FC, FE, WV, GA, HA, HB, and HC their shelves are 1200 mm deep and 2700 mm in length, the heights are variable. This means that on each shelf three Euro pallets (1200mm x 800mm) and two block pallets (1200mm x 1200mm) fit next to each other. On the other hand, pallet racks GA, GB, GC and FD are only 800 mm deep. Therefore, these racks can only store two Euro pallets (faced with their long side to the aisle) next to each other. Table 2 shows the dimensions of the racks, the frames are included in the total length of the racks, which are 110 mm each.

*Table 2: Dimensions of pallet racks in mm (mm). The length per rack is the useful storage space (bay width * number of bays). The number of shelves high is the number of shelves per bay.*

Rack	Rack length	Rack length excluding frames	Frame depth	Frame height	Number of storage levels high	Number of pallet locations
FA	16970	16200	1200	7000	6	108
FB	19780	18900	1200	7000	5	105
FC	19780	18900	1200	7000	5-7	117
FD	19780	18900	800	7000	5-8	96
FE	19780	18900	1200	7000	5	105
WV	5730	5400	1200	5500	5	30
GA	7240	6800	800	7000	5	35
GB	7240	6800	800	7000	7	49
GC	7240	6800	800	7000	8	56
HA	5730	5400	1200	5000	5	30
HB	5730	5400	1200	3500	4	24
HC	4830	4500	1200	5000	5	25

To manage the warehouse, a counterbalance truck and a reach truck are employed (see section 3.2.2, Lift trucks). The counterbalance truck is used to retrieve incoming items from outside and move them within the warehouse. Due to its wide turning radius, it cannot operate within the warehouse lanes. The reach truck is used to place items inside the racks, as it has a narrower turning radius. The reach truck currently in use can operate in aisles that are approximately 2750 mm wide (the precise turning width is not known) and can lift up to 1400 kilograms. Items that exceed this weight limit are stored in another warehouse where a counterbalance truck can operate.

2.3 Current capacity

Based on section 2.2 the current capacity is stated. This is expressed in the number of pallet locations. This will also be the measurement for the layouts designed in chapter 4, Formulating solutions. According to the warehouse management system (WMS), there are 520 pallet locations in use in the racks. This is including bigger-sized pallets. If everything would be stored on Euro pallets, there would be 780 pallet locations (=sum of the number of pallet locations per rack, from Table 2). The WMS shows that there are 791 different SKUs stored in 520 locations, so some pallets carry more SKUs. Therefore, it is interesting to test the impact of storing identical SKUs behind each other.

Later in this study, alternative layouts will mainly focus on warehouses F, G and Stop. After all, this is where the most opportunities for alternative layouts lie. Warehouse H has little to offer in this respect because of its constrained space. The racks can be 7000 mm high in warehouses F, G and Stop and there is currently space for 701 pallet locations. To calculate the total number of pallet locations in the other layouts, it must be known how many shelves high the racks are on average. In warehouses F, G and Stop are there on average 6 shelves placed on top of each other.

2.4 Current storage allocation policy

The different SKUs at Twence have a wide range of characteristics. Therefore, Twence currently stores the inventory based on its characteristics. This is shown in table 1. When an order arrives at the entrance, it is registered at the receiving area. While registering, the warehouse employees look at the function and size of each item and based on these they assign it to a certain warehouse. Table 2 shows where different types of SKUs are stored and Figure 2: Distribution of warehouses, shows where on the site these warehouses are located. However, when inventory enters a certain warehouse there is not yet a clear storage policy. The policy that currently comes closest is the random storage policy. Under a randomized storage policy, is the decision on the location of items left to the operator of the warehouse (Rouwenhorst et al., 2000). However, each warehouse operator may apply a different method. Some employees prioritize storing based on functionality while others focus more on size, resulting in an inefficient combination of random and classification-based sorting without clear classes.

The warehouses central to this research have two distinct types of storage for pallet loads. Warehouses F, G, and H are dedicated to storing spare parts, which are necessary for factory maintenance and replacements. These parts are often stored for extended periods, as it is difficult to predict when they will be needed. Failure to keep these spare parts in inventory could lead to significant delays in obtaining replacement parts. In contrast, the Stop warehouse holds inventory that is ordered by factory employees for daily operations. These items have faster delivery times than the large-sized spare parts.

An effective storage allocation policy in the future may involve class-based storage (see section 3.3). This approach could consider factors such as size and throughput time for each SKU. Higher-demand SKUs could be stored closer to operator posts, reducing travel time. As shown in Figure 9, storing many SKUs close to operators is not necessary, as around 20% of SKUs account for 80% of all order picks.

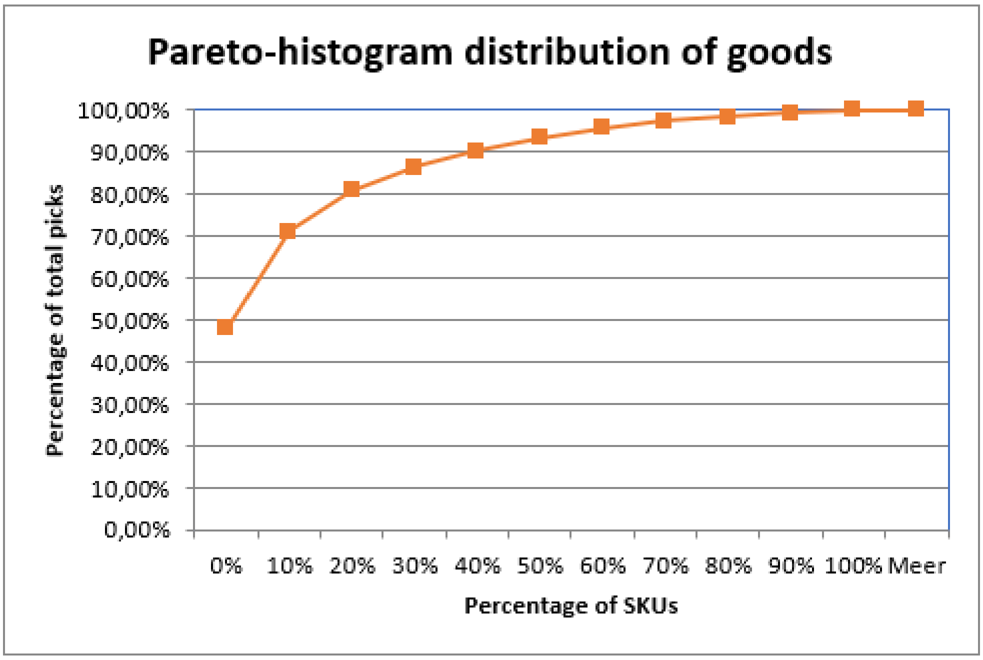

Figure 9: Pareto diagram showing that a few SKUs are responsible for most of the demand.

2.5 Summary

To summarize, there are several areas for improvement in the current warehouse layout. The large roll-up doors between warehouses F and G should be examined to determine whether they can be removed to improve retrieval efficiency. Additionally, ground storage should be optimized to take advantage of vertical space by considering the placement of pallet racks above the existing ground storage. By doing so, more storage capacity can be achieved, and SKUs that cannot be stored in racks due to weight can still be stored on the ground under the racks.

Moreover, implementing a different storage allocation policy could further enhance the warehouse's efficiency. Recall from Figure 9, that the analysis of order data revealed that 20% of SKUs are responsible for approximately 80% of all orders. Therefore, dedicating an easily accessible area of the warehouse to these frequently ordered SKUs could help warehouse operators retrieve them quickly and efficiently, resulting in reduced order retrieval times.

3 Literature review

Now the current situation is discussed, a literature review is conducted. The findings from these chapters will provide the foundation for the development of alternative solutions. The literature review begins in section 3.1 by exploring the basic principles of warehouse management. Section 3.2 delves into the principles of internal warehouse layouts, the design considerations that need to be taken into account, and the various storage methods and lift trucks available. The existing storage allocation policies are analysed in section 3.3. Finally, section 3.4 focuses on the KPIs that are relevant to the warehouse operations at Twence. Section 3.5 summarizes the chapter and states which parts of the literature review are included in the research.

3.1 Warehousing principles

A warehouse is a building used for the storage and distribution of goods. It plays a crucial role in the supply chain management process by providing a central location for product storage, organization, and distribution.

One of the primary functions of a warehouse is to store inventory. This includes raw materials, finished products and spare parts. Warehouses are typically designed with specialized storage systems, such as racks and shelves, to ensure that goods are stored efficiently and safely. In addition to storing inventory, warehouses are also responsible for receiving and inspecting incoming products as well as organizing and labeling items for easy access and retrieval. After storing goods in a safe and organized manner, proper inventory management is needed. This involves keeping track of the quantity, location and condition of the goods being stored. Proper inventory management helps to ensure that products are readily available when needed and helps to minimize the risk of lost or damaged goods (Frazelle, 2002).

Another main function of a warehouse is to process orders. Normally, this involves receiving and verifying customer orders, selecting the appropriate products from inventory, and preparing them for shipment (Sheffi, 2005). For Twence are shipments to and orders from customers not relevant since no finished products are produced. The orders that should be processed are from factory employees and contractors who need spare parts from the warehouse.

The warehouse of Twence is a "service parts distribution center," which is known to be one of the most challenging types of warehouses to manage (Bartholdi & Hackman, 2019). These warehouses store spare parts for expensive and complex capital equipment, which results in many parts with varying characteristics. This makes it difficult to predict the demand for individual parts, leading to a high level of variance in demand, and requiring a large safety stock. Additionally, many parts have a long lead time, which further increases the need for extra safety stock, as speed is of the essence when it comes to repairing production lines in a factory. Longer repair times result in increased costs for an organization. Overall, service parts distribution centers require more storage space, increasing the total travel distance and making order picking less efficient (Bartholdi & Hackman, 2019).

Besides storage and order processing, a warehouse for spare parts also has other functions. According to Frazelle, (2002) and Rushton et al., (2000) are these:

- To provide a buffer to smooth variations between supply and demand.
- To enable procurement savings through large inventory purchases.
- To cover for planned or breakdown production shutdowns.
- To cover for seasonal fluctuations in demand.
- To protect inventory from theft, fire and weather.

A big aspect of warehousing is warehouse design. Warehouse design is not only about the physical design inside and outside the warehouse, but also about choosing the types and quantities of equipment, operating systems and methods, information and communication systems and staff levels (Rushton et al., 2000). According to Rushton et al., (2000), the design of a warehouse contains the following steps:

- Define system requirements and design constraints.
- Define and obtain data.
- Analyse data.
- Establish what unit loads will be used.
- Postulate basic operations and methods.
- Consider possible equipment types for storage and handling.
- Calculate equipment quantities.
- Calculate staffing levels.
- Prepare possible building and site layouts.
- Evaluate the design against system requirements and constraints
- Identify the preferred design.

In this research, the focus is first on obtaining the required data and analysing this data. The chosen unit loads are only Euro pallet loads to fit the research scope. The study also covers design constraints, equipment types, possible site layouts, and their evaluation, along with the preferred design. Additionally, a roadmap is developed for Twence, highlighting the crucial steps required for the design of a warehouse that were not in the scope of this research.

To conclude, effective warehouse management is essential for the smooth operation of a business. It helps to ensure that products are available when needed, minimizes the risk of lost or damaged goods, and facilitates the efficient distribution of products. As such, warehouses play a vital role in the supply chain of Twence and many other businesses.

3.2 Internal warehouse layout

This part of the literature review for this research is about the internal layout of warehouses. The internal warehouse layout refers to the physical design inside an already existing warehouse. The eventual goal of Twence is to centralize its large inventory. One way to achieve this is by looking at ways to increase the storage capacity of the central warehouse for pallet loads. Twence is willing to change its complete internal layout, so one way of doing this is by looking at the existing storage methods and the corresponding equipment.

3.2.1 Storage methods

Shah & Khanzode, (2015) state that SKUs can be stored in a palletized and non-palletized way, and it gives for each an overview of the most common storage and handling methods, see Appendix C, Taxonomy for storage and handling system (Shah & Khanzode, 2015). As stated in Section 2.1.2, the unit loads that are used at Twence are wooden pallets, mostly Euro pallets (800mm x 1200mm). Here the research looks at the different types of racks. Some racks will improve the storage density and thus capacity but have as a trade-off that they make retrieval less efficient. Figure 10 shows how different storage methods score on different KPIs (Rushton et al., 2000).

Figure 10: Comparison between different storage methods.

Factor	Block	Drive-in	APR	DD	VNA	Mobile	Live	Push Back	High Bay
Use of Floor Area	5	5	1	3	3	5	5	5	4
Use of Building Volume *	5 to 2	5	2	3	3	5 +	5	5	5
Ability to Go High	1	4	4	4	5	4	4	4	5 +
Speed of Throughput	4	3	5	4	5	1	5	3	5
Access to Stock	1	1	5	4	5	5	2	2	5
Suitability for Picking	2	1	5	4	4	1	5	1	1
Stock Rotation (FIFO)	1	1	5	4	5	5	5	3	5
Product Damage	1	3	4	4	4	4	4	4	5
Easy to Manage	3	3	5	4	5	5	5	3	5
Fire Protection	5	3	4	3	3	1	3	2	2
Rack Cost	5 + no cost	3	4	3	3	1	1	1	3
Other Costs†									

* depends on building height
† depend on overall system

APR adjustable pallet racking
DD double deep racking
VNA very narrow aisle racking – access by high rack stacker truck lifting to say 12/13 metres in say 1.8-metre aisle
FIFO First-in-first-out stock rotation

Rushton, A., Oxley, J., & Croucher, P. (2000). Handbook of Logistics and Distribution Management. Kogan Page.

Rushton et al., (2000) state the key factors influencing the choice of storage methods:

- The nature and characteristics of the inventory held.
- The effective horizontal and vertical utilization of the building volume.
- The desired accessibility to every item.
- Compatibility with information system requirements.
- The personal safety in the warehouse.
- The maintenance of inventory conditions.
- The overall system costs.

Finally, Rouwenhorst et al., (2000) established a warehouse design framework for a strategic, tactical and operational decision-making approach. The strategic level focuses on warehouse design decisions that have a long-term (5 years) impact and concern high investments. It should be checked with Twence for what term they want to impact the warehouse design. Because according to Rouwenhorst et al., (2000), for long-term impact there should be focussed more on warehouse layout and for tactical level (2 years) impact there should be focussed more on the storage location assignment. However, for this research, it might be best to take parts of both levels and combine theories about layout and storage location assignment.

Block stacking

Block stacking, in which palletized goods are directly stored on top of each other, is a basic and widely used storage method around the world. It is particularly useful for companies with a low number of SKUs and low-value products (Richards, 2011). One of the main advantages of block stacking is the cost savings from not needing storage racks, as well as the efficient use of floor space. However, block stacking is only advisable for warehouses where the last-in-first-out (LIFO) principle is acceptable (Rushton et al., 2000). This means that each row should contain the same SKU and be completely emptied to avoid trapping older inventory at the back. While this can decrease the average utilization rate per pallet location, it also means that pallet loads cannot be stacked too high, limiting the use of vertical space.

Adjustable pallet racking (APR)

Another popular storage method is APR, also known as single deep racking, which stores all pallets in a single row. This type of rack consists of upright frames and horizontal beams that support the pallet loads, with adjustable beam heights to optimize the use of vertical space (Rushton et al., 2000). However, this function is not commonly used due to the preference for standard height pallet locations, which appear more organized and aesthetically pleasing (Richards, 2011). APR is also used for wide aisle and narrow aisle storage.

Wide aisle racking is the most common and versatile racking system and does not require specialized handling equipment. It is typically used with a counterbalance truck, allowing for easy placement and retrieval of loads. This rack can store a wide range of items on pallets and offers easy access to each pallet, as well as being easy to install, repair, and adjust. However, the use of a counterbalance truck requires a wider turning circle, resulting in more space being reserved for aisles rather than storage. The use of other trucks, which have a smaller turning circle, can reduce the aisle width (Richards, 2011).

The use of other lift trucks enables the aisles to become narrower, the required aisle width can be reduced to as little as 1.6 meters, enabling more efficient use of storage space. Some trucks still need to rotate, but the trucks that can operate in the very narrow aisles have forks that extend from the side, removing the need for turning space. However, narrow aisle racks can be more complex to install and operate compared to wide aisle racks and may require a very flat floor, especially at heights greater than 10 meters, as well as a guidance system such as guide rails to assist the trucks. Some trucks can achieve the same ails width without the need for a very flat floor and guide rails (Richards, 2011).

Double deep racking

Double deep racking is a type of storage system that is similar to APR, but with deeper storage bays. It is designed to allow businesses to store pallets two deep in each storage bay, rather than just one deep as with APR. While it improves space utilization by reducing the number of needed aisles, a business should be able to lose some directly free access to stock. However, this is not as nearly as much as with block, drive-in or push-back storage (Rushton et al., 2000). To avoid this double handling, it is advised to fill each lane with a single SKU. This may result in lower utilization of pallet positions, around 85%, due to unoccupied spaces when an SKU has an odd number of pallets (Bartholdi & Hackman, 2019; Rushton et al., 2000). To reach the further placed pallets, a double-reach truck is needed.

Push-back racking

Push-back racking is a type of high-density storage system. It consists of inclined rails on which pallets are placed, mounted on carts that can be pushed back into the rack as new pallets are added. When a pallet is needed, the front pallet is removed, and the rest of the pallets roll forward to fill the space. This uses LIFO inventory management. A push-back rack is normally between three to five pallets deep and each lane consists of the same SKU (Richards, 2011; Rushton et al., 2000).

Push-back racking is known for its efficiency and safety, as it reduces the amount of time and labour needed to retrieve pallets and reduces the need for powered material handling equipment compared to other multi-layer deep racks. However, it may be more expensive to install than other types of racking systems and may not be as durable in environments with heavily loaded pallets or subject to vibration (Rushton, 2010).

Drive-in and drive-through racking

This type of racking allows trucks to drive into the racks to place and retrieve loads (Bartholdi & Hackman, 2019). It functions the same as block stacking, but now the loads do not rest on each other, but on racks. Each lane should be dedicated to a single SKU, resulting in a pallet position utilization of about 70 per cent (Rushton et al., 2000). This type of racking is advantageous compared to block stacking because it can be used for loads that are not suitable for stacking and it allows for higher storage (Rushton et al., 2000). With drive-in racking, the storage and retrieval processes are performed from the same aisle. Therefore, the LIFO process takes place. On the other hand, drive-through racking takes the storage place on one side and the retrieval on the other side of the rack, resulting in a first-in-first-out (FIFO) process (Bartholdi & Hackman, 2019). A disadvantage of the drive-in and drive-through racking is that manoeuvring through the narrow lanes requires a skilled driver, which is more expensive (Bartholdi & Hackman, 2019).

(Powered) Mobile racking

Mobile racking, also known as "compact storage," is a type of storage system that is used to maximize the use of space in warehouses and other storage facilities. It consists of rows of pallet racks or shelving units that are mounted on mobile bases and can be moved easily using a variety of mechanized or manual systems (Richards, 2011; Rushton et al., 2000). This allows for a greater number of storage lanes to be placed within a given area, while still allowing access to individual lanes. Mobile racking systems can be used to store a wide range of materials, including palletized goods, boxes, bins, and other items (Rushton et al., 2000).

The retrieval process becomes slower when space utilization increases significantly, as the right aisle must first be made accessible. However, this layout is suitable for storing a large number of SKUs that make up the "Pareto tail", where a small portion of the inventory accounts for a large portion of all orders. The “slower moving” SKUs, which have low stock and low throughput, can be placed in the mobile racks where retrieval is less efficient (Rushton et al., 2000).

Automated Storage and Retrieval System (AS/RS)

AS/RS is a more advanced storage method and uses a computer to manage and control the movement of loads (Rushton et al., 2000). AS/RS systems typically consist of racks, with one or more cranes running through aisles between racks to store and retrieve loads. These cranes do not need an operator and thus are fully automated (Roodbergen & Vis, 2009). There are different types of AS/RSs and they are classified based on the type of storage and retrieval system it uses. This research focuses on palletized storage. For this type of inventory, is the unit load AS/RS interesting.

The advantages of an AS/RS over non-automated systems, are that it saves labour costs, improves space utilization, increased reliability and reduces the number of error rates (Roodbergen & Vis, 2009). Disadvantages are that it is a costly installation, with a long payback period (according to Zollinger, (1999) $634.000 per AS/RS aisle), and it lacks flexibility (Roodbergen & Vis, 2009).

3.2.2 Lift trucks

To operate in the aisles there are different types of lift trucks. Some storage methods mentioned in section 3.2.1, require different lift trucks than those currently used at Twence. An elaboration on the features of these lift trucks is given in Table 3: Different types of palletized lift trucks.

Table 3: Different types of palletized lift trucks

Type of truck	Explanation	Aisle width
Counterbalance lift truck	This versatile lift truck is commonly used for carrying loads at the front of the vehicle. The weight of the truck is distributed towards the back to prevent tipping. Despite being robust and fast, these trucks require a 90-degree turning angle for accessing pallets in racks, resulting in wider aisles compared to other types of lift trucks (Rushton et al., 2000).	Sit down version: 3.7-4.6 meters Stand-up version: 3.1-3.7 meters
Reach and double reach truck	The lift truck is designed with a reach mechanism that can extend to access pallets in storage racks, allowing for narrower aisles. The lift truck can be classified as a reach truck if it can reach one rack deep, or a double reach truck if it can reach two racks deep. This truck rotates 90 degrees to align with the pallet rack, extends the reach mechanism to place or retrieve the load, and then retracts the mechanism so the load sits atop the central weight of the truck (Rushton et al., 2000). Additionally, reach trucks are often supported by outriggers that extend forward to prevent the truck from tipping over, in this case, the bottom level of the pallet rack is raised by a few centimetres (Bartholdi & Hackman, 2019).	2.1-2.7 meters
Turret truck	Turret trucks are designed to operate with a little more aisle space than their width (Richards, 2011). They utilize a turret that turns 90 degrees to the left or right, eliminating the need for the truck to rotate. However, due to the narrow aisles, a guidance device such as rails, wire or tape is required to navigate. Additionally, the use of a super flat floor is also needed which can add to the cost, and they also require large transfer gangways to switch between aisles(Bartholdi & Hackman, 2019; Richards, 2011).	1.5-2.1 meters
Articulated forklift truck	This is a type of lift truck that has a flexible joint in the middle of the vehicle, allowing the front and rear sections of the truck to turn independently of each other. Allowing for a much tighter turning radius than traditional lift trucks, making them well-suited for narrow aisles (Richards, 2011). One of the main advantages of articulated forklifts is their ability to navigate tight spaces and manoeuvre around obstacles with ease. They are also well suited to work in outdoor terrains, thanks to their higher ground clearance and	1.7-2.0 meters

	ability to turn in tighter spaces. They are also good at handling heavy loads (Richards, 2011). Articulated forklift trucks may have higher acquisition and maintenance costs compared to other types of lift trucks. They also require more operator training and can be harder to operate. The efficiency of put-away and retrieval tasks will depend on the skill level of the operator (Richards, 2011).	

3.3 Storage allocation policy

According to Gu et al., (2007), there are several ways to determine the physical location of where arriving items will be stored. The overall theory is called the "storage location assignment problem (SLAP)". One theory which applies to this research is the storage location assignment problem based on product information (SLAP/PI). This theory is designed for warehouse situations where only product information is known about items and not the complete information about for example the arrival and departure time of each item. These individual items can be stored in different ways. These three ways are discussed here:

Dedicated storage policy

According to the dedicated storage policy, every item is assigned a specific storage location (Fumi et al., 2013). This policy can lead to higher tool retrieval efficiency as more popular items can be stored in better locations and workers can learn the layout, reducing the need for a WMS (Bartholdi & Hackman, 2019). However, it also decreases the pallet location utilization and therefore, the necessary storage capacity increases (Bartholdi & Hackman, 2019; Gamberini et al., 2008). As the current goal of Twence is to improve the storage capacity of the central warehouse, this policy may not be the best choice at this time. On the other hand, Twence wants to centralize its inventory to get a better overview of the inventory locations, and this policy can improve this overview (Gamberini et al., 2008). It may be worth considering when there is enough storage capacity available in the future.

Randomized storage policy

Under a randomized storage policy, the decision on the location of items is left to the operator of the warehouse (Rouwenhorst et al., 2000). When an item is received, the operator locates a vacant space and places the item there, while recording its location for future retrieval. This policy increases picking time due to the necessity of searching for the desired product but decreases the required storage capacity (Gamberini et al., 2008). This policy might be interesting to this research since it provides the maximum storage capacity for a warehouse. While the randomized policy may provide more storage space, it may not meet Twence's needs for easily findable and traceable inventory.

Class-based storage policy

The class-based storage policy is a method of organizing and storing items within a warehouse that combines elements of both randomized and dedicated storage policies. Under this method, inventory is grouped into classes based on factors such as demand, product type, and size. Each class is then assigned to a designated block of storage locations within the warehouse. Within these blocks, items are stored randomly, making use of the space more efficiently and improving the overall organization and access to inventory (Larson et al., 1997). A warehouse normally uses two to five storage classes (Gu et al., 2007).

One commonly used method for classifying inventory is the ABC classification, which groups items based on their turnover rate. Items are divided into three classes: A (fast-moving), B (slow-moving), and C (non-moving). Appendix D, ABC classification (Sarudin & Shuib, 2016) shows what an ABC classification looks like in a warehouse (Sarudin & Shuib, 2016). This method can be useful for Twence, as it allows for the fast-moving items to be stored in a more easily accessible location, close to the warehouse operator's office, while the slow-moving and non-moving items are stored in less accessible locations. The items that have less demand tend to be bigger at Twence. If these items are placed somewhere, they are not easily replaced by someone who forgets to record the new location. Thus, the ABC classification could result in higher use of space while providing a better overview for warehouse employees.

Another interesting criterion to consider is classes based on their functionality, also called "correlated storage or family grouping" (Rouwenhorst et al., 2000). In this case, products often used simultaneously are stored at nearby positions. For Twence it is also interesting to store similar-sized products in the same area. This way the height of the beams in the racks can be adjusted to make better use of the space.

3.4 Performance measurements

There are many indicators to measure how well a warehouse is performing. Appendix E, Warehouse performance indicators(Staudt et al., 2015) shows many of the most common performance measurements (Staudt et al., 2015). In this section are the indicators discussed that are interesting for Twence to measure.

Measuring warehouse performance is important for efficient and effective operations. A warehouse performance measurement system includes metrics for measuring resources (input), results (output), efficiency, and effectiveness. These metrics can include personnel, equipment, and materials used, storage capacity, orders fulfilled, and inventory accuracy (Kusrini et al., 2018).

Some companies, such as Twence, store most of their inventory for long periods. To ensure cost-efficiency, large quantities of these items are typically stored in inexpensive storage systems such as APRs. The primary design consideration for this type of warehouse is maximizing storage capacity while keeping both investment and operational costs low (Rouwenhorst et al., 2000). Furthermore, items such as spare or work-in-progress parts, which have uncertain demand but must be quickly retrieved to prevent production delays, have different requirements. For these items, response time is the most critical factor (Rouwenhorst et al., 2000). Finally, recall from section 3.2.1, that Rushton et al., (2000) mentioned that the accessibility of each item influences the choice of storage methods.

3.5 Summary

The information from the literature review that is mainly used is about the different storage methods. These storage methods have the most influence on the stated KPIs. From the literature review on these methods in section 3.2.1 it can be concluded that not all these storage methods are relevant for Twence. Storage methods such as block stacking, push-back and drive-in or drive-through racking are better suited for warehouses that store many pallet loads that store the same SKU. This way the identical SKUs can be stored behind each other. Recall from section 2.3 that Twence mainly stores different types of SKUs. Finally, the AS/RS will not be discussed since it is too expensive and it is especially useful for warehouses with fast-moving inventory, which is not the case at Twence. Therefore, are the following storage methods chosen to test (see section 4.2 Alternative layouts):

- APR (in the form of the currently used racks, long aisles and narrow aisles)
- Double deep racking
- Mobile racking

The lift trucks are also discussed as a means to operate in a certain storage method since some designs have smaller aisles and thus require other lift trucks. If the physical designs and requirements are stated, the best-suiting storage allocation policy is later in the research discussed per solution. Finally, to test the alternative internal layouts, the following KPIs are chosen, based on section 3.4:

- Storage capacity (in number of pallet locations)
- Average longest retrieval time (minutes)
- Longest possible retrieval time (minutes)
- Accessibility (% of pallet locations which are directly accessible)
- Costs to install the storage racks (€)

4 Formulating solutions

Based on knowing the current situation and its problems and finding methods by conducting a literature review, this chapter focuses on finding the best suitable solution for Twence's central warehouse. New layouts are designed by incorporating methods from the literature and examining the existing layout. Section 4.1 outlines the process of designing alternative layouts, including the methods and assumptions used. In section 4.2, the alternative layouts are presented, and the design choices, lift truck matching, and storage allocation process are explained. Section 4.3 evaluates the layouts by measuring different KPIs. With these KPIs are the layouts compared with each other in section 4.4. Here an overall score is determined by calculating a weighted average of the KPIs. Additionally, a sensitivity analysis is performed in the section to assess the robustness of the final score.

4.1 Designing alternative layouts: Process and Assumptions

This chapter aims to design alternative internal layouts for Twence's central warehouse and deliver a tool to test the layouts and measure the impact. The tool should give a measurable impact on the chosen KPIs and Twence should be able to use the tool itself.

The first step was to measure the dimensions of the warehouse using measurement devices and CAD (Appendix A, Dimensions of the central warehouse). With these measurements, the central warehouse is mapped in Microsoft Publisher (see Figure 11). In this map different internal layouts are drawn on a scale of 1:100. The layouts are further worked out in Microsoft Excel to calculate the later stated KPIs and compare the results. Publisher in combination with the dimensions is used to calculate the available space for aisles and storage places for the alternative layouts.

Figure 11: Measurements of aisles and storage places of the current layout in Publisher

The space for racks is calculated based on "beams". A beam is the space between two frames and is at Twence typically three Euro pallet places or 2700 mm wide, with a few exceptions where they are smaller, and are 1200 or 800 mm deep. Each frame is 110 mm wide. To calculate the length of a rack, the following formula is used, where n is the number of pallet beams and w is how wide that beam is (in the case of Twence mostly 2700 mm):

$$Length\ of\ pallet\ racks\ in\ mm\ =\ n * w + (n+1) * 110$$

Before presenting alternative internal layouts, certain assumptions are made. Adequate clearance must be maintained between walls and racks. Twence currently uses racks from Polypal Storage Systems, which require 50 mm of cross-aisle and 100 mm of down-aisle clearance space between pallets and walls. Additionally, 100 mm of clearance is required between connecting pallet rows (e.g. double deep racks).

Furthermore, it is assumed that ground storage is not an efficient use of space and efforts will be made to utilize above-ground storage. However, if space constraints make this impossible and ground storage improves overall storage capacity, it will be included in the layout. The roll-up doors are also removed in all layouts.

Finally, the aisle widths and rack depths in warehouses F, G and Stop currently differ because in F the width between the wall and support pillars is 8900 mm and in G and Stop this is 8700 mm. The alternative layouts consist of continuous racks (except for the layout based on the current situation), so the narrowest point of 8700 mm is taken to calculate the space for aisles and racks. The narrowest aisle to drive through is currently 1750 mm wide; this minimum width will be maintained in the alternative layouts. The side aisles will be at least 3000 mm wide to accommodate all types of trucks and any type of load for easy movement.

4.2 Alternative layouts

After stating the required processes and making assumptions, the alternative layouts are designed in Publisher. All layouts are validated with the warehouse operators. The following layouts are developed and evaluated:

- Layout 1: Based on current layout. Here a lean method is applied, resulting in the removal of the roll-up doors and replacing ground storage with racks where possible.
- Layout 2: Long aisles. This improves the storage capacity but reduces the retrieval efficiency.
- Layout 3: Layout with double deep racks. Here similar SKUs are stored behind each other. The other SKUs are stored in normal racks.
- Layout 4: Mobile racks. This storage system moves on tracks, allowing for more compact storage.
- Layout 5: Narrow aisles. Here the use of specialized lift trucks allows for narrower aisles resulting in better use of space.

Warehouse H does not change in the layouts, so only warehouses F, G and Stop are shown in the figures. The legend from Figure 11 applies to all layouts. Each layout is further elaborated on in this chapter.

4.2.1 Layout 1: Based on current layout

The layout based on the current situation (see Figure 12) maintains the existing racks while making several changes to improve the placing and retrieval process and the storage capacity. The roll-up doors are removed, and some ground storage is replaced by pallet racks. Recall that this is done to improve efficiency and make better use of space. On the right side, two pallet racks are added, each approximately four beams high. However, the top rack is limited by a window at 4900 mm, and the other rack is limited by pipes on the ceiling. These pallet racks are also included in other layouts.

The only aisle width that changes is on the right side, which will become the widest aisle at 3300 mm. The narrowest aisle remains at 2800 mm, allowing Twence to continue using their existing reach truck.

The relevance of the storage allocation policy to the layout is limited. A dedicated storage policy may not greatly increase the number of pallet locations for Twence. However, organizing inventory based on size can optimize storage space utilization by allowing for adjustable beam heights. Additionally, heavy pallet loads are best placed on the ground on the side for easier handling by counterbalance trucks, which have there enough space to operate.

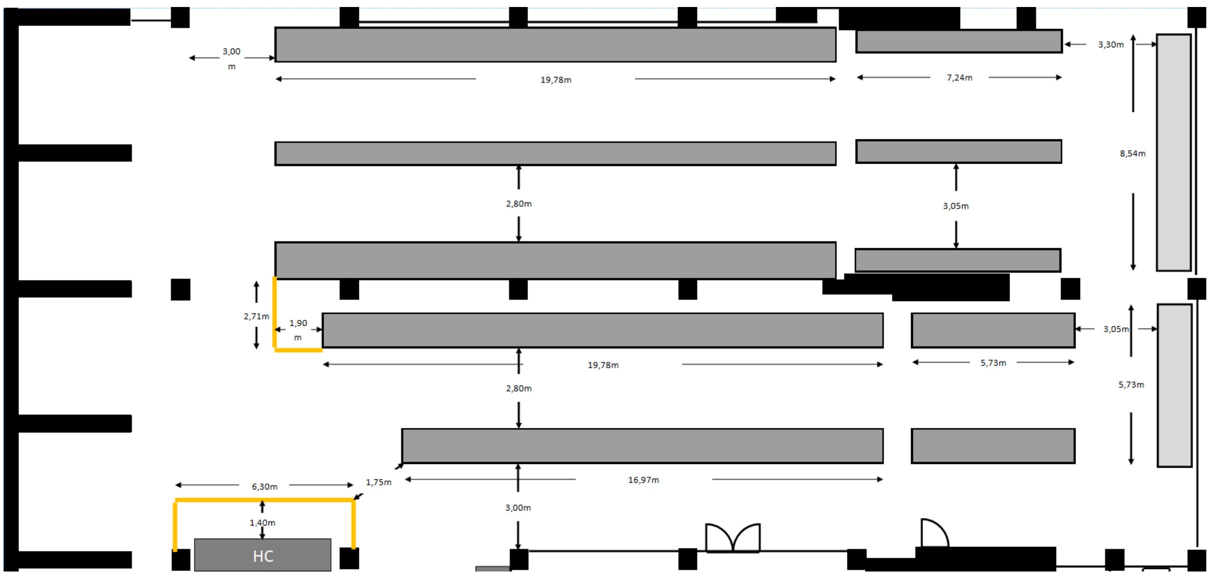

Figure 12: Design of layout based on current situation

4.2.2 Layout 2: Long aisles

Starting the research, Twence’s warehouse operators and asset manager mentioned in a meeting that improving the total storage capacity should be the main goal. Twence is dealing with inventory with a low turnover rate. The fastest-moving SKU has a demand of 11 items per year. This relatively slow-moving inventory results in a lower need for efficiency in the warehouse. Therefore, the idea of the layout with long aisles (see Figure 13) is that this efficiency is completely traded for a higher storage capacity.

To further optimize the layout, the width of the aisles will be reduced to 2700 mm, 100 mm narrower than the current setup. However, this may require Twence to acquire a new reach truck, as the current one may not be able to operate in the narrower aisles. Though most reach trucks can operate in the new aisle width.

Furthermore, all ground storage is replaced by pallet racks. On the right side pallet racks are added. These racks are three Euro pallets or, including frames, 2920 mm long. The aisle is 2700 mm wide, but since the frames are 110 mm wide, the pallets will fit exactly in the space and can be easily retrieved.

To optimize the storage allocation, Twence could implement a policy of placing inventory based on ABC classification. This allows for popular SKUs to be stored at the beginning of the long aisles, improving efficiency because there is only one entrance to each aisle. Additionally, larger or heavier pallets could be placed in warehouse H or on the right side of the long aisles. The racks on the right allow for trucks to reverse rather than turn in the aisle and allow for the use of counterbalance trucks for retrieving items that cannot be carried by reach trucks.

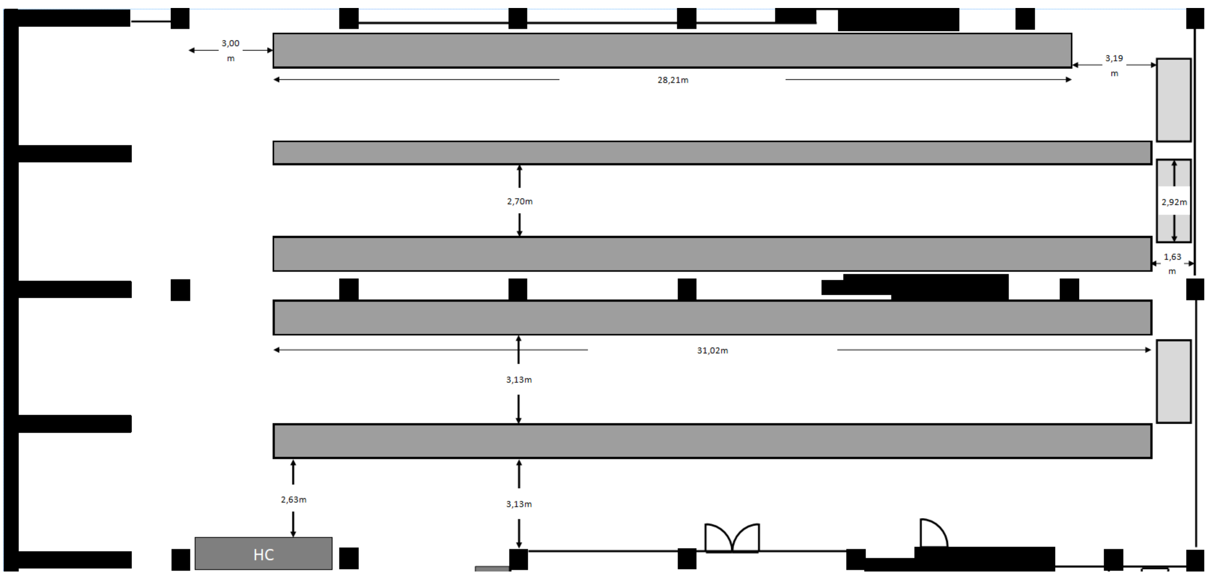

Figure 13: Design of layout with long aisles

4.2.3 Layout 3: Double deep racks

Certain SKUs in the central warehouse have more items that each must be stored on a separate pallet. Identical items can be placed behind each other, in so-called double deep racks (see Figure 14). This decreases the number of aisles, increases storage capacity and does hardly influence the accessibility of items. It will decrease the pallet location utilization a bit because if an item is retrieved from the warehouse, its pallet location will stay unoccupied till an identical item enters the warehouse. Appendix F, Double articles shows which SKUs are double and where they are stored. There are 32 double SKUs, stored on 97 pallet locations, while there are approximately 360 Euro pallet locations in the de double deep rack. This means that for a large part, different SKUs should be stored behind each other resulting in lower accessibility. Here the advice is to store slow-moving SKUs in the deeper rack, resulting in fewer pallet movements.

The narrowest aisles are just in the case of the layout with long aisles of 2700 mm, also possibly resulting in the need for a new reach truck. The yellow area depicts the area that is strictly for walking. Here the space between the doors and the pallet rack is too small, so it is unsafe to drive there with lift trucks.

Besides storing identical items behind each other, the overall storage allocation policy is less important in this layout. The ABC policy will hardly result in improvement since the aisles can be entered from both sides. Storing inventory based on size and weight is more interesting. This will result in more storage locations. In case Twence also wants to store its inventory for which a counterbalance truck is needed, they can place those SKUs on the ground under the racks on the right. Here there is just enough space to turn.

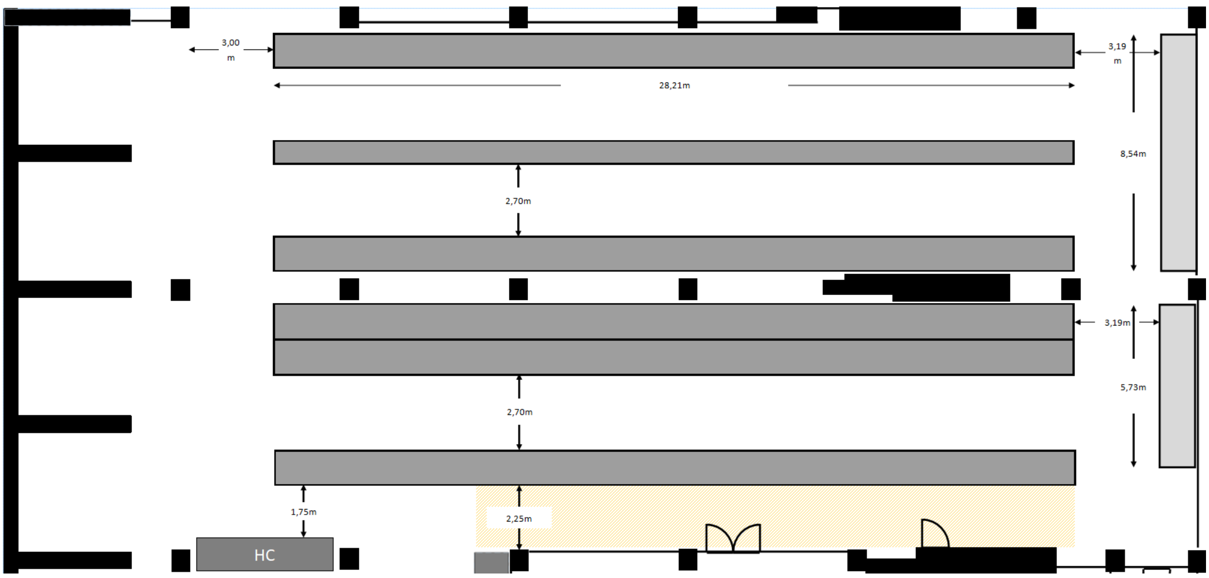

Figure 14: Design of layout with double deep racks

4.2.4 Layout 4: Mobile racks

This layout maximizes space utilization by using the minimum number of aisles. Figure 15 shows the design. Each mobile rack only requires one aisle. The outer racks of a mobile rack are fixed and the racks within can be adjusted in groups of two by moving them along a rail, manually or through automation. For this layout different clearances and sizes are used than for the layouts containing APRs, these measurements are used by STILL B.V., a rack specialist. The sizes and clearances of the mobile racks are depicted in Appendix G, Sizes and clearance of mobile racks (STILL intern transport B.V.,)(only the sizes for the racks and not the aisle are used).

The narrowest aisle between racks is 3180 mm wide and the aisle in the upper mobile rack is 3450 mm. In both aisles can the current reach truck easily operate in the mobile racks it is also possible to acquire a standing reach truck to lift heavier items. In the shorter mobile racks is the aisle width 4260 mm wide. This is enough for both the current reach and counterbalance truck.

It is recommended to store faster-moving SKUs in the long mobile racks, in warehouse H or in the racks on the right, as they have more directly accessible pallet places. Heavy items could also be stored in the central warehouse using counterbalance trucks, as the shorter mobile racks and side racks have ground storage underneath them and thus heavy SKUs could be placed there.

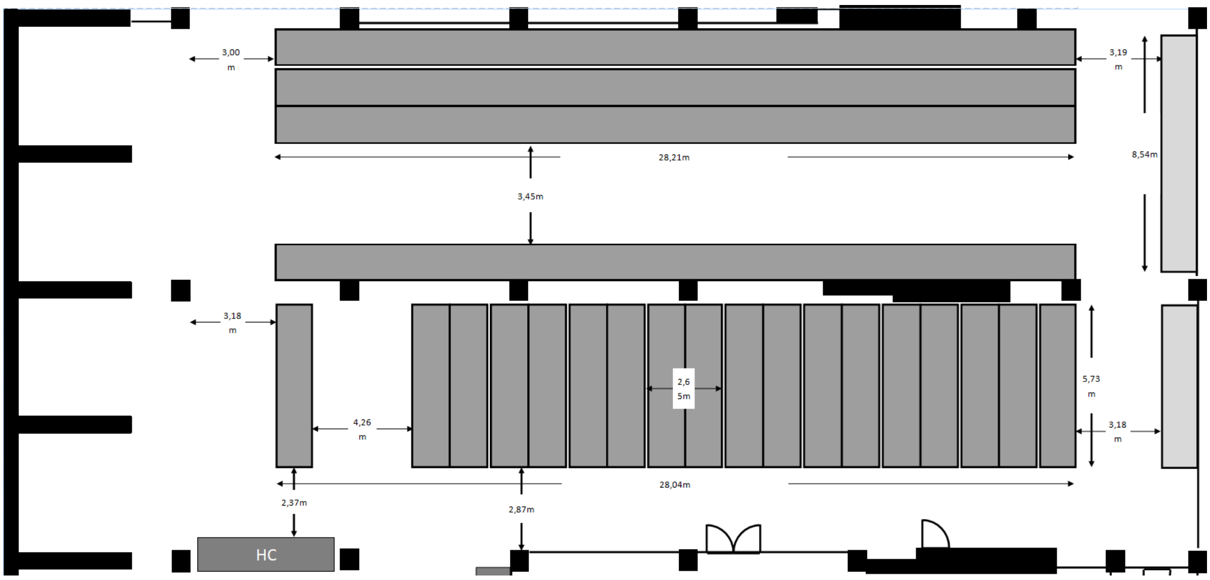

Figure 15: Design of layout with mobile racks

4.2.5 Layout 5: Narrow aisles

Figure 16 shows the layout with narrow aisles. This layout still consists of APRs, but the difference is that they are placed closer to each other than in the current layout. Narrow aisles result in better use of space because more space can be used for racks. The narrowest aisle here is 1850 mm and the widest on the right side is 3190 mm wide.

To operate in these aisles, Twence must purchase a new forklift truck. There are two options: a turret truck and an articulated truck. The turret truck requires a very flat floor and wide aisles at the end of the narrow aisles, and therefore the aisles on the sides should be left wider. However, the articulated truck does not have this requirement and can operate on less flat floors and narrower aisles. Therefore, it is recommended to acquire an articulated forklift truck for this layout.

Twence should consider that not all objects can be stored in all locations. For example, the widest object found is 2200 mm wide and cannot be stored in warehouses F and G. For these large, non-standard-sized pallets, it is recommended to store them in either warehouse H, in the racks on the sides or the area for ground storage. As the aisles are accessible from both sides, the ABC storage distribution does not have a major impact on efficiency in this layout either. Again, storage based on size is recommended.

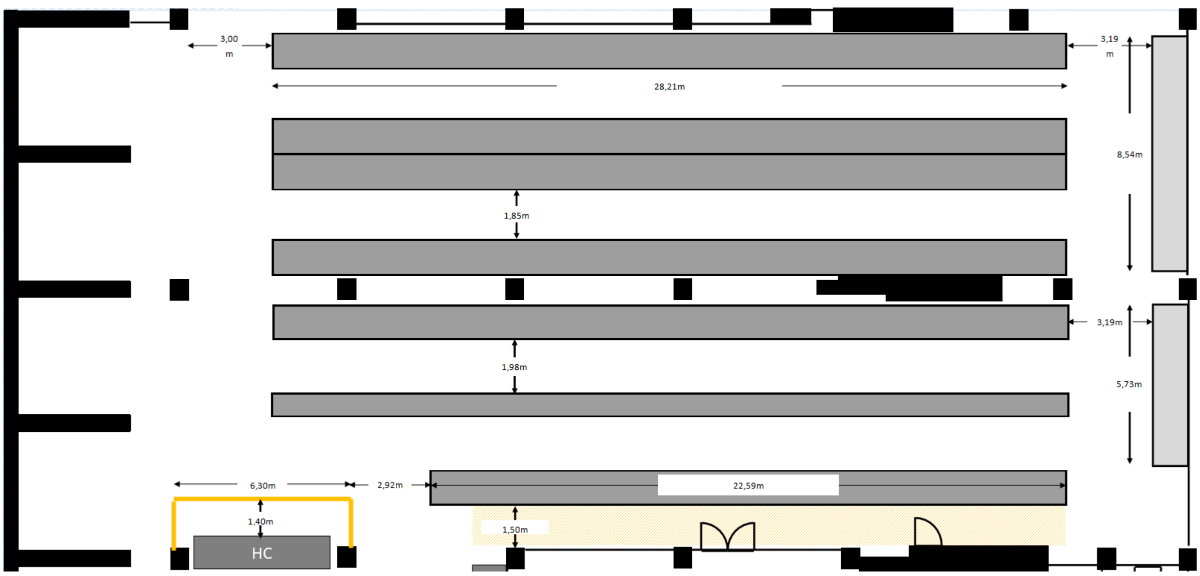

Figure 16: Design of layout with narrow aisles

4.3 Impact of alternative layouts

After drawing the alternative internal layouts in Publisher (see Figure 17 for an overview of the layouts), the layouts are drawn in Excel. The first step was to get square cells in Excel. Then the drawings can be pasted from Publisher into Excel so they can be drawn over in by colouring the cells. Each cell represents 400mm x 400mm. This allows calculations of the dimensions and how much space there is for storage. The pallet racks are either two cells (800 mm) or three cells (1200 mm) deep and each beam including the frames is considered seven cells wide (2800 mm). Figure 18 illustrates the current layout as an example, depicting how it would appear in Excel.

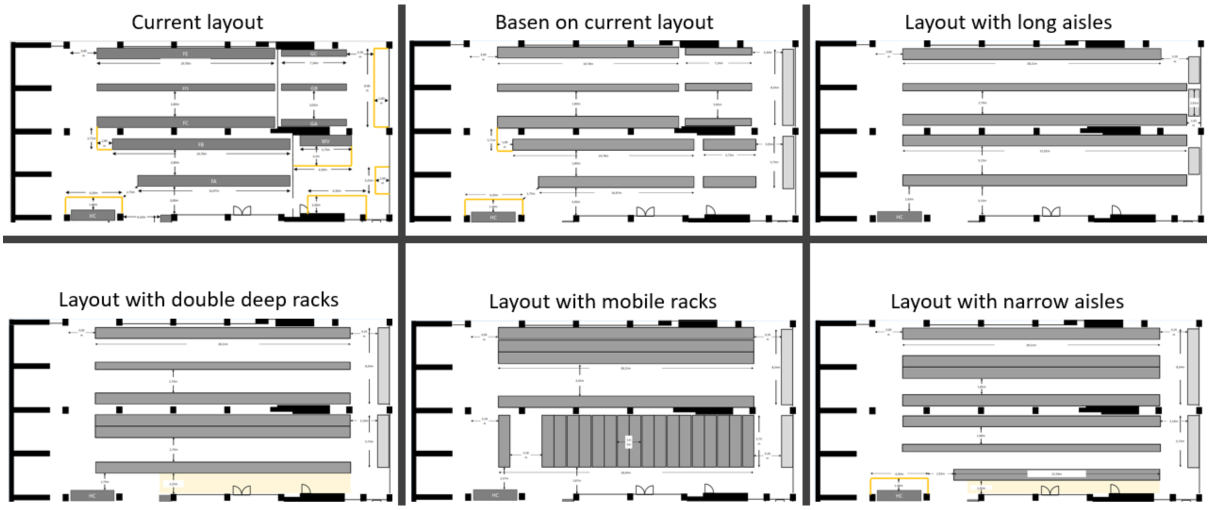

Figure 17: Overview of the layouts

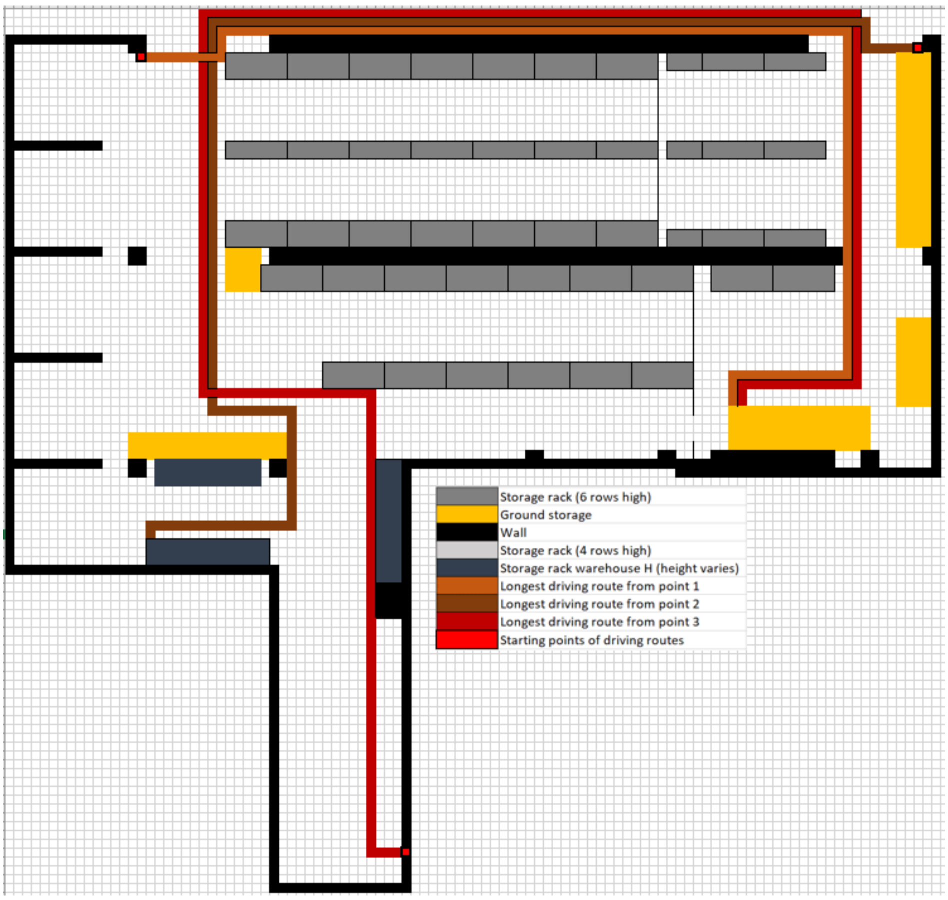

Figure 18: Current layout displayed in Excel

Then in Excel, the function “CountCellsByColor” is added using Visual Basic Analysis (VBA). This function counts the number of cells in a given range with a certain colour. Since each cell represents a size of 400mm x 400mm, KPIs such as the number of pallet locations and walking distance and time can be calculated. How the CountCellsByColor works is stated below:

$$= CountCellsByColor(data\_range;\ cell\_colour)$$

To use the formula, it's important to select the "data_range," which consists of the cells used to draw the layout. For example, in Figure 18, all cells should be selected. Next, select the "cell_colour" by choosing a cell with the desired colour displayed in the "Colour" column of Table 4. Table 4 displays the results obtained from using this formula.

Table 4: Number of cells in the Excel layouts with a certain colour

Colour	Current layout	Based on current layout	Long aisles	Double deep racks	Mobile racks	Narrow aisles
Storage rack (6 levels high)	815	857	1057	1190	1596	1358
Ground storage	282	74	0	0	0	54
Storage rack (4 levels high)	0	105	63	105	105	105
Storage rack warehouse H (height varies)	120	120	120	120	120	120
Longest driving route from point 1	138	122	116	122	126	121
Longest driving route from point 2	164	141	192	161	142	142
Longest driving route from point 3	247	171	188	170	157	169

Based on interviews with Twence employees and the literature review in section 3.4, the following KPIs have been identified as critical for this research:

- The total number of pallet locations
- Response time
- Accessibility
- Costs

4.3.1 Total number of pallet locations

The central KPI for this research is the total number of pallet locations, which is calculated using the CountCellsByColor function in Excel. Each cell represents 400mm x 400mm, so one Euro pallet (800mm x 1200mm) is equivalent to six cells. Figure 18 shows how the current layout is displayed in Excel. The coloured lines are discussed in section 4.3.2. The other layouts are shown in Appendix H, Alternative layouts designed in Excel. On one beam, three Euro pallets fit. Each beam is approximately 2800mm wide and is equivalent to seven cells in the Excel model. To calculate the number of pallet locations, the formula is: (CountCellsByColor/6) * (6/7) * height. This formula eliminates the space for racks and clearance, so it only counts the number of pallet locations. The height of the racks varies in the Excel model, where the dark grey cells represent 6 rows high, the light grey 4 rows and the yellow is ground storage (where no frames or clearances are considered). It is important to note that no layout changes are done in warehouse H and it has 79 pallet locations, so 79 is added to the formula, and the result is rounded down. Resulting in the following formula:

$$Number\ of\ pallet\ locations = \left\lfloor \frac{\#\text{dark grey cells}}{6} * \frac{6}{7} * 6 + \frac{\#\text{light grey cells}}{6} * \frac{6}{7} * 4 + \frac{\#\text{yellow cells}}{6} + 79 \right\rfloor$$

The formula provides an estimate of the number of pallet locations. The aim is to compare the results of various layouts rather than obtaining an exact number. The accuracy of the Excel model is verified by also counting the actual number of pallet locations. Table 4 displays the outcomes of the different layouts. The minor difference in the number of pallet locations between the model and the actual warehouse layout can be explained by the model's assumption of a standard width of three Euro pallets per rack, whereas the current warehouse layout includes some racks that are narrower than this standard. Consequently, the accuracy of the model decreases when these narrower racks are used. It is important to note that these narrower racks are only present in the current layout, and based on this layout, the model's accuracy may be lower. However, for other layouts without these narrower racks, the model is likely to be more accurate.

Table 5: Number of Pallet locations per layout according to the model and the exact number

Layout	Pallet locations according to model	The real number of pallet locations
Current layout	824	820
Based on current layout	885	883
Long aisles	1021	1021
Double deep racks	1159	1159
Mobile racks	1507	1507
Narrow aisles	1312	1312

4.3.2 Response time

The response time is critical for companies that primarily store spare parts, as it is crucial for quick repairs. However, the central warehouse of Twence is not very large in size, so retrieval time is not a significant issue for warehouse operators. In this research, the retrieval time is stated to indicate the layout's efficiency.

Twence's central warehouse has three entrances for forklift trucks (recall from Figure 8), all are used approximately the same amount, and there is no data on where the retrieval processes start. Therefore, the efficiency of the warehouse is measured by the average longest retrieval time. For each entrance, the longest retrieval time is calculated by the CountCellsByColor function in Excel. Every furthest retrieval route gets a different colour and the number of cells is then multiplied by the size of each cell (which is 400mm x 400mm) to obtain the total distance of the longest route (see routes in Figure 18).

Warehouse operators have set a speed limit of 5 Km/h for lift trucks. This speed is used to calculate the retrieval times. Besides the longest retrieval time per entrance, the longest retrieval time possible is included in the efficiency assessment. Here, Excel calculates which of the three routes is the longest, and this way the worst of the worst-case scenario weighs heavier in the assessment than the other retrieval routes. Table 6 shows the results.

Table 6: Average longest and longest possible retrieval times per layout

Layout	Average longest retrieval time (minutes)	Longest possible retrieval time (minutes)
Current layout	1.76	2.37
Based on current layout	1.39	1.64
Long aisles	1.59	1.84
Double deep racks	1.45	1.63
Mobile racks	1.36	1.51
Narrow aisles	1.38	1.62

The results are validated by measuring the average longest retrieval time in real life. An operator drove from every entrance to its furthest retrieval point and recorded a time of 1.84 minutes, which was only 4.55% longer than the model's prediction.

4.3.3 Accessibility

The accessibility of SKUs is measured as the percentage of SKUs that are directly accessible. This KPI is critical because the higher the accessibility, the faster the placement and retrieval process goes, which improves the overall warehouse productivity and efficiency.

This KPI is measured by counting the number of pallet locations that are not directly accessible. This number is then divided by the total number of pallet locations. The only exception to this calculation is for the double deep racks since if double SKUs are stored behind each other, the SKU is still directly accessible. There are currently 84 pallet loads that can be stored two deep without reducing the accessibility. This means that 42 pallet locations should be subtracted from the number of pallet locations that are not directly accessible. Table 7 shows the results.

Table 7: Accessibility of different layouts.

Layout	Number of pallet locations not directly accessible	Accessibility
Current layout	0	100.00%
Based on current layout	0	100.00%
Long aisles	0	100.00%
Double deep racks	138	88.09%
Mobile racks	936	37.89%
Narrow aisles	0	100.00%

4.3.4 Costs

Companies like Twence store most of their inventory for extended periods. To achieve cost-efficiency, a significant amount of these items are typically stored in cost-effective storage systems such as APRs. The primary design consideration for this type of warehouse is to maximize storage capacity while minimizing both investment and operational costs. The cost assessment is based on information provided by STILL Intern Transport B.V. Currently the heaviest items in the rack are 1,400 kg. APRs to carry this weight cost €50 per pallet location and mobile racks €205 per pallet location to install.

The costs for each layout are calculated in the Excel model by considering the number of pallet locations that need to be installed. Reusing existing racks from the current layout will not incur additional costs. A cheapness score is used to compare the results of each layout. The score ranges from 100% for the lowest cost to 0% for the highest cost. The score is calculated using the following formula:

$$Cheapness\ score = \frac{highest\ cost - cost\ of\ layout}{higest\ cost} * 100$$

In this scenario, the highest cost is €292,740 and the cost of the layout is the cost of installing racks for the layout in question. Table 8 shows the results.

Table 8: Cost score per layout

Layout	Rack installation costs	Cheapness score
Current layout	€0.-	100.00%
Based on current layout	€3,050	98.96%
Long aisles	€47,100	83.91%
Double deep racks	€54,000	81.55%
Mobile racks	€292,740	0.00%
Narrow aisles	€61,200	79.09%

Please note that the costs mentioned do not include the expenses for purchasing a new lift truck. This is because the prices of these trucks are difficult to obtain, and it is unclear whether a new lift truck is necessary for some layouts. However, in the case of narrow aisles, it is certain that a new lift truck will be required. The validation of these costs is explained in more detail in section 5.1.

4.4 Comparing the layouts

To determine the best overall layout, the scores of each KPI for the alternative layouts are compared. These scores are weighted based on the relative importance of each KPI to Twence. These weights are established in collaboration with the asset manager and warehouse operators of Twence. The scores are based on how much the KPIs changed compared to the current layout. The results with the weights applied are shown in Table 9.

Table 9:Total weighted score per layout

Layout	Based on current layout	Long aisles	Double deep racks	Mobile racks	Narrow aisles
Pallet locations (0.5)	7.40%	23.91%	40.66%	82.89%	59.22%
Average longest retrieval time (0.1)	20.59%	9.65%	17.49%	22.59%	21.31%
Longest possible retrieval time (0.1)	30.77%	22.27%	31.17%	36.44%	31.58%
Accessibility (0.2)	100.00%	100.00%	88.09%	37.89%	100.00%
Cheapness cost score (0.1)	98.96%	83.91%	81.55%	0.00%	79.09%
Weighted score	**38.77%**	**43.54%**	**50.97%**	**54.92%**	**62.81%**

The layout with the narrow aisles and the one with mobile racks have the highest scores and are therefore recommended for use. Recall that the scores are based on the weights assigned by the asset managers and warehouse operators. To evaluate the effect of different weight combinations, a sensitivity analysis has been performed (as shown in Figure 19: Sensitivity analysis). It demonstrates the impact of changes in the weights of the KPIs on the total score. As there are too many possible weight combinations to calculate manually, the weighted average of the KPIs, such as the average longest and longest retrieval times, accuracy, and costs, is compared with the assigned weight to the storage capacity, since this is the central KPI of the research. This analysis seeks to understand the effect of changes in the weight assigned to storage capacity on the total weighted score and the importance of the other KPIs.

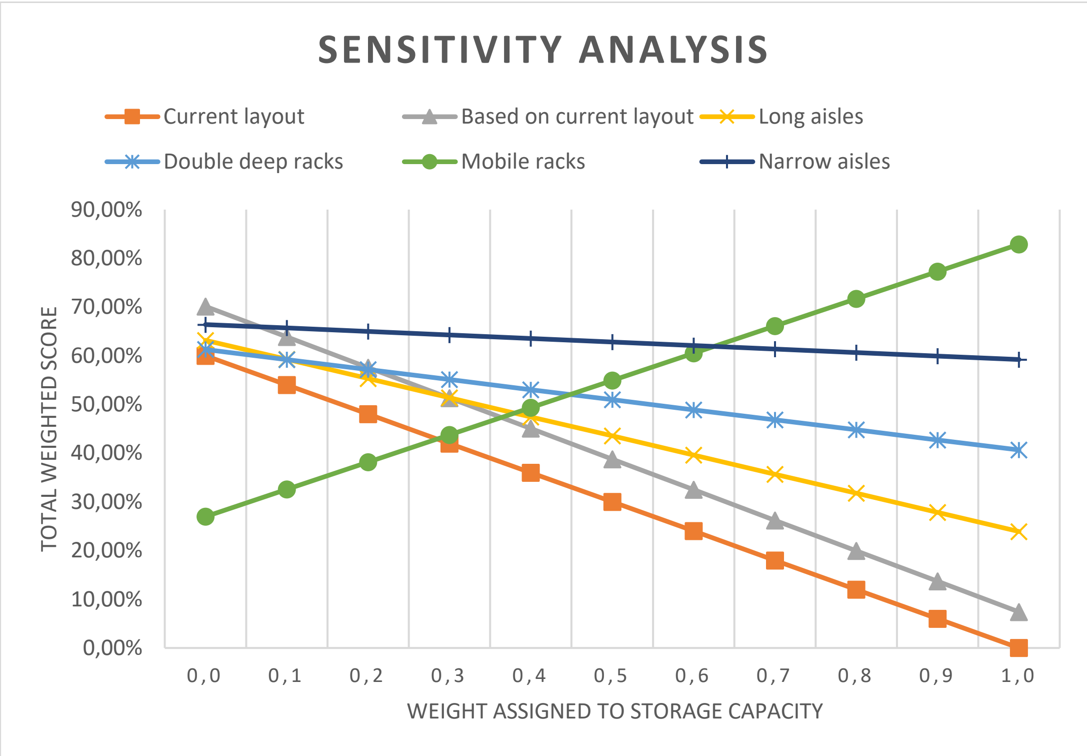

Figure 19: Sensitivity analysis

The sensitivity analysis performed in this case not only validates the recommended solutions of the layout with narrow aisles and the layout with mobile racks but also helps in making informed decisions. The results of the analysis show that these two layouts consistently score better compared to the others, except in the unlikely case that the weight of storage capacity is under 0.1. Currently, the layout with narrow aisles is the recommended solution. However, if Twence decides to lower the importance of storage capacity, this recommendation remains unchanged. On the other hand, if the importance of storage capacity is increased, the layout with mobile racks becomes the more likely recommendation.

5 Discussions

In this chapter, the outcomes of the research are examined. Section 5.1 evaluates the validity of the results, while sections 5.2 and 5.3 address the limitations of the research method and the available data, respectively.

5.1 Validity

The research result shows that the layouts with mobile racks and narrow aisles have the highest number of pallet locations. This aligns with the findings from the literature review, as these methods are known to optimize available space. Initially, it was thought that the layout with mobile racks would score better due to the high assigned scoring weight to the number of pallet locations, but it performed poorly in terms of accessibility and costs. As a result, the layout with narrow aisles, despite providing 195 fewer pallet locations and requiring investment in a new lift truck, had a better overall score.

The inclusion of a new lift truck has made the cost analysis less accurate as it was not accounted for in the initial evaluation. The decision to purchase a new lift truck was made because it was unclear whether many alternative layouts required one, and even if they did, it was difficult to determine the pricing. To validate the recommendation of the narrow aisle layout, it is assumed that this layout requires a new truck for €80,000, which is the cost of a new narrow aisle truck (turret truck) from Jungheinrich, a lift truck seller. With this cost considered, the overall score for the narrow aisle layout is 60.08%, which is still significantly higher than the score for mobile racks, which is 54.92%.

The average longest retrieval time and storage capacity are validated by comparing them with what they would be in real life if you measure them precisely instead of using the model. This showed that the current measurements in the model are reliable. However, the model will measure the number of pallet locations less accurately if beams are added that are less than three pallet locations wide. Both the KPIs for storage capacity and warehouse efficiency are not exact, but their goal is to give an indication to Twence about the impact of a warehouse layout.

5.2 Method

This research is a heuristic study, utilizing practical and experience-based methods to find solutions. The benefit of this approach is its ability to rapidly find solutions, which are practical and flexible. However, the solution produced by this research may not be the optimal solution since an optimization model is not employed. As the movement of goods within Twence is relatively slow and the warehouse is relatively small, there is no immediate requirement for a perfectly optimized warehouse. The primary need is for alternative, improved layouts. If Twence has an idea for a potential improvement to the current layout, they can test the impact of this layout using the Excel model.

5.3 Data availability

The research faced some limitations in terms of data availability. There was limited information about the product characteristics and the demand for some SKUs was not known. Furthermore, the location from where each order is retrieved was unknown. This made it challenging to determine the closest point to the operator for each layout as there are multiple entrances to the warehouse. As a result, the study could only provide general guidance on the storage allocation policy and not specific placement recommendations for each item. Therefore, the average retrieval time could not be calculated, so the worst-case scenario was taken and the average longest retrieval time and longest possible retrieval time were calculated instead.

6 Conclusion & recommendations

This chapter summarizes the findings and conclusions of the research and presents recommendations for improving the internal warehouse layout. In section 5.1, the key findings and conclusions of the study are discussed. Section 5.2 presents recommendations for the implementation of the optimal warehouse layout based on the key performance indicators. Finally, section 5.3 discusses the contribution of this research to both theory and practice.

6.1 Conclusion

The research first aimed to understand the current state of warehouse operations at Twence. By addressing the sub-research question *"How is the current situation of the warehouses set up at Twence?"*, this chapter examined the inventory types, layout, capacity, and storage allocation policy. To gain a comprehensive understanding, an overview of the distribution of different inventory types and the location of warehouses was obtained. This information allowed for an understanding of which inventory could potentially be transported to the central warehouse if additional storage space were available. Additionally, this chapter provided insight into the warehouse processes, including the arrival of orders and the storage of pallet loads. The conclusion is that the current storage allocation policy is not optimized, and could benefit from being based on demand or inventory size. An analysis of demand per SKU revealed that 20% of SKUs account for 80% of demand, further highlighting the potential benefits of this approach. It was during this phase of the research that the decision was made to remove the roll-up door to improve efficiency and to place racks above ground storage areas, resulting in more storage capacity.

After the current situation was analysed to identify areas for improvement, the literature was reviewed for potential solutions. The chapter addresses the sub-research question "*Which methods and theories exist in the scientific literature about warehouse design to improve storage capacity?"*. Firstly, it explains the basic principles of warehouse operations, including the specific type of warehouse used by Twence and important considerations for that type of warehouse. The internal layout was also discussed with a focus on increasing storage capacity. The research examined various storage allocation policies and their potential to improve efficiency and pallet location numbers. It was found that there is random, class-based and dedicated storage. To improve storage capacity it is best to store inventory based on size and to improve efficiency it is often best to store it based on demand. Finally, the chapter outlined KPIs for warehouses that store a large variety of SKUs for long periods, which are storage capacity, retrieval time, accessibility and costs. These are therefore chosen as the KPIs central to this research.

The next sub-research question is *"How can the found theories be applied to the central warehouse?"* Alternative internal layouts were designed using Publisher and measurements were calculated, including clearances between racks, pallets and walls. The layouts were then drawn in Excel and an impact sheet was created to measure the KPIs. The KPIs were weighted in the impact sheet with storage capacity at 0.5, average longest retrieval time at 0.1, longest retrieval time at 0.1, accessibility at 0.2 and costs at 0.1. The layouts were compared and the highest-scoring solution was found to be the layout with narrow aisles, closely followed by the layout with mobile racks.

The action problem, *"How can the storage capacity of Twence's central warehouse be improved by 10% by testing different layouts?"* has been answered by comparing different layouts and measuring their impact on storage capacity, costs and efficiency. The layout based on the current situation improves the storage capacity by only 7.40%, but it is the cheapest and easiest to implement. It also shows that the removal of the roll-up doors improves the longest possible retrieval time by 30.77% and the average longest retrieval time by 20.95%. The layout with long aisles scores better on pallet locations, with an improvement of 23.91%, but scores worst on efficiency. The layouts with double deep racks, mobile racks, and narrow aisles score better in storage capacity and efficiency than the layout with long aisles. Therefore, the layout with long aisles is not recommended. The layouts with double deep racks, mobile racks, and narrow aisles score better in storage capacity and efficiency than the layout of the long aisles. However, the use of double-deep racks is not practical as only 84 out of 360 pallet locations in the double-deep rack can be used for double SKUs, meaning that 138 SKUs are not directly accessible. This means that to retrieve a specific pallet, a load must first be removed from the rack. Therefore, it is not recommended to use double-deep racks. The layout with narrow aisles and the layout with mobile racks score best and are recommended. They both score well in capacity and efficiency, but the mobile racks score much worse in accessibility and are more expensive, costing around €292,740, compared to the narrow aisles which will approximately cost €61,200.

The best storage allocation policy depends per layout. Table 10 summarizes the storage policy and placement of heavy or large pallet loads. To maximize storage capacity, a size-based policy is recommended, in which the height of the beams is adjusted to optimize space utilization and increase the number of pallet locations. The ABC storage policy, which prioritizes high-demand items, is easiest to implement in the layout with long aisles and a single entrance to each aisle. It is also suitable for mobile racks, as these items can be placed in the more easily accessible longer aisles. However, this policy may be less effective in layouts with multiple entrances, as it is difficult to determine which entrance is most frequently used and thus, which storage points are the most easily accessible.

Table 10: Advised storage allocation policy for different pallet loads.

Layout	Storage allocation policy	Placement of heavy and larger pallet loads
Based on current layout	Size-based	• Ground under the racks. • Ground storage areas. • Ground under racks in warehouse H.
Long aisles	Demand-based (ABC classification)	• Ground under the racks on the right at the end of the aisles. • Ground under racks in warehouse H.
Double deep racks	Size-based, with the slow-moving SKUs stored in the deeper less accessible rack.	• Ground under the racks on the right. • Ground under racks in warehouse H.
Mobile racks	Size-based, with fast-moving SKUs in the long racks	• Ground under the mounted mobile racks. • Ground under racks in warehouse H.
Narrow aisles	Size-based	• Ground under racks on the right. • Ground storage area. • Ground under racks in warehouse H.

6.2 Recommendations

Two layouts scored best and are thus considered in the recommendations. These are the layout with narrow aisles and with mobile racks. The number of pallet locations is the main KPI and the central goal of this research. In this aspect scores the layout with mobile racks better, but it is much more expensive. Both layouts score comparable in efficiency, with an exception for accessibility. However, poor accessibility is not a big problem in the layout of mobile racks since the movement of the racks does not take long. The main trade-off is that the layouts with mobile racks create 195 extra pallet locations, but cost an estimated €231,540 more (excluding purchasing a new lift truck to operate in narrow aisles). Therefore, it is suggested that the most efficient way to improve the storage capacity of the warehouse is to implement the layout with narrow aisles, which score well on all the measured parameters and are relatively inexpensive to implement.

This research aims to present potential improvements for Twence. The layout with narrow aisles is suggested based on the highest score in the Excel model, but alternative layouts may also be appropriate. The final choice is for Twence to make, taking into account the required storage capacity and allowable costs. So the first step for Twence is to assess its expected growth in the coming years and how much storage that will require. Looking at the literature, while changing the internal layout of a warehouse, it is best to plan at least for the coming five years. Once this capacity is known, consideration can be given to the desired layout. This is best done with a company that specializes in internal warehouse layouts. They can review the measurements made and tell more about feasibility and costs.

Once the desired layout is known, the most appropriate storage allocation policy should be determined. If the goal is to maximize pallet locations, a size-based policy would be appropriate. If sufficient pallet locations remain, another option is to allocate them by function. This will increase warehouse efficiency and findability, especially for orders requiring multiple items.

Finally, while this research has helped to increase storage capacity in the central warehouse, it is important to note that Twence should continue consulting with companies that can assist with managing inventory levels. Additionally, an issue with a lack of overview in inventory locations is also attributed to employees not properly updating the WMS. Therefore, it is recommended to improve the usability of the WMS to ensure proper tracking and management of inventory. Further research should be conducted to explore ways to improve the WMS and to ensure the smooth operation of the warehouse.

Table 11 presents a roadmap outlining the actions required to implement a solution based on the activities discussed in this section. The priority column indicates the order in which the activities should be carried out, and the actors column specifies the people, groups, or organizations responsible for each activity. If a company is responsible for an activity, the type of company is identified along with a logical example based on their involvement in this research or existing contact with the company.

High-priority activities are essential to the implementation of the solution, and without their completion, a new layout cannot be built. Medium-priority activities can be carried out after the best layout has been installed, and low-priority activities are optional improvements that can be made to the warehouse operation.

Table 11: Roadmap for Twence to implement the solutions

Priority	Activity	Actors
High	Assess expected growth in required storage capacity for the next 5 years.	• Researcher (student or assigned employee) • Logistic company (e.g. Gordian)
High	Find the allowable costs and come up with an investment plan.	• Asset management • Board of Twence • Researcher (student or assigned employee)
High	Design and install the final layout	• Asset management • Storage system company (e.g. STILL or Polypal)

High	Remove roll-up doors	• Facility management • Asset management
Medium	In the case of a new lift truck, find a new lift truck and obtain the necessary certification to operate the truck.	• Warehouse operators
Medium	Find out which materials need special care or placement.	• Factory employees • Warehouse operators • Researcher (student or assigned employee)
Low	Apply the most suitable storage allocation policy.	• Warehouse operators
Low	Redesign the WMS to improve inventory location accuracy.	• IT department • Warehouse operators • Asset management • Logistic company (e.g. Gordian)

6.3 Contribution to practice & theory

This research provides an overview of the current storage problem at Twence and suggests potential improvement solutions. The impact of these solutions has been analysed, but recall that this research is based on heuristic methods rather than optimization research, so there may be better solutions available. To explore other potential solutions, Twence is encouraged to use the Excel model provided to test alternative internal layouts.

Furthermore, this research can serve as a roadmap for testing other sub-warehouses. Twence can easily adapt the Excel model for their other sub-warehouses by adjusting the physical layouts while maintaining the same colour scheme. The research can be replicated, and a more detailed explanation of how to design the model for sub-warehouses will be provided to Twence for future use.

This research presents a new method for demonstrating the efficiency of a warehouse, which contributes to the field of theory. Traditionally, the literature relies on the average retrieval time as a KPI for measuring warehouse efficiency. However, in situations where data is lacking, such as at Twence, calculating the average retrieval time may not be possible. Instead, this research proposes using the worst-case retrieval scenario - identifying the furthest retrieval point - as a more practical method for measuring warehouse efficiency. This approach has not been previously reported in the literature, and it offers the advantage of being both easy and fast to implement, as it does not require data on product demand. Furthermore, the method of identifying the furthest retrieval point is especially useful for warehouses with multiple entrances and warehouses where there is not one specific retrieval starting point, making it a versatile method that can be applied to a variety of warehouse configurations.

6.4 Future research

By increasing the storage capacity, Twence hopes to store more inventory in the central warehouse. Here are the warehouse operators located and thus, Twence hopes, to increase the overview of their inventory. However, during discussions with Twence employees, it was discovered that the issue was not solely caused by a lack of storage capacity. Some employees were found to not consistently record item retrievals in the WMS. Further research should be conducted to find ways to motivate employees to better follow procedures in the WMS, thereby enhancing item findability and location accuracy. This could be done by redesigning the WMS.

Recall that the recommendations of this research are based on the future storage requirements of Twence. For the action problem, it was stated that this research should aim to improve the storage capacity by at least 10%, but the sensitivity analysis in section 4.4 also shows that the best solution depends on the assigned significance of each KPI. Therefore, Twence should get an overview of the required storage capacity for at least the coming five years.

Additionally, future research should also address the issue of preventing the warehouse from becoming fully utilized again despite the increased storage capacity. This research should focus on finding ways to optimize the use of available space. It should determine which inventory items are critical to keep in the warehouse at all times and the optimal levels of each item to maintain in stock. Doing so will help ensure that the storage capacity is utilized efficiently and effectively, even as the warehouse grows.

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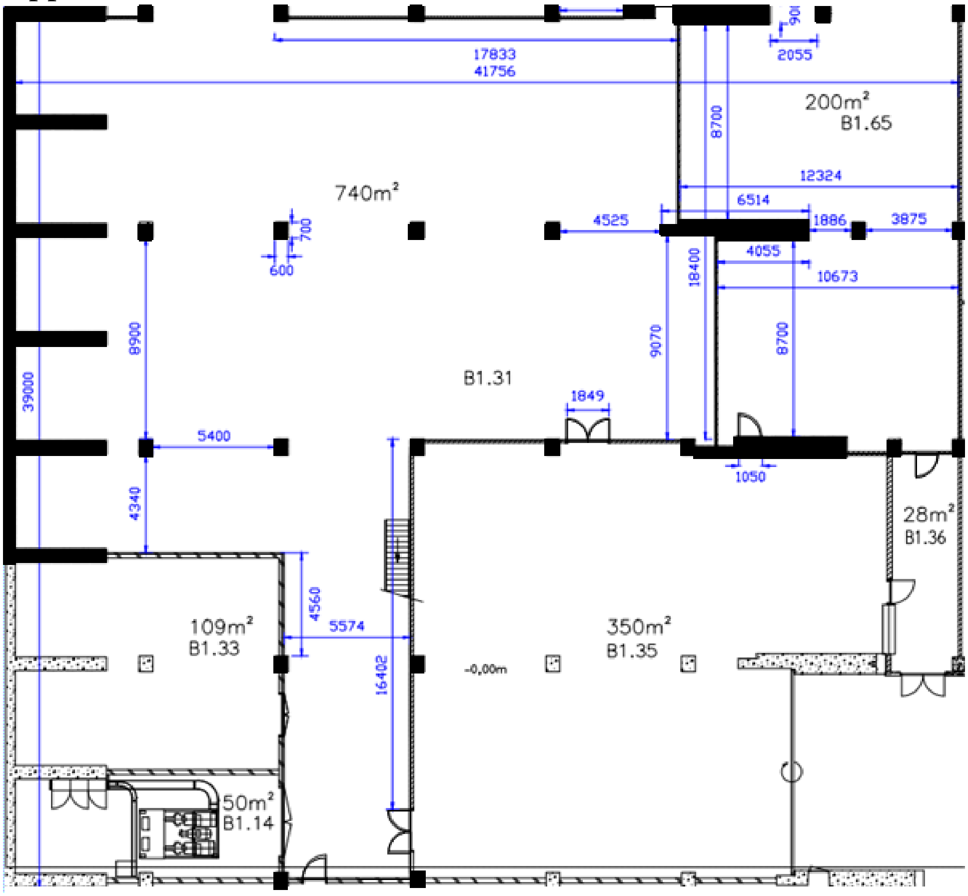
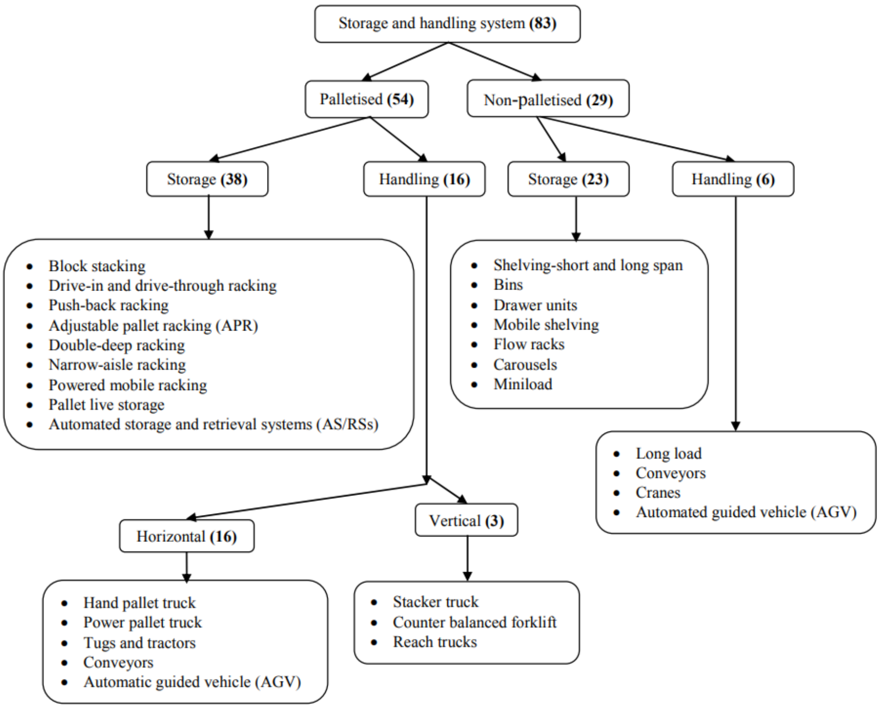
Appendices

Appendix A, Dimensions of the central warehouse

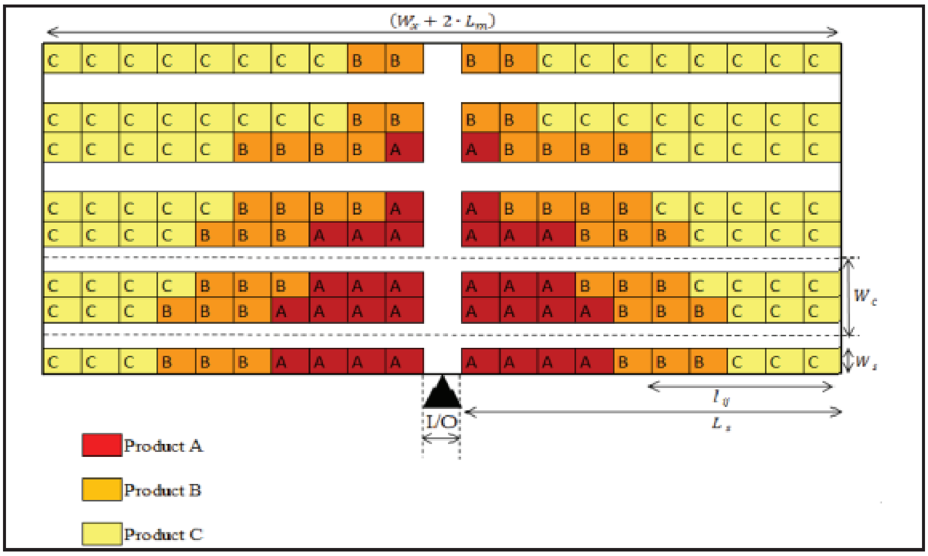


Appendix B, Roll-up doors

Appendix C, Taxonomy for storage and handling system (Shah & Khanzode, 2015)



Appendix D, ABC classification (Sarudin & Shuib, 2016)



Appendix E, Warehouse performance indicators(Staudt et al., 2015)

Dimensions	Indicator name
Time	Order lead time Receiving time Order picking time Delivery Lead Time Queuing time Putaway time Shipping time Dock-to-stock time Equipment downtime
Quality	On-time delivery Customer satisfaction Order fill rate Physical inventory accuracy Stock-out rate Storage accuracy Picking accuracy Shipping accuracy Delivery accuracy Perfect orders Scrap rate Orders shipped on time Cargo damage rate
Cost	Inventory cost Order processing cost Cost as a % of sales Labour cost Distribution cost Maintenance cost
Productivity	Labour productivity Throughput Shipping productivity Transport utilisation Warehouse utilisation Picking productivity Inventory space utilisation Outbound space utilisation Receiving productivity Turnover

Appendix F, Double articles

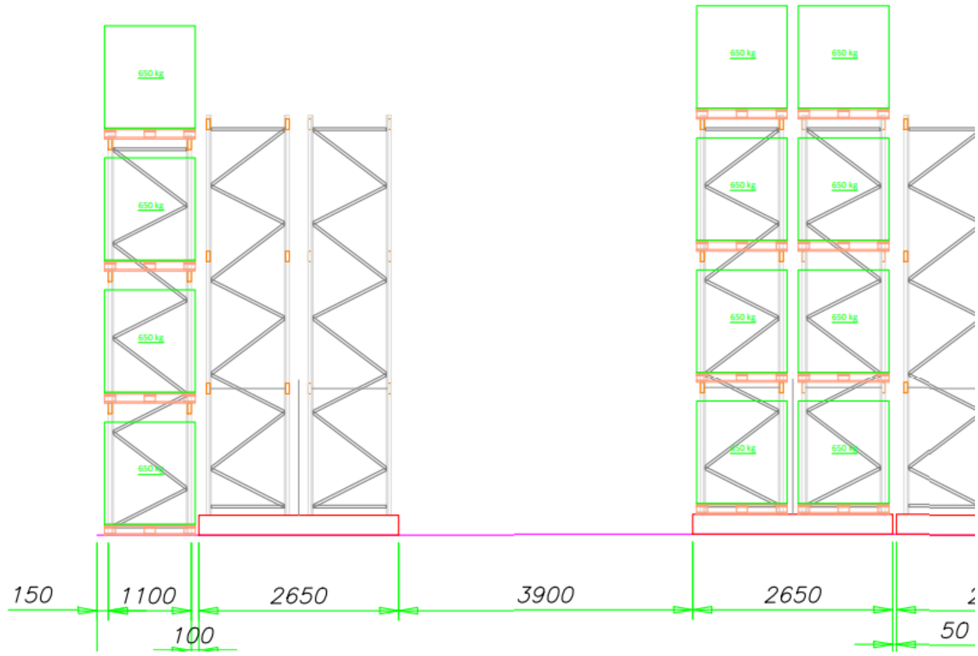
Double articles central warehouse

art.	locatie
207558	FA.05.02A
	FA.05.02B
	FD.03.02A
	FD.03.02B
300365	FA.06.03B
	FB.02.03B
214806	FB.01.04B
	FB.01.04C
	FA.01.05C
208058	FC.02.01A
	FD.03.05B
208057	FC.02.01A
	FD.03.05B
205534	FC.06.03A
	FC.06.03B
	FC.06.03C
205535	FC.06.04A
	FC.06.04B
	FC.06.04C
206744	FC.07.03A
	FC.07.03B
	FC.07.03C
210194	FC.07.04A
	FC.07.04B
	FC.07.04C
206835	FD.02.03A
	FD.03.04A
207550	FD.04.03A
	FD.04.03B
	FD.04.04A
	FD.04.04B
	FD.04.05A
	FD.04.05B
200901	FD.05.01A
	FD.05.01B
	FD.05.02A
	FD.05.02B
	FD.05.04A
	FD.05.04B
200899	FD.05.03A
	FD.05.03B
206892	FD.05.05A
	FD.05.05B
209627	FD.06.01A
	FD.06.01B
212170	FD.06.04A
	FD.06.04B
	FD.06.05A

Double articles central warehouse

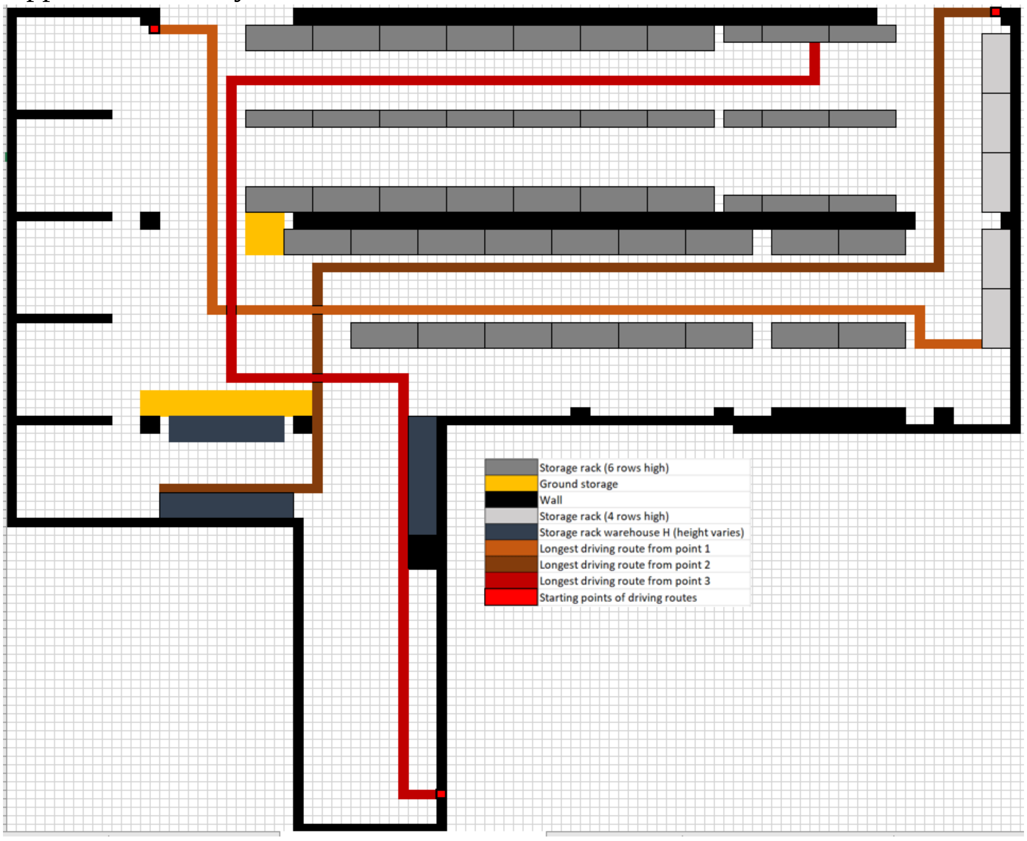
art.	locatie
207550	FD.06.05B
	FD.06.06A
	FD.06.06B
103717	FE.01.03A
	FE.01.03B
	FE.01.04A
209817 & 209818	FE.04.02A
	FE.04.02B
	FE.04.02C
	FE.04.03A
	FE.04.03B
	FE.04.03C
	FE.04.04A
	FE.04.04B
	FE.04.04C
206458	HA.01.03A
	HA.01.04A
	HA.01.04B
	HA.01.04C
	HA.02.04A
	HA.02.04B
	HA.02.04C
210624	HB.01.04A
	HB.01.04B
	HB.02.04C
210627	HB.01.04C
	HB.02.04A
	HB.02.04B
207555	HC.01.00A
	HC.01.00B
200900	HC.02.03A
	HC.02.03B
207952	GA.01.03B
	GA.02.01B
211976	GA.01.04A
	GA.03.01
211751	GA.03.02
	GB.03.05
211863	GB.02.05
	GB.02.06
301010	GB.01.05A
	GB.01.05B
211705	GC.01.03A
	GC.01.03B
	GC.01.04B
300152	GC.02.02A
	GC.02.08B
211352	GC.02.04
	GC.02.05

Appendix G, Sizes and clearance of mobile racks (STILL intern transport B.V.,)

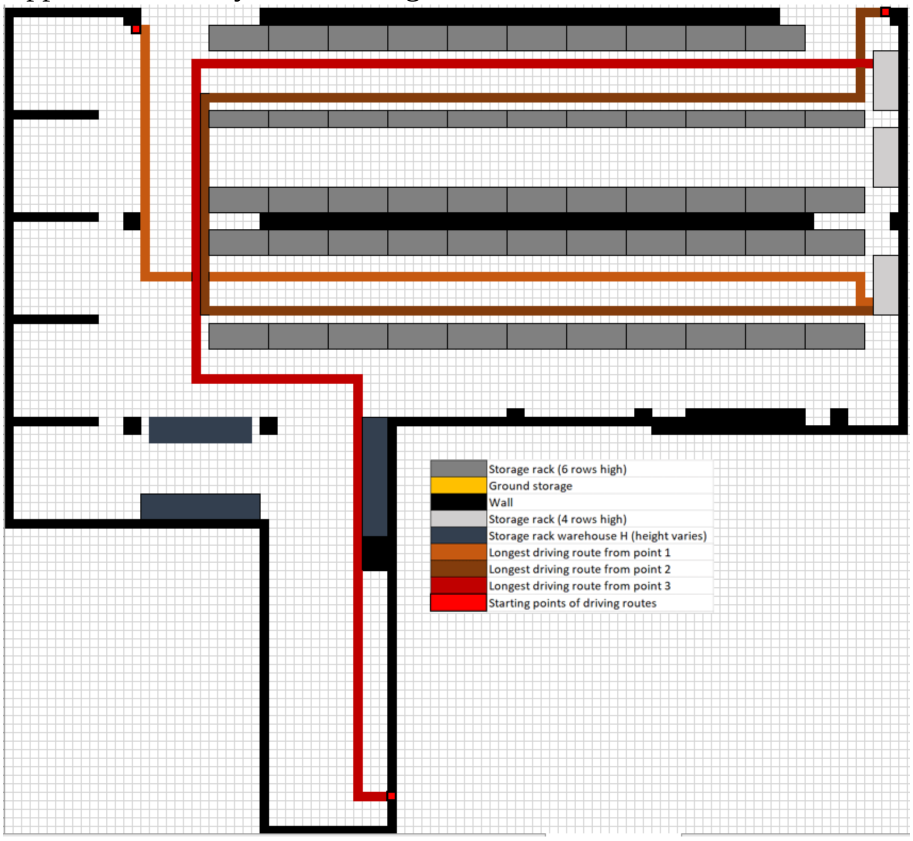


Appendix H, Alternative layouts designed in Excel

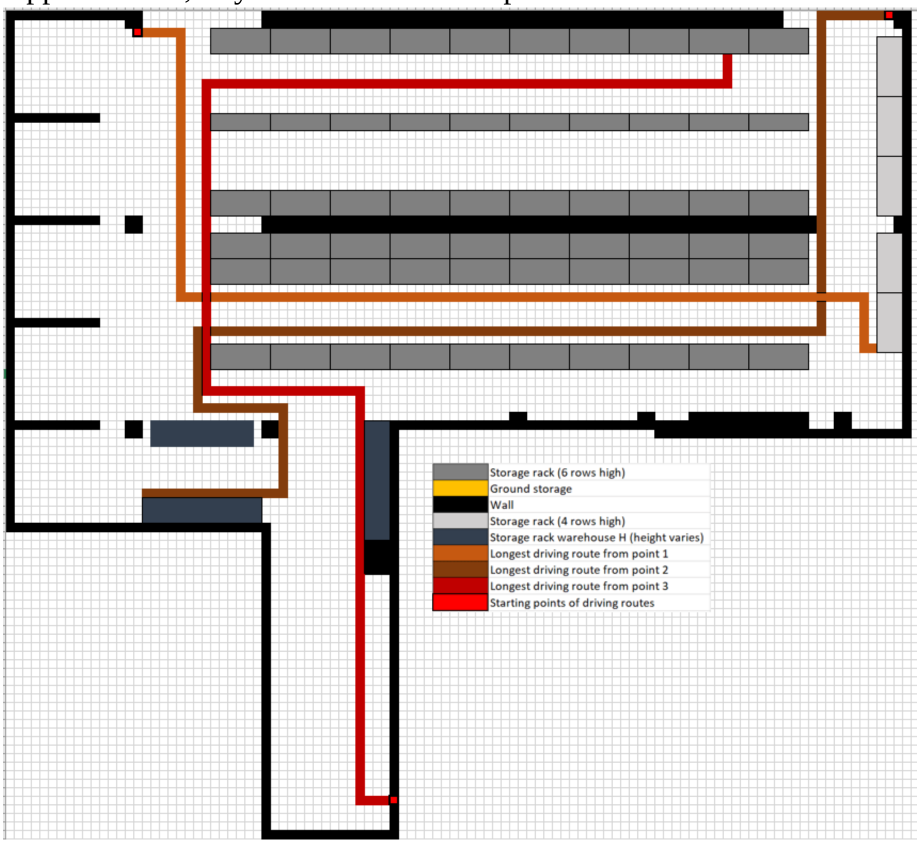
Appendix H.1, Layout based on the current situation



Appendix H.2, Layout with long aisles in Excel



Appendix H.3, Layout with double deep racks in Excel



Appendix H.4, Layout with mobile racks in Excel

Appendix H.5, Layout with narrow aisles in Excel