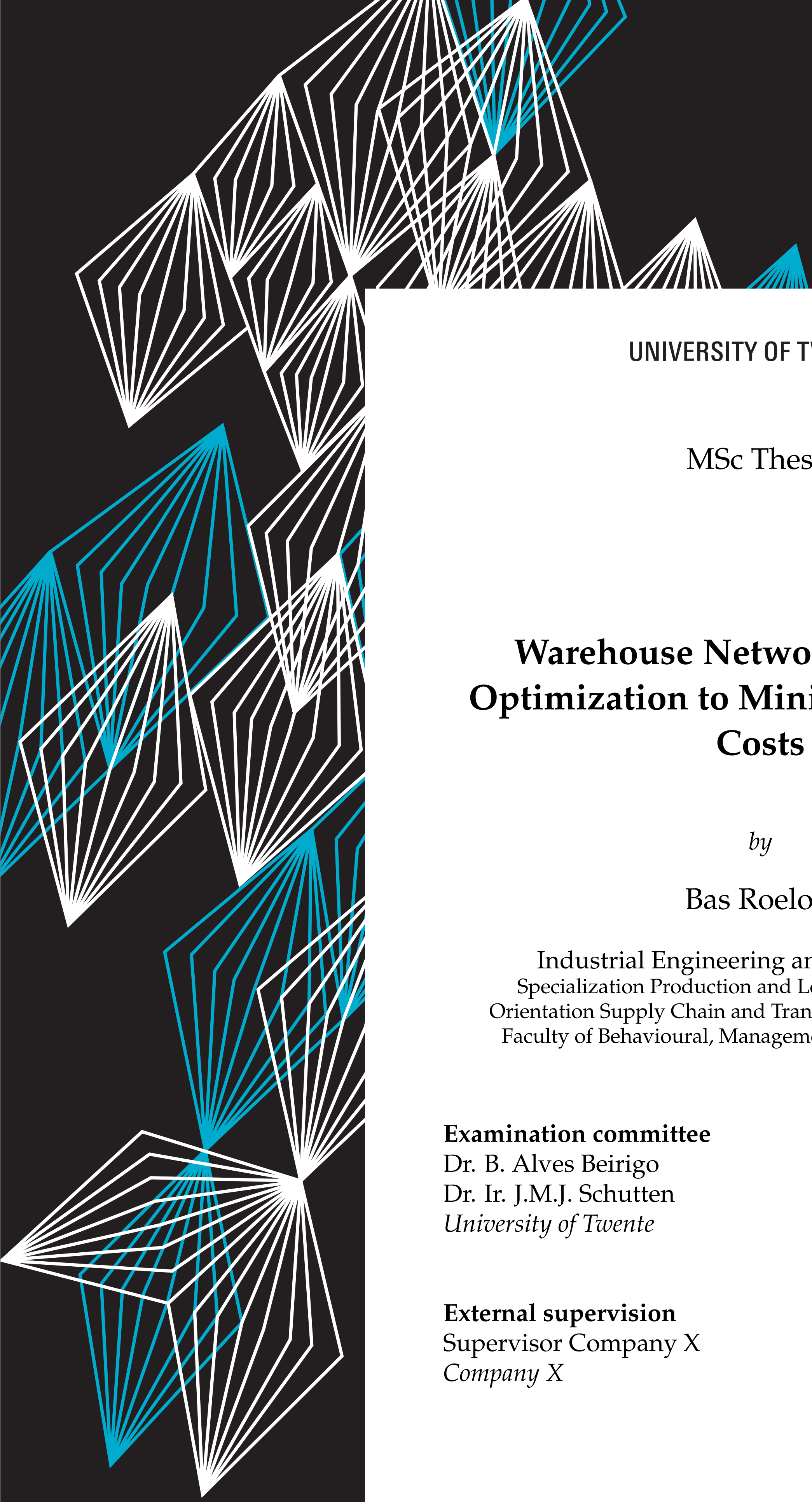

UNIVERSITY OF TWENTE.

MSc Thesis

Warehouse Network Structure Optimization to Minimize Logistics Costs

by

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Industrial Engineering and Management
Specialization Production and Logistics Management
Orientation Supply Chain and Transportation Management
Faculty of Behavioural, Management and Social Sciences

Examination committee
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External supervision
Supervisor Company X
Company X

2024

Management Summary

This management summary provides an overview of the MSc thesis, which addresses the Warehouse Location Problem (WLP) specific to the challenges faced by Company X.

Problem Definition

Company X faces significant logistics costs due to the current network design of its supply chain. With operations spanning across multiple countries, these high costs are due to the separate handling of warehousing services by each facility, high storage costs due to misaligned production and demand, and high shuttle and handling costs from inefficient SKU slotting and ad-hoc decision-making. The core problem identified is the lack of a clear strategy for optimizing warehouse locations, capacities, and Customer/SKU allocations to these warehouses.

Research Approach

The research aims to address the core problem by developing an optimized supply chain network structure for Company X. The main research question guiding this study is:

To what extent can the logistics costs be reduced by optimizing the overall supply chain network structure?

This involves conducting a context analysis to map the current situation and identify the data needed for optimization, including transportation, handling, fixed, and shuttle costs, along with demand data for various customers and storage space requirement data for SKUs. From this data the transportation cost and shuttle costs are modeled by means of regression models, since we had to make estimations of the costs from these potential warehouses to the customers. For selecting potential warehouse locations, we utilized a clustering method to find the centers of demand points and propose potentially interesting warehouse locations. In the literature study, we reviewed the Warehouse Location Problem (WLP) and the Facility Location and Allocation Problem (FLAP) to understand existing methodologies to optimize the warehouse network structure. This identified the problem solved in this thesis as the Single-Objective Multi-Stage Multi-Period Multi-Product Discrete Warehouse Location Problem, with dynamic capacity, outsourced and owned warehouses, and deterministic parameters.

To solve the problem at Company X, with as scope the volume of Facility Y, a mathematical model is formulated that is developed using Python. To address different strategies, scenarios were formulated, each with a slightly different criteria. Based on these scenarios, experiments were setup that considered different utilization rates of the storage capacity and storage space requirements (average and peak requirements). These experiments were solved using the Gurobi and the standard CBC solver to find the optimal solution and the results were compared with the current situation.

Results

The experiments indicated cost savings ranging from 0.1% to 1.4% of the total costs. These savings primarily come from reductions in fixed and shuttle costs, while transportation and handling costs remained relatively unchanged. Significant savings were observed in scenarios with utilization rates of 90%, highlighting the importance of efficient capacity management. Optimal scenarios suggested a capacity requirement of approximately 6,000 tons when warehouses utilized 90% of the storage capacity during average stock requirements. External warehouse WH1 consistently played a crucial role across all scenarios, with warehouse WH3 being utilized in a select number of periods. Fixing the storage capacity at external warehouse WH1 without the option for short-term contracts at external warehouse WH1 resulted in cost savings of around 0.6% in average stock requirement conditions. This approach requires variable capacity management at warehouse WH3 to maintain cost efficiency.

The study showed that the efficiency of the Gurobi solver is much higher compared to the CBC solver in terms of computation time. However, reducing the size of input data sets could make CBC a suitable alternative.

Discussion of the Final Result

Contribution to Theory

This research contributes to the theory by applying the theory of the Warehouse Location Problem. Based on the literature review, we found that traditional models typically address WLPs by either focusing solely on demand volume, neglecting the incorporation of storage capacity constraints, or by incorporating detailed operational parameters such as production input and demand output to determine the storage space requirements, leading to complex and computationally intensive models. To the best of our knowledge, we introduced a slightly different approach by creating a model that on a strategic and tactical level includes both the demand volume and storage space requirement considerations as input to find the optimal warehouse location. Our model provides on a strategic and tactical level where, when, and how much storage capacity is required, this is useful for finding the potential first and then move on to a very detailed analysis, rather than the other way around.

Contribution to Practice

This research makes a contribution to practice for businesses seeking to optimize their warehouse locations. Using the model, companies can make informed decisions regarding warehouse choices, capacity requirements, and customer allocations in different time periods, leading to cost savings. Furthermore, the model allows for scenario analysis and experimentation, allowing businesses to evaluate different scenarios efficiently. After the evaluation of the tool with Company X, the contribution is supported, as the company plans to use the model whenever a similar problem arises.

Recommendations

Based on the findings and conclusions drawn from the study, we recommend Company X to utilize the optimization tool annually to reassess the optimal external warehouse locations based on evolving portfolio needs. This periodic review ensures that warehouse locations remain cost-effective and aligned with current operational demands. The tool should be employed when evaluating potential new warehouse locations or the possibility of closing existing external warehouses.

We specifically recommend Facility Y, if a utilization rate of 90% is desired during average and peak periods, the following:

- If short-term contracts are no option whatsoever, we recommend using external warehouse WH1 with a storage capacity of 4,500 tons and external warehouse WH3 with a storage capacity of 3,000 tons. This is recommended since only in 3 months, this storage capacity at external warehouse WH3 is required, against lower fixed costs compared to external warehouse WH1. This decreases costs by around 0.1% to 0.3%.
- If short-term contracts are an option, we recommend using a fixed storage capacity of 4,500 at external warehouse WH1 and a variable storage capacity of 3,000 tons or lower at external warehouse WH1 as well, depending on the period. This decreases costs by around 0.8%.
- If short-term contracts are not an option at external warehouse WH1, we recommend using a fixed storage capacity of 4,500 at external warehouse WH1 and a variable storage capacity of 3,000 tons or lower at external warehouse WH3, depending on the period. This decreases costs by around 0.6%.

Company X should leverage the optimization tool for allocating customers and SKUs to external warehouses (excluding external warehouse WH1) based on optimal cost solutions across multiple periods. This approach ensures efficient distribution and minimizes logistics costs. Lastly, we recommend the Gurobi solver over CBC due to its superior computation time efficiency.

Preface

Dear reader,

You are reading the Master thesis "Warehouse Network Structure Optimization to Minimize Logistics Costs". This research is executed at Company X as final assignment for my Master Industrial Engineering and Management at the University of Twente. This thesis aims at minimizing the logistics costs for Facility Y by optimizing the warehouse network structure.

At Company X, I have gained invaluable insights into the logistics and supply chain management field, and I am profoundly grateful for this opportunity. I felt part of the logistics team at the headquarters and I want to thank Company X for providing me with this experience.

A special thanks to my supervisor at Company X, who guided me throughout the research and made me feel part of the team. I want to thank him for all the effort and useful feedback he gave me during the research. His enthusiasm and curiosity about the results and progress during our meetings greatly motivated me. He was always available and responded very quick when I needed data or help. I also want to thank all other stakeholders at the company involved in this project, who provided me with useful insights and were always keen to know more. Without the insights and feedback of my company supervisor and the project's stakeholders during the research, this thesis would not have been possible.

I also really want to thank my UT supervisor Breno Alves Beirigo. I really enjoyed our meetings, and he was always willing to provide me feedback or help on short notice. He really helped me out in times when I was having difficulties, and got stuck between the wishes of the company and the university. I learned so much more about approaching a problem, using literature to your advantage, and writing a thesis thanks to him. I would also like to thank Marco Schutten for his support during the preparation phase of the thesis and for the final feedback. His assistance in finding the right supervisor and his initial support were crucial to my thesis journey.

Finally, I would like to thank my family and friends for their support during the execution time of this research. They always supported me and helped me to finish this thesis. I especially want to thank my father, who provided extensive feedback and opinions about the research, which greatly enhanced the quality of my thesis.

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Enschede

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Contents

Acronyms

FIFO First in, First out. 20

FLAP Facility Location-Allocation Problem. 23, 25–30, 32–34, 36, 38

FTL Full Truck Load. 5

OEE Overall Equipment Effectiveness. 3

WH Warehouse. 4

WLP Warehouse Location Problem. 23, 32–34, 36, 38, 39, 41, 45, 47, 48, 51, 53, 71, 74

Glossary

3PL Third-party logistics is an organization's long term commitment of outsourcing its distribution services to third-party logistics businesses. 5, 17

Converting plant The converting plant, owned by Company X, is the plant where the product of the facilities are used as raw material, that is converted to an end-product for the end-consumer. 1, 2, 13

Facility Y Facility Y is one of the production facilities of Company X that produces the products that are used as raw material for the Converting plant. 2

FIFO FIFO (First-In, First-Out) is an inventory management method where the oldest stock (first-in) is used or sold first (first-out) to ensure that older items are utilized before newer ones. 18, 20

Make-To-Order Production strategy where the manufacturer commences operations upon receipt of an order from a customer. 9

Make-To-Stock Production strategy that involves producing or manufacturing goods based on anticipated consumer demand. 9

SAP A software tool that centralizes the management of data and makes it accessible for everyone within a company. 20

Side Run A side run in production refers to the process of manufacturing a secondary or alternative product line alongside the main production, often using the same machinery or facilities to maximize efficiency and resource utilization. 3, 16

SKU Stock Keeping Unit is a unique identifier for a product that helps manage inventory by tracking its features, quantity, and location. 2–4, 79, 80

SKU Slotting SKU slotting involves strategically organizing and placing stock-keeping units (SKUs) in specific locations within a warehouse to optimize storage space, improve picking efficiency, and reduce overall handling time. 4

Turnover Rate The stock turnover rate is a ratio that determines how soon an enterprise sells its goods and products and replaces its inventories during a specific period (e.g., a month). It is calculated by dividing the cost of goods sold by average inventory. 17, 40

Utilization Rate The Utilization Rate of a warehouse the percentage of the warehouse's total storage capacity that is being used. 17

List of Figures

List of Tables

Chapter 1

Introduction

This introductory chapter provides a comprehensive overview of the context, objectives, and structure of this MSc thesis. Section 1.1 gives an introduction of the company, while Section 1.2 addresses the specific challenges faced by the company. Section 1.3 describes the core problems. The main research question, along with its scope and limitations, is described in Section 1.4, and Section 1.5 outlines the sub-research questions. Furthermore, Section 1.6 presents the research design together with an overview of the thesis.

1.1 Company Introduction

Company X is one of the best companies in Europe, when it comes to producing product P. With a great number of employees spread all over the world, Company X has a yearly revenue in the billions.

Almost all of the raw materials used for producing product P are sourced from Company X's own production facilities, so consistency is always a key attribute of their products. Because those products are 100% renewable and produced sustainably, they help reduce the environmental footprint of their customers.

1.2 Problem Description

Company X has an integrated supply chain, where the production facility produces products that are used as raw material for the Converting plant. This process looks as follows (see Figure 1.1):

1. First, recycled material is collected, from which products are created at the production facility.
2. Next, these products are stored in either an internal or external warehouse.
3. From either the internal or the external warehouse the products are transported to the converting plants (internal customers) by a third party.
4. At the converting plant the products from the production facility are converted to an end-product.

5. The end-products are transported to the end-consumer by a third party.

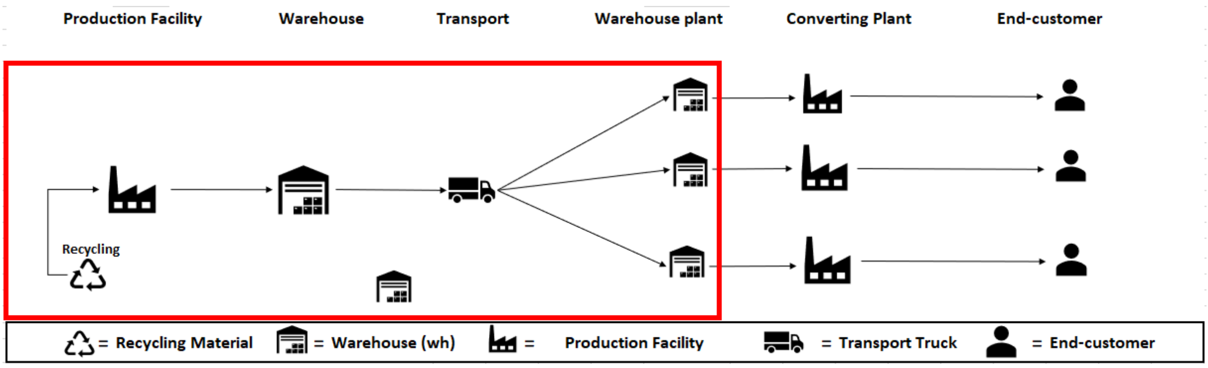


Figure 1.1: Simplified Supply Chain Process of Company X. The focus area of this thesis is within the red square.

In recent years, Company X is facing the problem that the transportation and warehouse costs in logistics have risen by 30%, resulting in an increase of millions of euros in logistics expenses across Europe. Currently, each facility organises the warehousing separately, which may not be optimal for the end-to-end supply chain. This is resulting in high expenses on warehouses and transportation costs (or shuttle costs) from Facility Y to external warehouses in Europe.

1.3 Core Problem

Before the core of a problem can be found, the action problem has to be identified. An action problem is the discrepancy between a norm and a reality as perceived by the problem owner (Heerkens and Winden (2017)). In Section 1.1 and Section 1.2 we presented the information necessary to derive the overarching action problem that requires solving. The action problem is formulated as follows:

"The Logistics costs of the current network design are too high"

To find the root cause of the action problem, a problem cluster is made in Figure 1.2. This leads to the identification of the core problem (Heerkens and Winden, 2017).

Starting from the action problem, we see that currently the logistics costs of the warehouse network design are high. This is due to 3 reasons, namely 1) the transportation costs to the internal customer (Converting plant) are high; 2) the shuttle costs to and handling costs at external warehouses are high; 3) and the storage costs are high. Each of these 3 causes has its own set of causes, which are explained separately.

First, the transportation costs to the internal customer is high because each facility handles the warehousing services and usage separately, regardless of what would be the best for the whole supply chain network. The reason for this problem is that there is no clear strategy on how to optimize the warehouse location, capacity, and the SKU allocation to warehouses.

Second, the storage costs are high because of the high stock levels (much capacity is needed to store this stock). The stock levels are high, because production is not aligned with demand. One of the reasons why is that production output prevails meeting

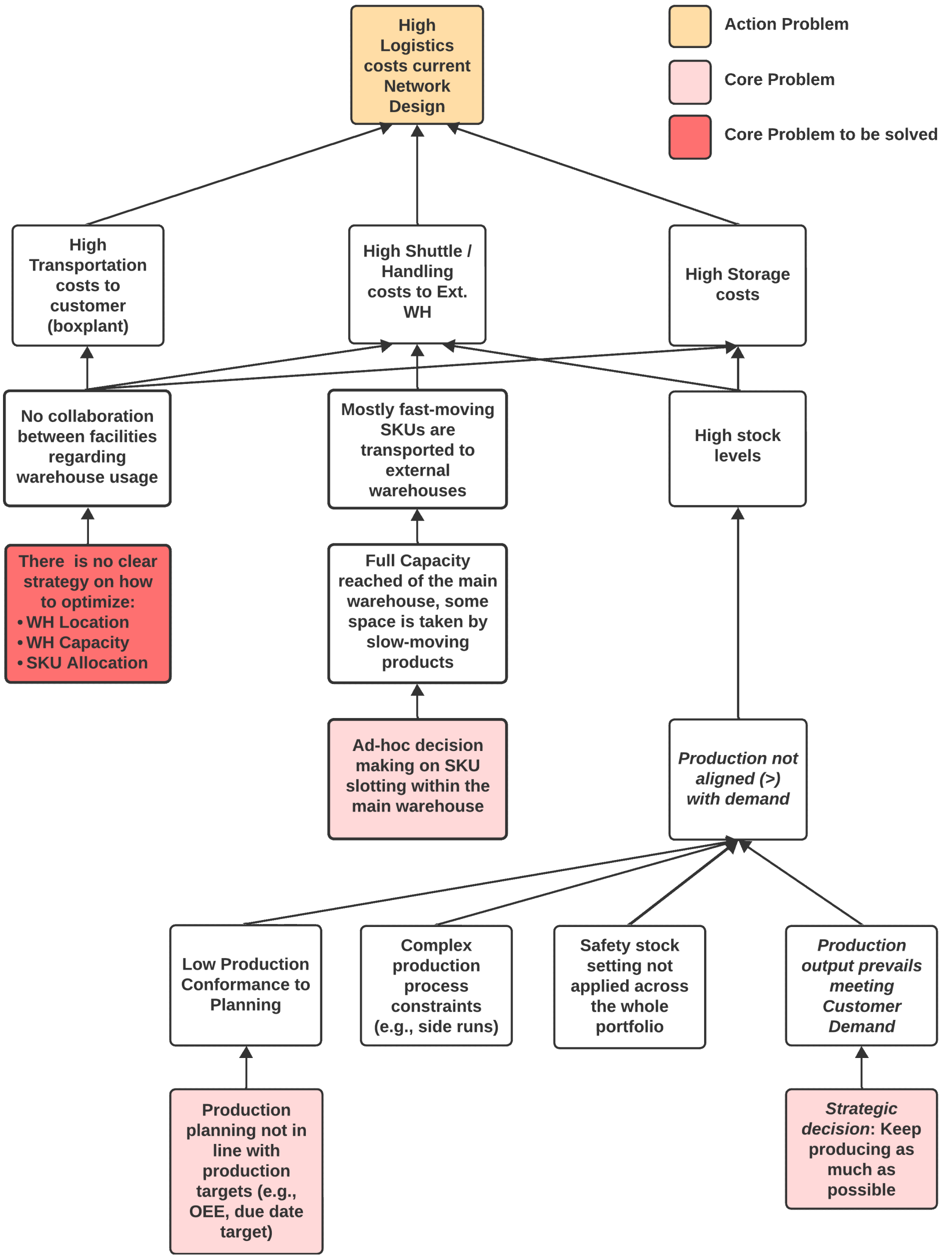


Figure 1.2: Problem cluster Company X

customer demand, meaning that the company prefers to produce as much as possible, even though there is no demand for it. This is the case because of a strategic decision made in which they prefer to keep producing as much as possible. The second reason for the wrong alignment of production and demand, is that the safety stock setting is not applied across the whole portfolio, meaning that for some SKUs the safety stock is higher than required according to the setting. Moreover, the production planning has to deal with complex production process constraints, resulting in for example side runs, and more stock of particular SKUs. The fourth reason for the wrong alignment is the low production conformance to planning, meaning that production deviates from the planning regularly. The reason for this is that production planning is not in line with production targets (e.g., Overall Equipment Effectiveness (OEE) target, due date target, etc.).

Lastly, we have the high shuttle and handling costs. All the reasons described before result in these high shuttle and handling costs, including an additional reason, which is that mostly fast-moving SKUs are transported to external warehouses, because the main warehouse capacity is reached and some space is taken up by the slow-moving products. The reason why is the ad-hoc decision making on SKU slotting within the main warehouse. Currently the forklift drivers decide themselves (without a clear strategy) where to store which SKU within the main warehouse.

From the problem cluster, 4 core problems are identified, of which 1 is solved in this research. The core problem to be solved is ”there is no clear strategy on how to optimize Warehouse (WH) location, WH capacity, and SKU allocation.” Solving this core problem has a great impact on the organization, as it provides structure and strategy on how to make decisions regarding warehouse locations and capacity and provide insights in which customers and (type) of SKUs to allocate to these warehouses. We stress the importance of the other 3 core problems, because these will have a big impact on the organization in general. By aligning production and demand, many problems are solved and costs are decreased. Moreover, by optimizing the warehouse SKU slotting, efficiency and throughput will increase, which may result in lower capacity requirements.

1.4 Research Problem

In Section 1.4.1 the main research objective is formulated. In Section 1.4.2 the scope and limitations of the research are provided.

1.4.1 Research Objective

As described in Section 1.3, one core problem is solved in this research. We aim to optimally locate warehouses within the network, with their corresponding capacity, and allocate SKUs to these warehouses. From this information, the main research question is formulated as follows:

”To what extent can the logistic costs be reduced by optimizing the overall supply chain network structure?”

1.4.2 Research Scope and Limitations

While we aim to provide a solution to Company X’s problems, certain simplifications or assumptions may be necessary due to the complexity of the problem and data availability.

Scope

1. The research will focus on only one facility, Facility Y, because of:
    - The high volume (to the Netherlands, Germany, Belgium, and France).
    - Significant external warehousing costs in the area.
    - Availability of data.

  - The limited time frame. If we were to focus on the volume of multiple facilities, this would require a lot of data research for gathering the correct input data for the model.

2. We do not consider vehicle routing, because the company outsources its transportation to 3PL and is dependent on the availability of trucks, where the shipments are Full Truck Load (FTL). Therefore, the costs for transport are based on euro per ton.

3. We consider production and demand as a given, from which maximum inventory levels are estimated. We do not consider production policy changes or any other changes regarding production, which would influence the inventory levels.

4. All warehouses considered are either warehouses owned by the company (facility warehouses) or warehouses that are rented (external warehouses). Only for the latter warehouse type the choice can be made not to open the warehouse, since owned warehouses must be open at all times.

5. The sole purpose is to minimize distribution and fixed warehousing costs, other objectives are not considered.

Limitations

- The input data for the model regarding the stock level is based on the current production policy and production performance. This may differ when the production policy or production performance changes. Therefore the stock level requirement will be an estimation.

- The shuttle and transportation costs data for lanes that are not used is not available and had to be estimated. Moreover, the costs per lane are dependent on the 3PL party and the availability of trucks on a particular day, which may result in fluctuations in shuttle and transportation costs data that is available.

- FTL cannot be considered in the model as this is of the operational level, which is not considered in this thesis.

1.5 Research Questions

Each chapter of this thesis corresponds to a sub-research question aimed at addressing specific aspects of the main research question. These sub-research questions are as follows:

1. **Chapter 2: Context Analysis**

    - **Q1:** What impact does the current way of working regarding warehouse usage and SKU allocation have on the logistics costs?

    This question is related to the first stage of the research approach, namely the analysis of the current situation. This question serves to identify the current factors that affect the performance of Company X's Facility Y This can later be used to compare the impact the solution has on the situation.

2. **Chapter 3: Literature Review**

    - **Q2:** What methods and theories are relevant for optimizing warehouse network structures?

    This knowledge question serves to identify all methods and theories related to optimizing warehouse network structures. This will serve as the theoretical framework of this thesis.

3. **Chapter 4: Solution Design**

    - **Q3:** What is the most suited algorithm or methodology to solve Company X's Warehouse Location Problem?

    The methods and theories found in the previous stage of the research, will now be implemented. To achieve this, a design and implementation plan are determined. At the end of Chapter 4 the method is implemented, and the problem is solved.

4. **Chapter 5: Experimental Setup and Chapter 6: Results and Discussions**

    - **Q4:** How does the proposed solution perform compared to the current situation?

    After the solution method is developed, the method should be tested. Here the analysis is done, where a comparison is made between the current situation and the situation after implementation. Here the effect of the optimization will be outlined, and insights are given.

5. **Chapter 7: Conclusion and Recommendations**

    - **Q5:** What conclusions are obtained from the results, and what recommendations can be made to Company X?

    This question answers the main research question and will provide conclusions and recommendations. Also, future insights and improvements will be discussed.

1.6 Research Design and Methods

In Figure 1.3 an overview of the relations between research questions, input needed for the research questions, and output generated from the research questions are given. This figure shows the relation between the research questions (orange), what input is needed for each research question (green), and what output is generated by each research question (red). It also shows the chapters in which the research question is answered.

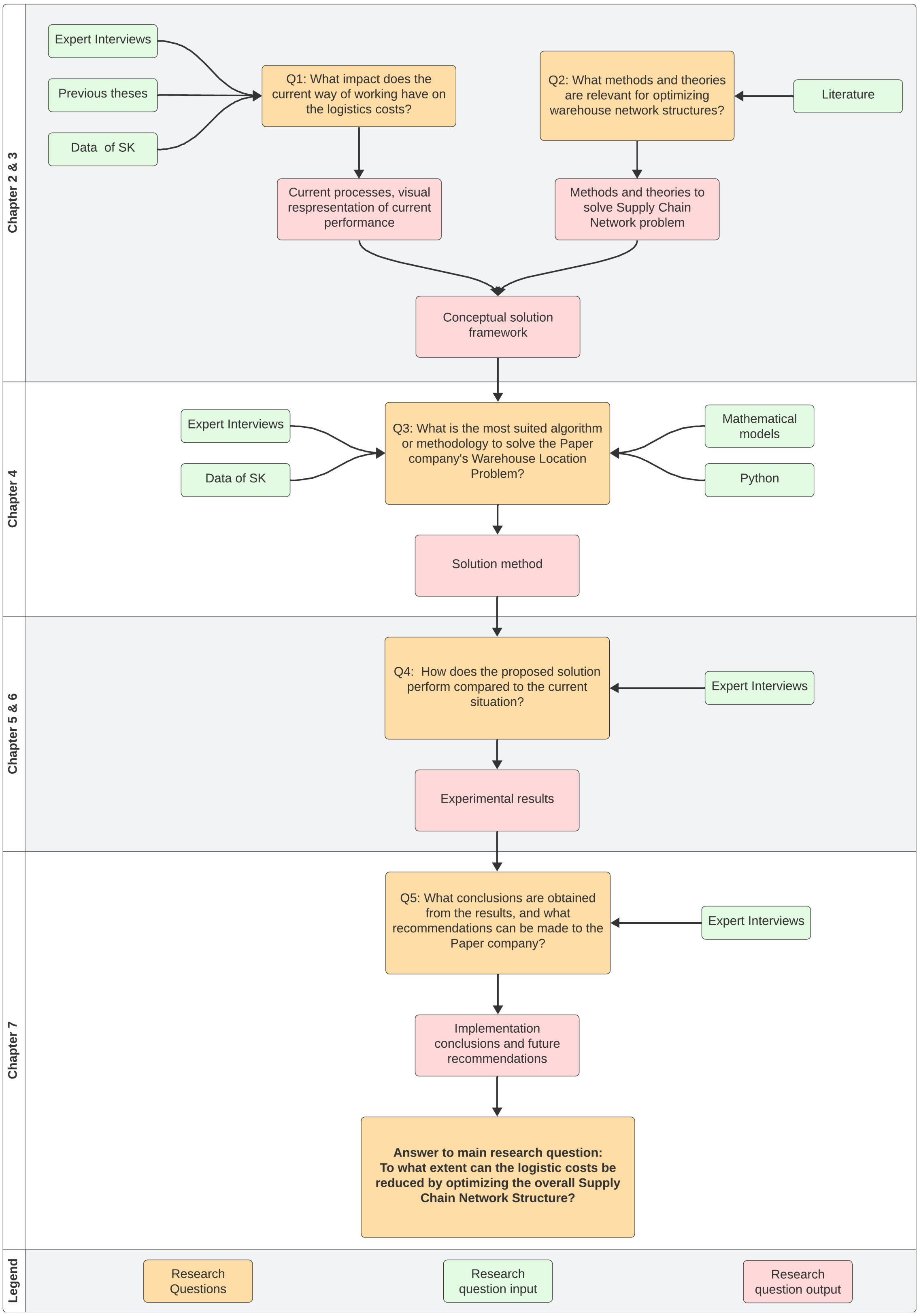


Figure 1.3: The Research design including the research questions (orange), and the inputs (green) and outputs (red) of each research question.

Chapter 2

Context Analysis

This chapter explores Company X's warehouse operations and structure, by answering the research question:

> *"What impact does the current way of working regarding warehouse usage and SKU allocation have on the logistics costs?"*

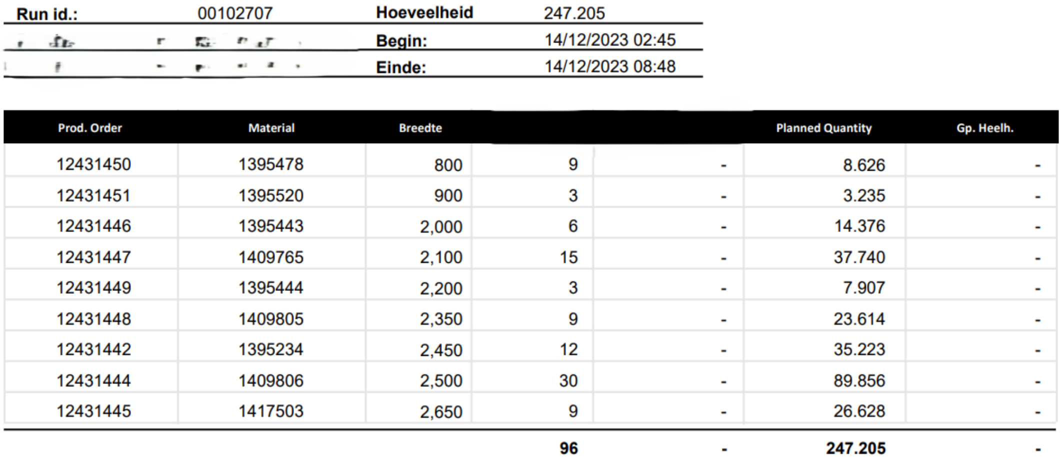
To answer this research question, Section 2.1 explains the current warehouse structure and logistics operations. We step into the performance and challenges faced in Facility Y's logistics and transportation network in Section 2.2. Last, a conclusion is made in Section 2.3.

2.1 Facility Y: Logistics Operations

Facility Y owns three machines, that produce a different portfolios of SKUs. The SKUs are differentiating in width, length, etc. The machines produce 24/7, including weekends and during holidays when there are no shipments, meaning no demand volume is shipped out during these periods. Most of the SKUs are supplied by a Make-To-Stock strategy, and the remaining volume by a Make-To-Order strategy. The production facilities therefore ensure that the converting plants (internal customers) always have stock available. The MTO strategy has a production cycle of 1 week (meaning that the SKU is produced every week) for most SKUs and and for some SKUs a 2 week production cycle.

Every time a SKU is produced, it arrives in the warehouse and must be stored. The storing process starts with the creation of a production schedule (see Figure 2.1 for an example), the logistics department takes this as input together with the available warehouse capacity to decide whether the addition of the produced quantity will exceed the capacity of the internal warehouse. If so, the produced quantity must be stored externally and shipments must be planned to this external warehouse. Based on the production schedule, products are produced and arrive in the central warehouse via a conveyor belt. The forklift driver picks up the product and stores it in any free space available. In Figure A.1 the process flowchart is given, showing the process of storing a product described above.

From Monday to Friday Facility Y loads approximately 103 shipments at the loading



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12431449	1395444	2,200	3	-	7.907	-
12431448	1409805	2,350	9	-	23.614	-
12431442	1395234	2,450	12	-	35.223	-
12431444	1409806	2,500	30	-	89.856	-
12431445	1417503	2,650	9	-	26.628	-
			96	**-**	**247.205**	**-**

Figure 2.1: Example of a production planning for one of the three machines

docks, arriving between 06:00 and 19:00. In Figure A.2 a process flowchart is provided, giving an overview of the logistic process for loading a Truck. The figures involved in this process are the truck driver, who arrives to collect the order; the doorman, who weighs the trucks and grants them access to the facility; an employee of the discharge department, who manages all logistics operations for loading the truck; the forklift driver, who physically loads the truck; and the planning department, which arranges the shipment scheduling. The process starts with the arrival of a truck at the facility. The truck driver reports to the doorman, who measures the starting weight of the truck. The doorman checks the truck details and provides an incoming freight carrier ticket. The truck driver parks at the designated parking location and reports at the ticket office. An employee of the discharge department enters the shipment number and prints the picking list for that shipment. After which he calculates the number of products for that shipment, determines the dock, and provides instructions to the truck driver. When the pick list is incomplete the planning department will be informed and the truck driver will be notified, and will contact his customer. If the picking list is complete, the forklift driver checks whether the truck has the right load securing materials. If not, the truck driver must purchase the missing materials. The truck driver drives to the dock, where the forklift driver checks the truck one last time. If there is anything wrong or missing, the employee discharge is consulted, and the truck must leave with no load. If the truck is OK, the forklift driver collects the SKUs and load them in the truck. When the truck is fully loaded and the picking list is completed, the truck driver leaves the dock and parks the truck to secure the load. Lastly, the truck leaves the facility and goes to the designated customer.

In Table 2.1 an overview is given for the shifts and forklifts assigned to the storing and loading process. For the storage process there are 2 forklifts and three shifts to be able to operate 24/7. The forklift drivers continuously pick up loads from the conveyor belt coming from production and store these in the warehouse. For the loading process there are two shifts and 7 forklifts of which there is always at least 1 in maintenance, so 6 forklifts are in use. From 19:00 no more trucks arrive to be loaded, therefore preparations are done for the next day during the second shift from 19:00 - 22:00.

	Storing Process	**Loading Process**
# of Shifts	3	2
06:00 - 14:00	Yes	Yes
14:00 - 22:00	Yes	Yes
22:00 - 06:00	Yes	No
# of Forklifts	2	6

Table 2.1: An Overview of the Shifts and Forklifts for the Storing and Loading processes

Since Facility Y does not have enough storage at the site itself, external capacity is needed. In Table 2.2 an overview is given of the stock capacity available for Facility Y. The Central Warehouse consists of Hal 14 & 15, which have 6 docks to their disposal. Hal 7 and Hal 8 are located on the site, as seen in Figure 2.2. The external warehouse WH1 is located near to the site and there is an external warehouse WH2 located farther away. The blue line represents the road trucks or forklifts have to travel to get to the designated warehouses.

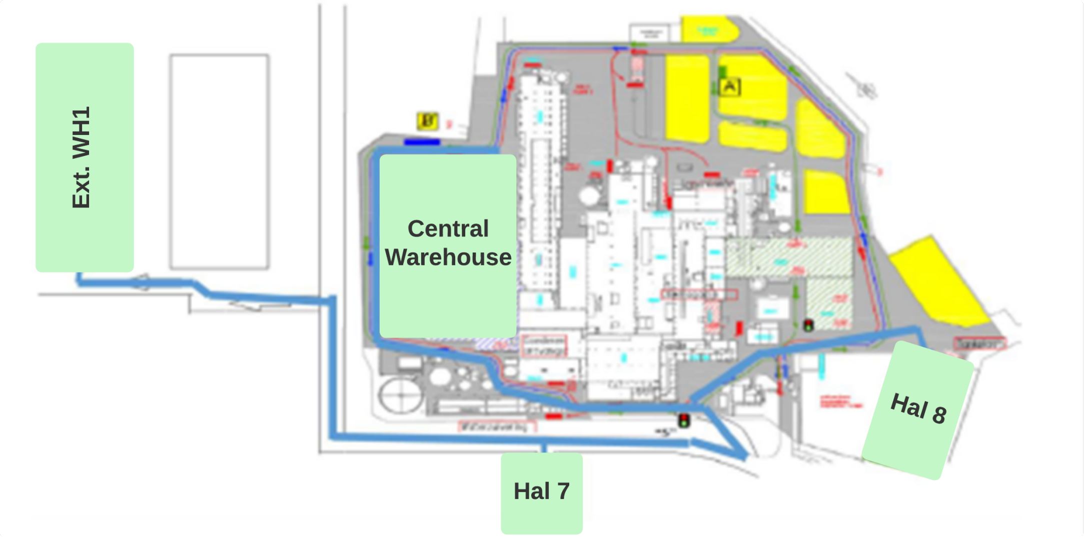


Figure 2.2: Lay-out Facility Y

Warehouse Location	**Maximum Capacity (tons)**	**# of Docks**
Hal 14 & 15	11,000	6
Hal 7	2,500	1
Hal 8	4,500	1
External warehouse WH1	3,000	1
External warehouse WH2	4,500	1

Table 2.2: An Overview of the Warehouse Storage Capacity of Facility Y

2.2 Performance and Challenges Facility Y

In this section the logistics operations of Facility Y, explained in Section 2.1, is elaborated upon by measuring the performance and the challenges of these logistics operations. We dive into the logistics and storage costs associated with Facility Y (Section 2.2.1), the stock available (Section 2.2.2), the order picking performance (Section 2.2.3), and other challenges related to the topic (Section 2.2.4).

2.2.1 Logistics and Storage Costs

In this section an overview of the costs associated with renting a warehouse, handling the products, and transportation are given, and we look into how these costs are divided over the customers. We start with the storage costs of Facility Y. The warehouses Hal 7 and Hal 8 are Company X's property and therefore no rent has to be paid. However, for the external warehouses WH1 and WH2 rent has to be paid for a dedicated storage space. These external warehouse contracts are for the long-term, and last between 1 and 1.5 years, thus changing these contracts must be determined on a tactical/strategic level. For the external warehouse WH1, there is a bit more flexibility to increase capacity (if possible at that time) for a certain number of months/periods. If Facility Y decides to increase the capacity of external warehouse WH1 in a certain period, the price for renting this space increase as well. To know how much it costs to increase the capacity, we calculated the price to store 1 ton of product. With this information the costs for any storage amount is calculated. By dividing the renting (fixed) costs with the storage capacity of each warehouse, we determine these costs. To determine the handling costs, we take the demand volume delivered from these warehouses to the customer in a certain period, and divide this by the handling costs in that period. In Table 2.3, the renting costs per ton per year and handling costs per ton are seen. For external warehouse WH1, the handling is done by their own employees. Therefore, the handling costs are much lower compared to external warehouse WH2, where the handling is done by a 3PL. On the other hand, we see that the fixed costs per ton of external warehouse WH1 are significantly higher compared to that of external warehouse WH2.

	Ext. WH1	**Ext. WH2**
Total Fixed Costs per year	€243,330	€181,472
Storage Capacity (tons)	3,000	4,500
Fixed Costs per ton per year	*€81.11*	*€40.33*
Total Handling Costs	€106,444	€61,154
Shipped Volume (tons)	25,344	7,194
Handling Costs per ton	*€4.20*	*€8.50*

Table 2.3: The fixed and handling costs per ton in the period 01/11/2022 - 01/11/2023.

To determine the shuttle and transportation the costs, regression models are created that are used to estimate these costs in euro per ton. A thorough explanation for this approach is provided in Section 5.4. Using the regression for Facility Y to external warehouses WH1 and WH2, the shuttle costs are €0.81/ton and €12.56/ton, respectively. This way the total costs of external warehouses WH1 and WH2 are calculated. In Table 2.4 the total costs per external warehouse are given from the period 1/11/2022 until 1/11/2023.

	Ext. WH1	**Ext. WH2**
Fixed Costs	€243,330	€181,472
Shuttle Costs	€20,529	€90,364
Handling Costs	€106,444	€61,154
Total Costs	**€370,303**	**€332,990**

Table 2.4: Storage and logistics costs warehouses from the period 01/11/2022 - 01/11/2023.

To provide an overview and create the base case in terms of costs of the current situation, Table 2.5 shows the total costs of the Facility Y, of which the shuttle and transportation costs are estimated via regression models. What we see in this table, is the importance of the transportation costs, which contributes to 84% of the total costs.

	Facility Y
Fixed Costs	€424,802
Shuttle Costs	€110,893
Handling Costs	€2,627,229
Transportation Costs	€15,915,877
Total Costs	**€19,078,800**

Table 2.5: The total (modeled) costs for the Facility Y from the period 01/11/2022 - 01/11/2023.

In Figure 2.3, the contribution of each customer to the transportation costs is shown. These customers are either internal (Converting plant owned by Company X) or external. The transportation costs depend on the distance, the carrier, and the number of transports. From this figure one customer stands out, which is customer 1. This is a converting plant, located in Slovak Republic, which the Facility Y supplies. In total 50% of the transportation costs comes from 23 out of 202 customers over the period 1/Nov/2022 until 1/Nov/2023.

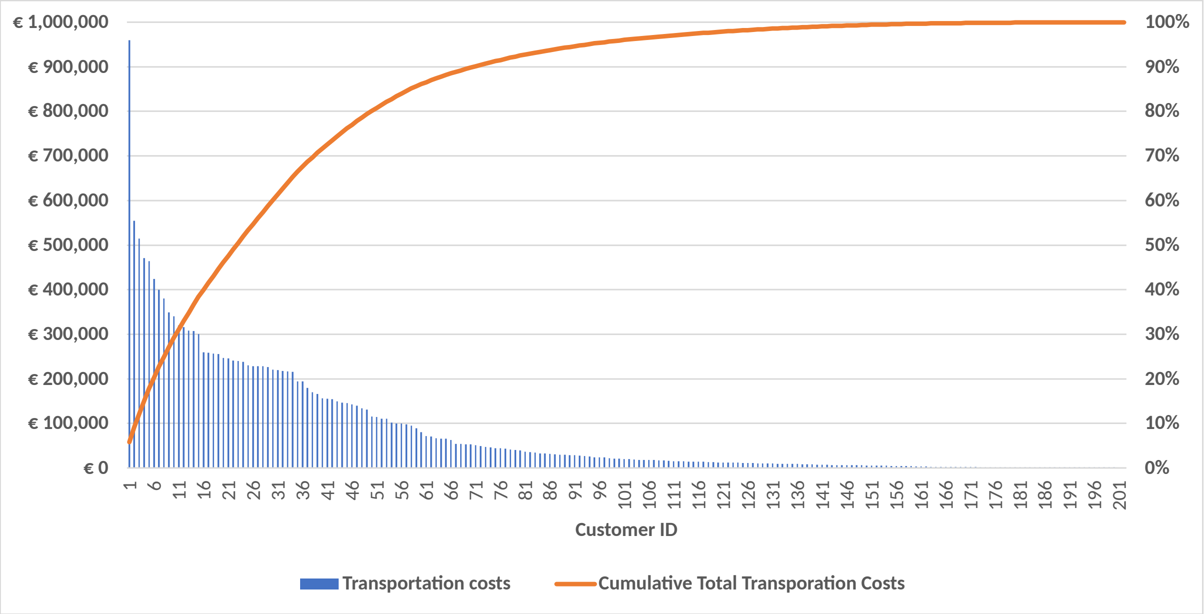


Figure 2.3: Pareto graph of the contribution of each customer to the transportation costs

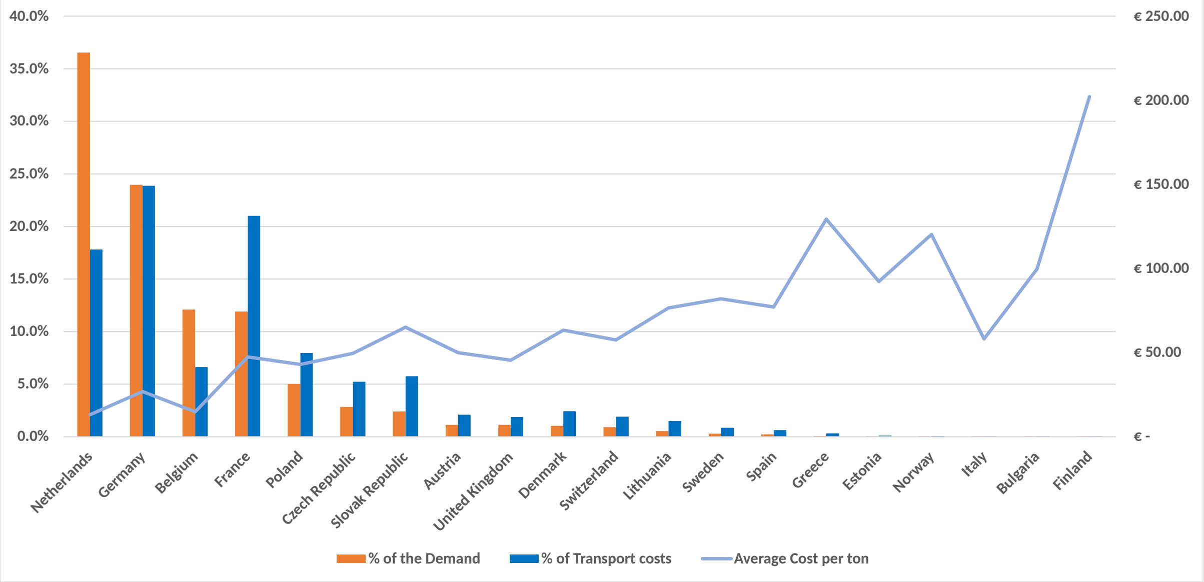


Figure 2.4: Overview of the demand and transportation cost contribution per country.

Figure 2.4 shows that the for the Facility Y the biggest market is in the Netherlands, followed by Germany, Belgium and France. We also see that the transport costs per ton to France are high compared to the other countries where Facility Y has a big market. To get a better overview of the spread of the demand, a map is provided in Figure 2.5.

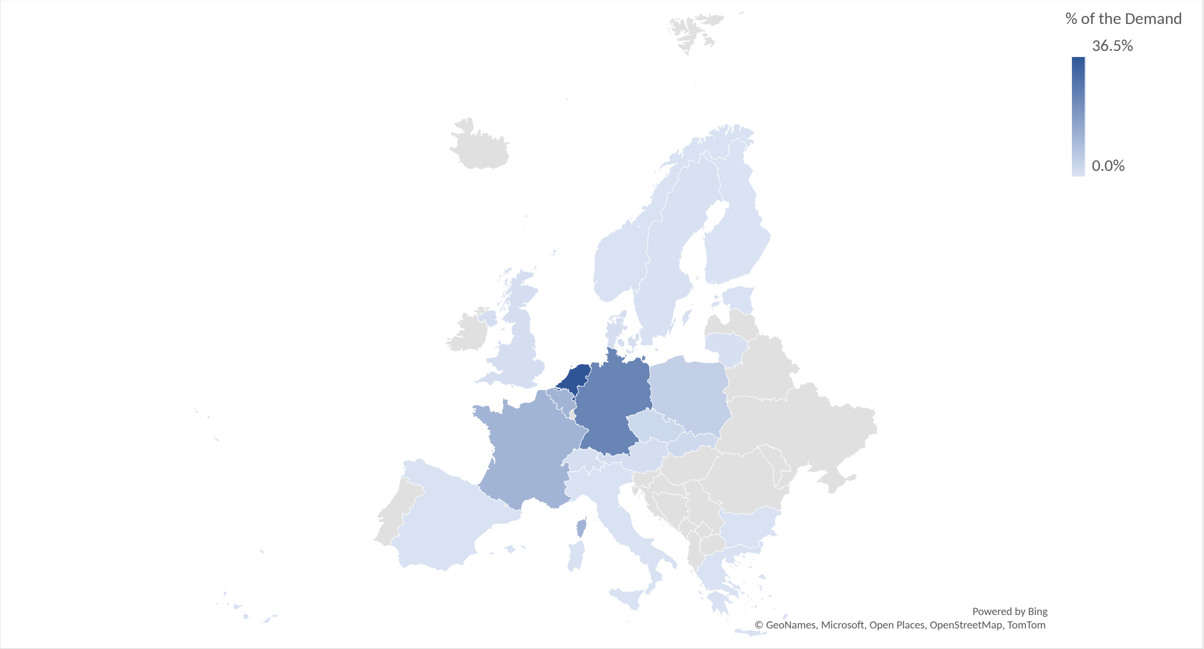


Figure 2.5: Demand spread of Facility Y over Europe

2.2.2 Stock Analysis

In order to get an idea of the contributions to demand and storage space of the SKUs in the portfolio of Facility Y, an ABC classification is made based on the contribution to the total demand volume shipped, as seen in Figure 2.6. In this ABC classification the 80-15-5 rule is applied, which in this classification means 80% of the demand volume is supplied by A-class SKUs, 15% by B-class SKUs, and 5% by C-class SKUs. From the figure, we see that a high number of SKUs is concentrated in the square area until a ”shipping amount (tons)” of 1.500 and until a ”# of orders” of 200 orders. Nearly all of the SKUs located in this area are B and C class SKUs. Furthermore, we see some SKUs in the A-class that stand out, as some have more than 20,000 tons of shipment. While you also have A-class products with fewer than 5,000 tons of shipment, the same goes for the number of orders.

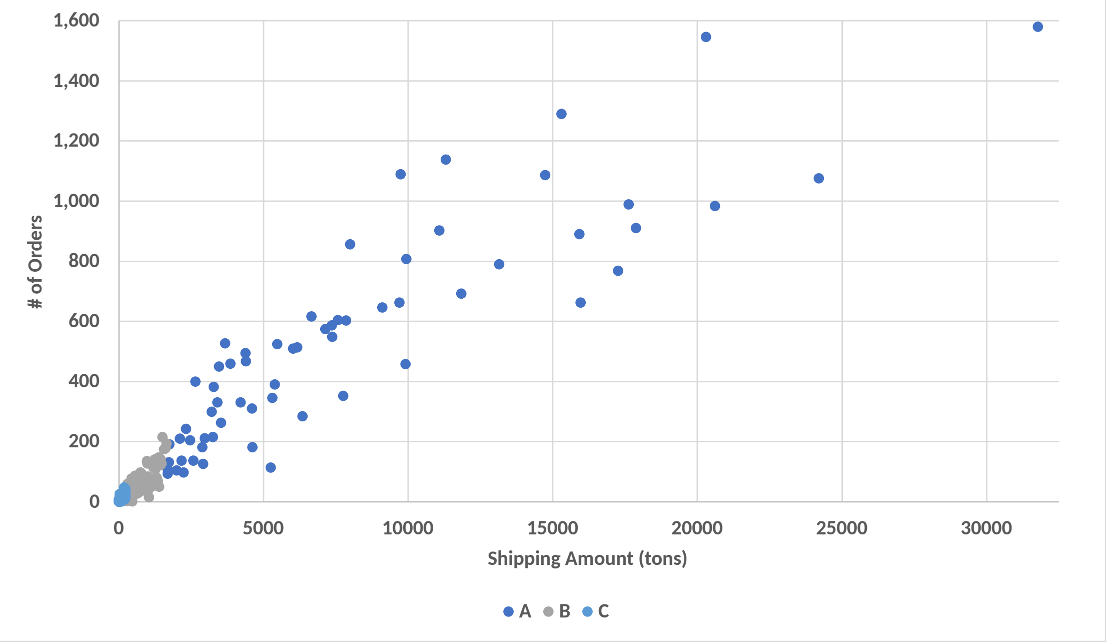


Figure 2.6: Division of SKUs in ABC classes

The summary of the division and contribution of the ABC classes is seen in Table 2.6. This table shows that 67 of the 883 SKUs are in class A, 156 of the 843 in class B, and 620 of the 883 in class C. This shows that throughout the year many C-class products are produced, of which mostly sideruns, as a result of the production complexities and contribute only a small amount to the overall demand. Besides, we see an overview of the stock at the main warehouse (Hal 14/15), the external warehouses on site (Hal 7, Hal 8, WH1), and the external warehouse WH2.

The internal storage capacity consists of multiple warehouse spaces, as explained in Section 2.1. The division of the volume within the warehouses in terms of ABC classes is given in Figure 2.7. This figure shows, that for all classes the stock is spread over all warehouses, and most of each class is kept at the biggest warehouse Hal 14/15. The spread of stock over the warehouses may result in trucks having to drive to multiple locations to be loaded. The spread is due to forklift drivers storing the products in the external warehouse (excluding external warehouse WH2), when there is no space left in Hal 14/15. Rather than moving the slow movers already in Hal 14/15 to the

	Class A	Class B	Class C
# of SKUs	67	156	620
% of Total Demand Volume	80%	15%	5%
% of Total Orders	77%	16%	7%
% of Stock in Hal 14&15	58%	24%	18%
% of Stock in External Storage On-Site	66%	23%	11%
% of Stock in External Storage WH2	100%	0%	0%

Table 2.6: ABC Classification contributions per class

external warehouses (excluding external warehouse WH2), they choose to move any product that comes from production to the external warehouses. What also stands out is the stock at external warehouse WH2, which only consists of A-class SKUs.

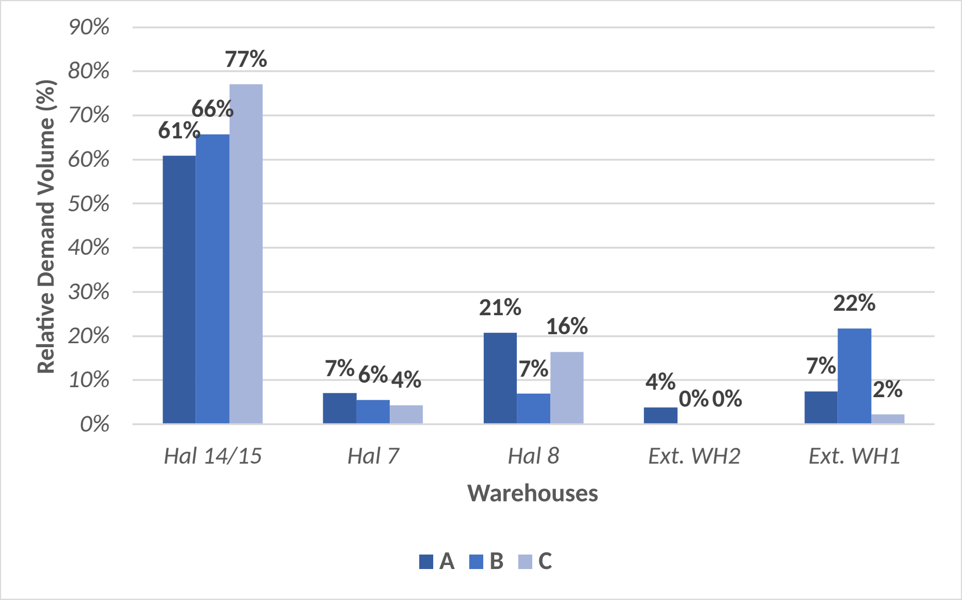


Figure 2.7: ABC Demand Volume Division Over Warehouses

Figure 2.8 provides an understanding of how stock moves across the year in these external warehouses and how this compares to the capacity of each warehouse. What we see from the figure is that the storage capacity for each warehouse is almost never reached, and the times the storage capacity is reached, there is space in a different warehouse to compensate. The average utilization rates of the warehouses are 59% for Hal 7, 63% for Hal 8, 74% for external warehouse WH1, and 61% for external warehouse WH2 over the period November 2022 till November 2023. Moreover, what we see from the figure is that the stock level is quite stable for most warehouses, except for the external warehouse WH2. We see that in one half of the year the stock level at the warehouse is rather low and in the other half year the stock is high. This shows potential for changing contracts with the 3PL supplier, since less space is required during these periods.

At the external warehouses WH1 and WH2 the Turnover Rates lie much lower, compared to Facility Y warehouse. Over a full year where the total demand volume is 618,000 tons, only 32,000 tons were supplied from the external warehouses WH1 and

WH2. On a monthly basis, the turnover rate at Facility Y warehouse is around 2.8 (the total stock is turned over 2.8 times in a month), at external warehouse WH1 around 0.9, and for external warehouse WH2 even lower. This is due to the current way of working of Facility Y, where external warehouses are only used to cover peak moments (e.g., in weekends when Facility Y keeps producing without any demand, creating excess stock). Stock stays in these external warehouse for a longer time, because Facility Y does not work FIFO and only retrieves these products if there is not enough product to supply the customer directly from Facility Y.

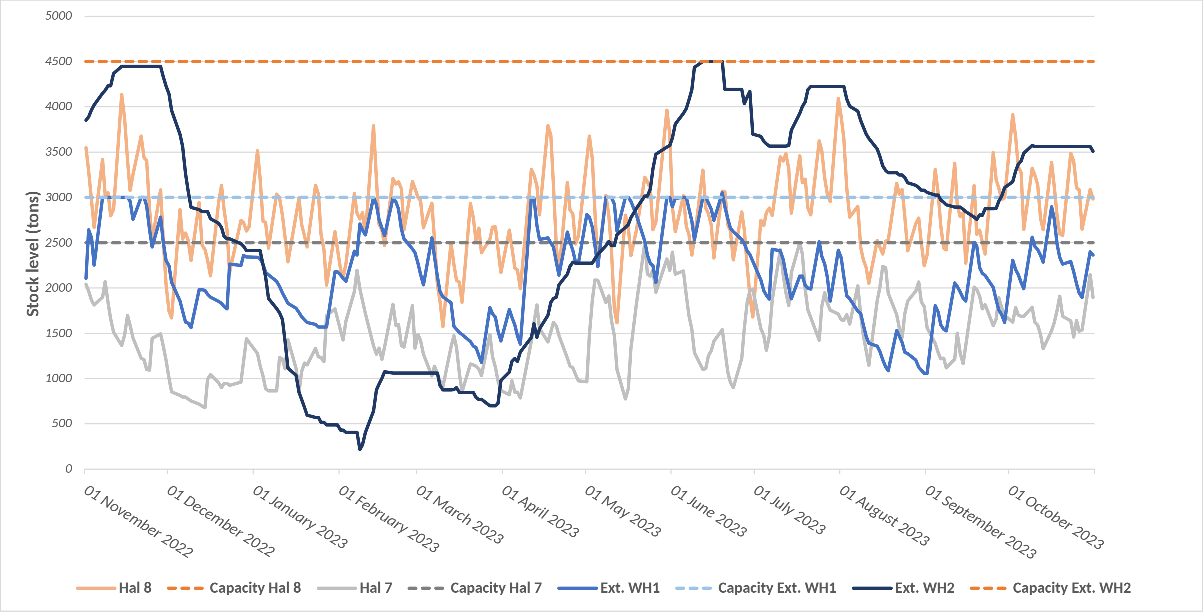


Figure 2.8: Stock development vs. capacity of the external Warehouses Hal 7, Hal 8, WH1, and WH2 (notice that Hal 8 and Ext. WH2 have the same capacity)

Figure 2.9 shows the amount that is added or removed from the warehouse over each weekend, from Friday 21:00 until Monday 06:00. In the weekends there is no demand from the converting plants and Facility Y keeps producing. This results in no SKUs leaving the warehouse, and at the same time SKUs keep coming in the warehouse. Not all SKUs produced during the weekend can be stored at the central warehouse, resulting in that the vast majority is stored at the external warehouses nearby. In the figure there can be seen that during the weekends the stock builds up with a big amount, on average 1091 for Hal 8, 200 for Hal 7, and 450 for external warehouse WH1.

In Figure 2.10 an overview is given of the average and peak inventory level evolution per month during the year from 11/2022 until 10/2023. This information is needed for solving the problem to get insight into how much capacity is required and when this is required. The figure shows that the inventory level was at their highest during November 2022, June 2023, and October 2023.

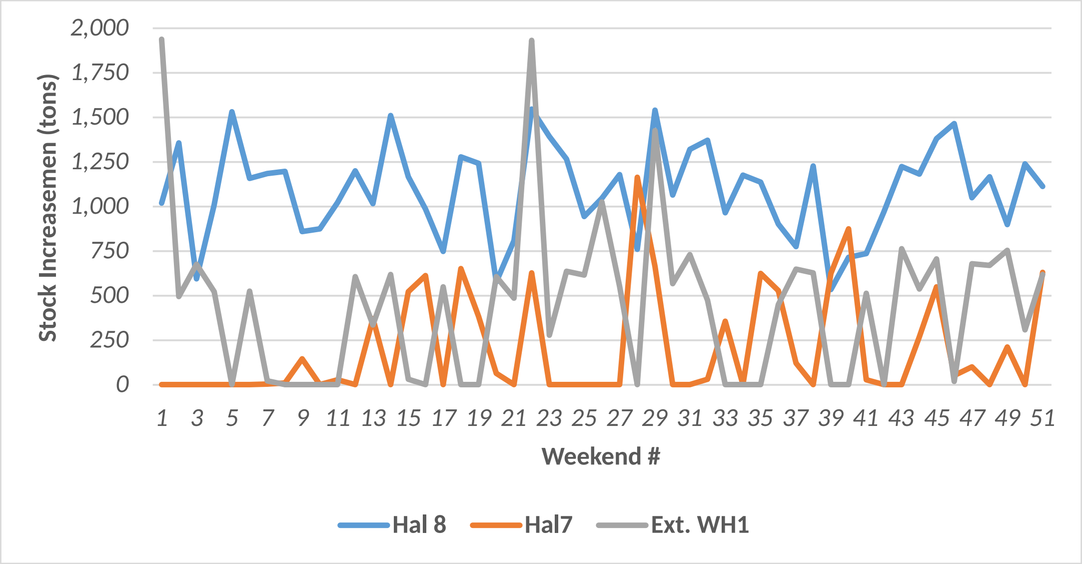


Figure 2.9: Increment in the stock level for every weekend period from Friday 21:00 until Monday 6:00

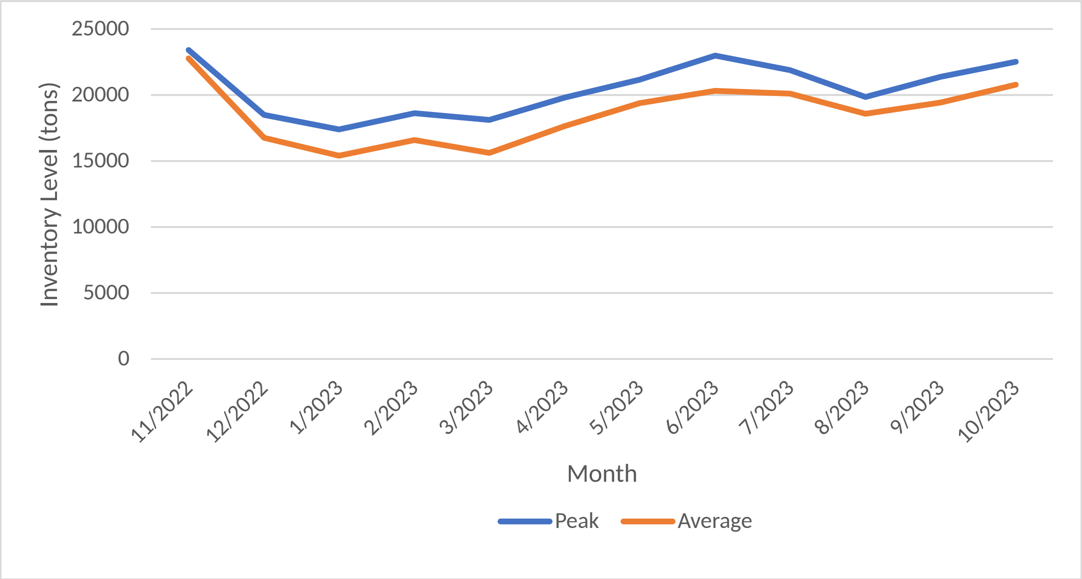


Figure 2.10: The Average and Peak inventory level evolution during the year.

2.2.3 Order Picking and Throughput Capacity

In Section 2.1, we explained the loading process at Facility Y. In this section we dive deeper into the details of this operation.

In Table 2.7, the activities of forklift drivers is given consisting of 3 steps. In this table the maximum loading capacities are provided based on the forklift driver occupation. From 06:00 until 09:00 there are 4 forklift drivers present, from 09:00 until 17:00 there are 5 forklift drivers present, and from 17:00 until 19:00 there are 4 forklift drivers present. Since we know the loading process is between 06:00 and 19:00, we can calculate the maximum number of trucks that can be loaded by the forklift drivers (maximum daily loading capacity). Based on the information from Table 2.7 we know the maximum loading capacity per hour, depending on the number of forklift drivers present. From this information the maximum daily loading capacity is calculated with the following formula:

[# of hours 4 forklift drivers are present * Hourly loading capacity with 4 forklift drivers present] + [# of hours 5 forklift drivers are present * Hourly loading capacity with 5 forklift drivers present]

Using this formula with the information collected, we get:

[3 hours * 8.37] + [8 hours * 10.47] + [2 hours * 8.37] = 125.61 Trucks.

Step 1: Collect picking list and drive to load location until start loading	00:04:44
Step 2: Picking and Loading	00:21:06
Step 3: Return with picking list	00:02:56
Total:	*00:28:48*
Max. Truck Capacity per hour (4 Forklift Drivers)	8.37
Max. Truck Capacity per hour (5 Forklift Drivers)	10.47

Table 2.7: Maximum loading capacity per hour (expressed in number of trucks) calculated based on the time needed per load

A truck has an average load of 25 tons, meaning the maximum daily loading capacity is [25 tons * 125.61 Trucks] = 3,125 tons per day, which is [3,125 tons per * 20 working days] = 62,500 tons per month. Based on the current performance, we know approximately 103 trucks are loaded per day, rather than 125. Using the same calculation we get: [20 working days * 25 tons * 103 Trucks] = 51,500 tons as the maximum throughput capacity per month for Facility Y. To get a more thorough understanding of picking activities, operational activities, and challenges at the site of Facility Y, we refer to Appendix B.

2.2.4 Other Challenges

Besides the topics already discussed, some other general challenges that play a role on the performance of the logistics department of Facility Y, are discussed in this section. The most significant ones are listed below:

- SAP does not calculate how to combine orders to get trucks as full as possible, this makes that the planning of transportation is done manually, which makes it very difficult to plan trucks optimally.
- Trucks have a time window in which they can be loaded, but trucks that arrive before this window are granted access based on the First in, First out (FIFO) principle. It regularly happens that stock for an order is not present in the warehouse. The reason for this is that a customer arrives to collect its order before the given time window by sales and transport planning (their order is still in production). These transport companies know that they work according to the FIFO principle, which means they are more likely to arrive earlier than planned. The challenge is that the customers arrive early, are granted access because of the FIFO principle, and are then provided with the SKUs intended for another customer. This ensures that the customer for whom the products were intended has to wait for the

products until they are produced (which is around the indicated time window for the customer who intervened). This results in peak arrivals of trucks and a lower throughput time.

- Only SKUs that are produced on machine 1 and machine 2 can be put on a truck to be transported to a surrounding warehouse (Hal 8 in this case), when the main warehouse is full. The SKUs coming from the machine 3 must be stored in the central warehouse (Hal 14/15), since currently there is no truck that can transport the SKUs coming from this machine.
- Dependence on skilled truck driver for the speed of loading and docking, thus the speed of loading a truck. There is a lot of miscommunication with truck drivers. Currently money is saved on transport costs, which results in the use of cheap transport suppliers from the East of Europe. These truck drivers do not talk any language understood by the warehouse staff leading to communication issues and do not posses the required skills of docking the truck, which results in a delay in the loading process.

2.3 Conclusion

This chapter has provided an in-depth understanding of the problem context by introducing Facility Y's Logistics Operations, by analyzing the performance of these operations, and by highlighting the challenges it faces in its transportation and loading operations. In the following chapters, we delve into the literature of the problems, followed by the formulation and solution of these problems, aiming to provide a tailored solution for Facility Y.

Chapter 3

Literature Review

This chapter provides a review of the existing literature related to the Supply Chain network problem. The purpose of this literature study is understand and address the most urgent problem encountered at Company X, as discussed in subsequent sections. The following research question is answered:

> *"What methods and theories are relevant for optimizing warehouse network structures?"*

In Section 3.1, we explain the role of warehouses and the main activities within a warehouse. In Section 3.2, we establish the concepts and principles of the supply chain network problem faced by Company X. In Section 3.3 and Section 3.4 we explore the methods and common features of the Facility Location-Allocation Problem (FLAP) and Warehouse Location Problem (WLP). In Section 3.5, we examine existing approaches used to solve the WLP. We place our related work in literature in Section 3.6. Last, we conclude the chapter in Section 3.7.

3.1 Warehousing Essentials

A warehouse is defined as a structural unit with all the resources and organizational arrangements necessary for the execution of the processes related to storage and inventory management (Kappauf et al., 2012). Warehouses are in charge of buffering the material flow along the supply chain, to adapt companies to the variability caused by factors such as transportation delays, batch production, seasonality of demand, and difficulties in suppliers (Gu et al., 2007). In recent years there has been an increase in research related to logistics performance in warehouses due to the pursuit of competitiveness by companies (Agarwal et al., 2006). This requires the warehouse to reduce and make inventory flexible, generate a faster response time, integrate themselves with 1) a greater number of Third-Party Logistics (3PL) providers and 2) multiple customers with diverse needs (Tian et al., 2010).

Cost and service levels are key factor for the company's success (Chopra and Meindl, 2016). The main activities of a warehouse (storage, preservation, and movement of products) are responsible for a lot of costs, due to the amount of economic, financial, personnel, and infrastructure resources required. On the other hand, storage is responsible for the service level offered to customers, since it affects lead time, orders fulfillment, product quality, and conditions (Frazelle, 2016). The optimization of cost and the service level are two of the main objectives for warehouse managers. These optimization initiatives include reducing unnecessary distances and movement, improving space utilization, improving equipment and labor utilization, accessibility to all items, among others (Tompkins et al., 2010).

3.2 Characterizing the Supply Chain Network Problem of Company X

In this section we explore the the Supply Chain Network Problem of Company X, by looking into the objective function in Section 3.2.1 and the constraints of the problem in Section 3.2.2. Lastly, we will find the corresponding taxonomy belonging to the Supply Chain Network Problem in Section 3.2.3.

3.2.1 The Objective Function

The objective for Company X is to minimize the total distribution costs by improving the network structure with the warehouses they have and candidate warehouses and ensure that there is always enough capacity available. Additionally, Company X wants to know which SKUs from which customer should be allocated where to minimize the distribution costs.

3.2.2 The Constraints

There are several constraints that must be taken into account:

- Storage capacity may not be exceeded.
- Demand must be satisfied.
- The warehouses at Facility Y should always be in use, since they are owned by Company X.
- Production (policy) must be considered as a given.

3.2.3 Taxonomy in Literature

From Section 3.2.1, we know that the objective is to minimize distribution costs by changing the supply chain network structure consisting of warehouses to which SKUs from customers are allocated. Based on this information, the problem is identified as a location problem. Within location theory, the following frameworks are found that could represent the problem:

- The Facility Location-Allocation Problem (FLAP). The goal is to locate a set of new facilities such that the transportation cost from facilities to customers is minimized and an optimal number of facilities have to be placed in an area of interest in order to satisfy the customer demand (Zeinab and Ensiyeh (2009)).
- The Warehouse Location Problem (WLP). The goal is similar to the one of the Facility Location-Allocation problem, but solely focuses on finding the optimal

warehouse locations, warehouse capacity, and customer allocation towards the warehouses (Bagherpoor et al. (2009)).

The main difference between both frameworks lies in the scope and focus of the problem, moreover, the FLAP is more studied in literature than the WLP.

3.3 The Facility Location-Allocation Problem (FLAP)

In this section we show relevant literature related to the FLAP framework. We describe common objective functions, constraints, parameters, assumptions, classifications, and models of the FLAP.

The problem of Company X is characterised as a location-allocation problem, where a company seeks the best location for a facility and allocates customers towards them. Within the framework of location-allocation problems there are many types and combinations of types that are addressed.

The FLAP is concerned with the optimal placement of facilities and optimal division of customers to facilities, to serve a certain objective function. Basically, it consists of four basic elements (Adeleke and Olukanni, 2020; Corneujols et al., 1990; Roelofs, 2021):

1. A set of locations where facilities may be built/opened. For every location, some information about the cost of building or opening a facility at that location is given.
2. A set of demand points (customers) that must be assigned for service to some facilities. For every customer, information regarding its demand and about the costs/profits incurred if served by a certain facility are provided.
3. A list of constraints to be met.
4. A function that associates to each set of facilities the cost/profit incurred if one would open all the facilities in the set and would assign the demand points to them such that the requirements are satisfied.

3.3.1 Objectives

With the FLAP the model represents the optimal locations of facilities and allocations of customers to facilities. It will do this by either minimizing or maximizing a certain objective. Common objective functions for the FLAP are (Adeleke and Olukanni, 2020; Alarcon-Gerbier and Buscher, 2022):

- Minimize the total costs (e.g., distribution costs, fixed costs, inventory holding costs, salary costs, production costs, etc.)
- Minimize the total distance to minimize delivery times, CO2 emissions, and costs.
- Minimize the maximum distance between the newly placed facility and all existing facilities.
- Minimize the number of facilities to be opened.
- Maximize the minimum service level to customers.
- Maximize the service level to ensure that customer demands are met promptly and adequately.
- Maximize the total profit.

3.3.2 Decision Variables

In a FLAP the problem owner wants to know where to place facilities and which customer to allocate to these facilities in order to minimize costs. Therefore, the two common decision variables in a FLAP are (Arango et al., 2023; Melo et al., 2009):

- Where to place a production facility in a continuous location space or which production facility to pick from a discrete set of locations.
- Which customers to allocate to which production facility.

3.3.3 Constraints

In order to realise a valid and feasible solution constraints must be added to the model. There are some common constraints for the FLAP, but for each specific problem constraints may be required that are problem specific. Common constraints for FLAP are (Zeinab and Ensiyeh, 2009; Corneujols et al., 1990):

- All customer demand must be satisfied.
- The (production and/or inventory) capacity of the facilities may not be exceeded.
- The maximum distance or travel time towards a customer may not be exceeded (regards to service level agreements).
- The investment in facilities may not exceed the budget.
- The maximum number of facilities that can or must be opened.
- The maximum number of facilities that can serve one customer.

3.3.4 Parameters

Parameters are required to be able to run the model. They are the data put into the model. Changing the input parameters, changes the behaviour, outcomes, or results of the model. Common input parameters for FLAP are (Melo et al., 2009; Arango et al., 2023):

- Coordinates of the facility and customer locations.
- Distance between facilities and customers.
- Distance cost per unit of measurement (e.g., kilometer).
- Fixed installation/renting costs of the facilities.
- Handling or operating costs per unit at each facility.
- Demand at each customer location.
- Facility production capacity.
- Facility inventory capacity.

3.3.5 Classifications

In order to create a manageable representation of a real-world system, assumptions (simplifications) are made. In the FLAP, the assumptions determine the classification of theFLAP. There are many classifications within the Facility Location Problem:

- **Discrete vs. Continuous solution space**

  In a continuous FLAP, the selection for the new facility can be any location within the space. A FLAP with continuous space gives as output the exact coordinates of the new facility location. However, distances have to be estimated (e.g., euclidean distance) to solve the problem. For a discrete FLAP there are a given set of choices for the facility's location (Litoff, 2015). Therefore the collection and reliability of the input parameters is much easier and accurate with a discrete solution space than with a continuous solution space.

- **Static vs. Dynamic Capacity**

  A FLAP with static capacity means that is it either uncapacitated or it has a specific capacity. When each (potential) facility has a capacity, which is the maximum demand it can supply, the problem is called a capacitated facility location-allocation problem. When the capacity constrains are not needed, we have the simple or uncapacitated facility location-allocation problem. Here the assumption is made that each facility produces and ships unlimited quantities of the commodity under consideration (Verter, 2011). A FLAP with dynamic capacity means that the facility have a capacity, but they allow scaling of the facility, so the capacity can be increased or decreased (Alarcon-Gerbier and Buscher, 2022).

- **Single-period vs. Multi-period**

  The main difference between the single-period and multi-period facility location-allocation problems lies in the planning horizon of decision-making. In a single-period problem, decisions focus on meeting immediate demand, optimizing resources for a short period. In a multi-period problem, decisions span a longer time-frame, involving both strategic and tactical considerations for facility locations and resource allocations over an extended planning horizon. Single-period models prioritize adaptability, while multi-period models emphasize long-term planning and efficiency. Moreover, in a multi-period FLAP demand fluctuations are included, since each period has different values (Alarcon-Gerbier and Buscher, 2022; Melo et al., 2009).

- **Deterministic vs. Stochastic parameters**

  The difference between deterministic and stochastic parameters in FLAPs is how uncertainty is handled in the input parameters. Deterministic FLAPs assume that all parameters are known with certainty and provide a single optimal and multiple feasible solutions, while stochastic FLAPs incorporate variability or uncertainty in one or more parameters and provide probabilistic solutions that account for this uncertainty (Melo et al., 2009).

- **Single-product vs. Multi-product**

  The main difference between single-product and multi-product FLAPs is the number of products considered and the complexity of managing multiple products within the facility network. Single-product FLAPs focus on optimizing facility locations and demand allocation for a single product, while multi-product FLAPs involve additional considerations related to managing multiple products within the same facility network (Irawan and Jones, 2019).

- **Single-Objective vs. Multi-Objective**

  Single-objective FLAPs aim to optimize a single criterion, while multi-objective FLAPs aim to optimize multiple conflicting objectives simultaneously, allowing for trade-offs between different criteria. The choice between single- or multi-objective approaches depends on the specific goals and preferences of decision-makers and stakeholders involved in the facility location problem (Arango et al., 2023).

- **Typical Location-Allocation decisions vs. Additional Supply Chain Decisions**

  Facility location decisions are frequently combined with other related supply chain decisions such as inventory and vehicle routing decisions. The FLAP focuses on the location and allocation decisions, however it does not focus on optimizing inventory or routing. There is literature that combines these problems into one to find an optimal solution for both, rather than finding two sub-optimal solutions. The small number of papers integrating decisions regarding inventory or routing, in particular those focusing on the strategic planning level, show that the existing literature is still far from combining many aspects relevant to supply chain management. In fact, this integration leads to much more complex models due to the large size of the problems that may result. This holds in particular when tactical/operational decisions are integrated with strategic ones (Melo et al., 2009).

3.3.6 Modeling Approach of Parameters

Distance

For the FLAP and other location problems there are different ways of calculating or determining the distance between two points or locations (Farahani and Hekmatfar, 2009):

- *Rectilinear distance*. This distance speaks for itself and is a very appropriate distance measure, and it is easy to treat analytically. As Figure 3.1 illustrates, there are several paths between X and P_i, however for every path the rectilinear distance is the same.

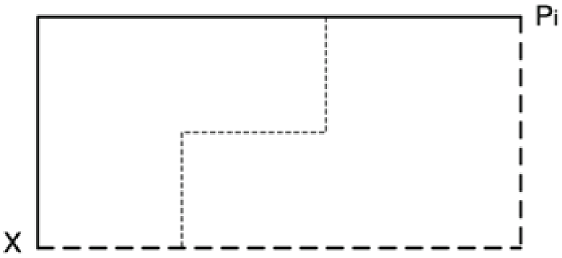


Figure 3.1: Different rectilinear paths between X and P_i.

- *Euclidean distance*. The Euclidean distance is the distance of a straight line from point A to point B.
- *Road map distance*. The road map distance approach of is a bit different than the other ones, but the most accurate approach. With the help of Google maps or Bing maps, the distances are retrieved between two locations through the road network. This is done by retrieving an API key from Google or Bing maps, which attains the distances between two points.

Demand

For the FLAP and other location models demand is either modeled as deterministic or stochastic, and over a single period or multiple periods. The choice for this has influence on the modelling complexity and accuracy.

In a multi-period or "dynamic" FLAP, the objective is to determine the spatial distribution of facilities at each time period of a finite planning horizon so as to minimize the costs for meeting customer demand (Correia and Melo, 2017). By making the model multi-period changes in demand are captured, which provide greater adaptability to changes in demand. Besides, multi-period models support long-term planning by considering implications of facility location and allocation decisions in each time period, which offer greater flexibility.

In a deterministic approach, all variables and parameters are assumed to have fixed, known values. There is no randomness or uncertainty in the system, thus the outcome of the model is entirely determined by the input variables. In a stochastic approach the model does incorporate randomness and uncertainty into the system. Variables and parameters are treated as random variables with probability distributions, and outcomes are probabilistic. In a deterministic approach, stochastic elements are introduced through scenario analysis with discrete variables. Each scenario has a certain probability, with which the model captures uncertainty and variability in the system (Correia et al., 2017).

Capacity

From the literature some ways of modelling the capacity of a production facility capacity are provided, however there is not much literature explaining how capacity is modeled for warehouses. The following ways of modelling capacity are found (Correia et al., 2017; Melo et al., 2009):

- *Production or Supply Capacity (Facility).* Capacity where the facility can only provided a maximum amount of a product.
- *Service Capacity (Facility or Warehouse).* Represents the maximum number of customers a facility can accommodate within a given time period.
- *Throughput Capacity (Warehouse).* The maximum throughput is the maximum flow a warehouse can handle or deal with within a certain period. This can be modeled in terms of products, tons of products, pallets, etc.
- *Storage Capacity (Warehouse).* Maximum amount of inventory a warehouse can hold at any point in time. This is often used in operational problems, where the dynamics of supply and demand can be simulated.

A dynamic aspect can be provided to capacity, by incorporating modular capacity (Correia and Melo, 2017). With modular capacity, warehouse capacity can be increased or decreased in a certain time period. Modular capacities are relevant when the capacity of a facility cannot increased or decreased continuously (Correia et al., 2017).

3.3.7 Basic FLAP Model

This section describes the basic mathematical model of the FLAP (Melo et al., 2009).

Parameters

- D_i: Demand of customer i.
- C_j: Capacity of facility j.
- F_j: Fixed costs for opening facility j.
- c_{ji}: Transportation costs of moving a unit of product from facility j to customer i.

Decision Variables

- x_{ij}: Binary variable indicating whether customer i is being supplied by facility j.
- y_j: Binary variable indicating whether facility j is open or not.

Mathematical Model

$$\text{Minimize:} \quad \sum_{j=1}^{m} F_j y_j + \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ji} x_{ij} \tag{4.1}$$

Subject to:

$$\sum_{j=1}^{m} x_{ij} = 1, \quad \forall i \in I \tag{4.2}$$

$$\sum_{i=1}^{n} D_i x_{ij} \leq C_j y_j, \quad \forall j \in J \tag{4.3}$$

$$x_{ij} \in \{0,1\}, \quad \forall i \in I, \quad \forall j \in J \tag{4.4}$$

$$y_j \in \{0,1\}, \quad \forall j \in J \tag{4.5}$$

The objective function (4.1) is the classical economic objective of minimizing costs. These costs are the fixed costs of each facility in the first part and the costs of supplying customer i by facility j in the second part. Constraint (4.2) indicates that customer i may only be served by 1 facility, x_{ij} says whether customer i is supplied by facility j. Constraint (4.3) makes sure that the sum of all demand supplied by facility j is smaller or equal to the capacity of facility j. Constraint (4.4) indicates that x_{ij} equals either 0 or 1. And lastly, constraint (4.5) indicates that y_j equals either 0 or 1.

3.4 The Warehouse Location Problem (WLP)

In this section we show relevant literature related to the WLP framework. We describe common objective functions, constraints, parameters, assumptions, classifications, and models of the WLP. In all sections the differences with the FLAP framework are discussed.

3.4.1 Objectives

With the WLP the model represents the optimal locations of warehouses and allocations of customers to warehouses by either minimizing or maximizing a certain objective. The main difference compared to the FLAP framework is that in the WLP production or the supply is considered as a given and no optimization is considered at production. Common objective functions for the WLP are (Bagherpoor et al., 2009; Arango et al., 2023):

- Minimize the total costs (e.g., distribution costs, fixed costs, inventory holding costs, handling costs, etc.)
- Minimize the total distance to minimize delivery times, CO2 emissions, and costs.
- Minimize the number of warehouses to be opened.
- Maximize the minimum service level to customers.
- Maximize the service level to ensure that customer demands are met promptly and adequately.
- Maximize the total profit.

3.4.2 Decision Variables

In a WLP the problem owner wants to know where to place warehouses and which customer to allocate to these warehouses in order to minimize costs. Therefore, the two common decision variables in a WLP are (Arango et al., 2023; Melo et al., 2009):

- Where to place a warehouse in a continuous location space or which warehouse to pick from a discrete set of locations.
- Which customers to allocate to which open warehouse.

3.4.3 Constraints

For the WLP there are some common constraints, as for the FLAP, but for each specific problem constraints may be required that are problem specific. The difference compared to the FLAP framework is that no production capacity is considered, only a supply input is given. Common constraints for WLP are (Zeinab and Ensiyeh, 2009; Bagherpoor et al., 2009):

- All customer demand must be satisfied.
- The capacity of each warehouse may not be exceeded.

- The maximum distance or travel time towards a customer may not be exceeded (in regards to service level agreements).
- The investment in warehouses may not exceed the budget.
- The maximum number of warehouses that can or must be opened.
- The maximum number of warehouses that can serve one customer.
- The maximum number of customers a single warehouse can serve.
- Each supply point has a given supply that cannot be exceeded (it can not supply more of a certain product than is given).

3.4.4 Parameters

For the WLP framework similar parameters are required, compared to the FLAP framework. No production cost or capacities are considered, only the supply point is considered to optimally place warehouses. Common input parameters for WLP are (Bagherpoor et al., 2009; Melo et al., 2009):

- Coordinates of the warehouse and customer locations.
- Distance between warehouse and customers.
- Distance cost per unit of measurement (e.g., kilometer).
- Fixed installation/renting costs of the warehouse.
- Handling or operating costs per unit at each warehouse.
- Demand at each customer location.
- Supply of product from manufacturing plant location.
- Warehouse storage capacity.

3.4.5 Classifications

The focus of the WLP is on finding the optimal warehouse location, and not production facility, as the case with the FLAP. However, the classifications are similar. The WLP has the same classifications as mentioned in Section 3.3.5, with the addition of:

- **Single-stage vs. Multi-stage**. In a single-stage WLP there is a direct relationship between the warehouse and customers, as the customers are directly served through the warehouses. Each warehouse is responsible for directly supplying the demand of its assigned customers. In contrast, a multi-stage WLP involved multiple levels of warehouses, where there are some warehouse with a more important or different role compared to others.
- **Owned vs. Outsourced Warehousing**. In some WLP a distinction is made between owned or outsource warehouses. The main difference here is that for owned warehouses an investment has to be made for the storage space, whereas for outsourced warehouses rent is paid for the storage space.

3.4.6 Modeling approach of Parameters

The modeling approach of parameters in the WLP is similar to how the parameter modeling is done in the FLAP. Therefore, we refer to Section 3.3.6 for insights into how to model the parameters.

3.4.7 Basic WLP Model

The basic or starting model of the WLP is similar to the starting model of the FLAP described in Section 3.3.7, in which the only difference is that the scope lies on a warehouse rather than a production facility. From this basic model, both the WLP and FLAP framework build upon.

3.5 Existing Approaches to Location Problems

In this section we describe existing approaches to solve location problem, in particular the FLAP and WLP. To solve small Location Problems, integer programming optimization methods are used. However, for larger Location Problems, heuristic methods or meta heuristic methods are utilized (Farahani and Hekmatfar, 2009). A heuristic is problem-dependent solution strategy, where Meta-heuristic is problem-independent solution strategy. For example, if we want to get the best shooting speed for a soccer robot, we use a specific heuristic. Because, it does not necessarily mean, the same heuristic will also be useful to get the best throwing speed of a basketball to score. But, if we design a strategy with parameters to tune which are applicable to both problems, then it will be a meta-heuristic. (Roelofs, 2021).

3.5.1 Exact solution methods

There are several exact solution methods that are used to solve Location Problems (Zeinab and Ensiyeh, 2009; Adeleke and Olukanni, 2020):

- *Integer Linear Programming (ILP)*. Formulate the Location Problem as an ILP model and solve it using optimization solvers such as CPLEX, Gurobi, or SCIP. ILP solvers guarantee an optimal solution, but they may be computationally intensive for large problem instances.
- *Branch and Bound (B&B)*. A technique used in conjunction with ILP solvers to explore the solution space efficiently by pruning branches that cannot lead to an optimal solution. It can handle larger problem instances compared to simple Integer Linear Programming solving.
- *Dynamic Programming (DP)*. DP breaks down the problem into sub-problems and solves them recursively. However, its applicability may be limited by the size of the problem due to exponential time complexity.

3.5.2 Heuristic and Meta-heuristic methods

There are several heuristic and meta-heuristic methods that are used to solve Location Problems (Zeinab and Ensiyeh, 2009; Adeleke and Olukanni, 2020):

- *Greedy Algorithms (GA)*. Greedy algorithms construct solutions step by step by making optimal choices locally. They are computationally efficient but may not always find the optimal solution.
- *Local Search Algorithms (LSA) — Heuristic*. Algorithms like Hill Climbing, Simulated Annealing, and Tabu Search iteratively improve solutions by making small modifications to them. These methods can escape local optima but may require many iterations.
- *Busacker-Gowen Algorithm (BGA) — Heuristic*. The Busacker-Gowen algorithm is a path-based algorithm specifically designed for solving the maximum flow problem in a network. It focuses on finding augmenting paths (paths from the source to the sink) that increase the flow while minimizing the total cost
- *The Langrangian Heuristic (LH) — Heuristic*. The Lagrangian heuristic combines three key components: A suitable Lagrangian relaxation of the problem, an efficient sub-gradient optimization procedure for solving the Lagrangian dual, and a primal heuristic for yielding feasible solutions. The heuristic aims to recover primal feasibility by finding feasible solutions based on the Lagrangian relaxation
- *Genetic Algorithms (GA) — Meta-Heuristic*. Inspired by the process of natural selection, GA maintains a population of candidate solutions and applies genetic operators such as mutation and crossover to evolve better solutions over successive generations.
- *Particle Swarm Optimization (PSO) — Meta-Heuristic*. PSO simulates the behavior of swarms of particles moving through a search space. Each particle represents a candidate solution, and they adjust their positions based on their own experience and that of neighboring particles.
- *Ant Colony Optimization (ACO) — Meta-Heuristic*. ACO is inspired by the foraging behavior of ants. It iteratively constructs solutions by simulating the movement of ants on a graph representing the problem space. Pheromone trails guide the construction process, with stronger trails indicating better solutions.

3.6 Related Work in Addressing Similar WLP Variants

Based on the literature study, we define the problem of Company X as a Warehouse Location Problem (WLP), because the focus lies on finding the optimal warehouse locations, rather than production facility locations. Because more work has been done regarding the FLAP framework, we learn from this research to include in the WLP of Company X. In tables 3.1 and 3.2, we relate the work of this thesis in literature. For the explanation of each column, we refer to Section 3.4.5 in which each classification is explained. Based on the literature review table, we solve the Single-Objective Multi-Stage Multi-Period Multi-Product Discrete Warehouse Location Problem (SOMSMPMPDWLP) with Dynamic Capacity, Outsourced and Owned warehouses, and Deterministic Parameters.

Table 3.1: A literature review table for the Warehouse Location Problem (WLP).

Paper	Objective *Function*[a]	Warehouse Location *DI — CO* [b]	Capacity *ST — DY* [c]	# of Warehouses *SI — MU* [d]	Product *SI — MU* [d]	Planning Horizon *SP — MP* [e]	Parameters *DE — SO* [f]
Correia et al. (2017)	MC	DI	DY	MU	SI	MP	SO
Adeleke and Olukanni (2020)	MNF	CO	DY	MU	SI	SP	DE
Nagy (2004)	MC	DI	ST	MU	SI	SP	DE
Sharma and Berry (2007)	MC	DI	ST	MU	SI	SP	DE
Melachrinoudis and Min (2007)	MC	DI	ST	MU	SI	SP	DE
Irawan and Jones (2019)	MC	DI	DY	MU	MU	SP	DE
Amin and Baki (2017)	MP + MOTD	DI	ST	MU	MU	MP	SO
Szczepanski et al. (2019)	MC	DI	ST	MU	SI	SP	DE
You et al. (2019)	MD	CO	-	MU	SI	SP	DE
Gao (2020)	MD	CO	-	MU	SI	SP	DE
Santosa and Kresna (2015)	MC	DI	ST	MU	SI	SP	DE
Brunaud et al. (2017)	MC	DI	DY	MU	MU	MP	DE
THIS THESIS	MC	DI	DY	MU	MU	MP	DE

[d] SI = Single; MU = Multi [b] DI = Discrete; CO = Continuous [c] ST = Static; DY = Dynamic [e] SP = Single-Period; MP = Multi-Period
[a] MC = Minimize Costs; MNF = Minimize Number of Open Facilities; MP = Maximize Profit; MOTD = Maximize On-Time Deliveries; MD = Minimize Distance [f] DE = Deterministic; SO = Stochastic

Table 3.2: Continued: A literature review table for the Warehouse Location Problem (WLP).

	Warehouse Type	Production	Storage Space Req.	Distribution Levels	Solution Approach
Paper	*OW — OS — B* [a]	*IN — OUT* [b]	*IN — OUT* [b]	*SI — MU* [c]	*B&B — LH — ILP — GRA — BGA — LSA* [d]
Correia et al. (2017)	OW	-	-	SI	B&B
Adeleke and Olukanni (2020)	OW	-	-	SI	LH
Nagy (2004)	OW	-	-	SI	ILP
Sharma and Berry (2007)	OW	IN	OUT	SI	ILP
Melachrinoudis and Min (2007)	OW	OUT	-	SI	ILP
Irawan and Jones (2019)	OW	-	-	MU	ILP
Amin and Baki (2017)	OW	OUT	-	MU	GRA
Szczepanski et al. (2019)	OW	OUT	-	MU	BGA
You et al. (2019)	OW	-	-	SI	LSA
Gao (2020)	OW	-	-	SI	GA
Santosa and Kresna (2015)	OW	IN	OUT	SI	LSA
Brunaud et al. (2017)	OS	OUT	-	MU	ILP
THIS THESIS	B	IN	IN	MU	B&B

[a] OW = Owned; OS = Outsourced; B = Both [b] IN = Input; OUT = Output [c] SI = Single-Stage; MU = Multi-Stage [d] B&B = Branch & Bound; LSA = Local Search Algorithm; ILP = Integer Linear Programming; GA = Genetic Algorithm; BGA = Busacker-Gowen Algorithm; GRA = Greedy Algorithm; LH = Langrangian Heuristic

3.7 Conclusion

This chapter has presented a literature study on the WLP and FLAP, with a specific focus on these problems characteristics and variants. We have explored the fundamentals of both problems and reviewed existing approaches. The knowledge acquired from this literature study is used in the next chapter, to develop a customized solution to address Company X's Single-Objective Multi-Stage Multi-Period Multi-Product Discrete Warehouse Location Problem with Dynamic Capacity, Outsourced and Owned warehouses, and Deterministic Parameters.

Chapter 4

Solution Design

The aim of this thesis is to reduce the overall logistics costs, consisting of distribution costs and storage costs, where we want to provide strategy in terms of the optimal warehouse location and capacity, and allocation of customer demand to these warehouses. In this chapter the solution design is presented and explained by answering the following research question:

"What are the most suited algorithms or methodologies to solve Company X's Warehouse Location Problem?"

In Section 4.1, a description of the solution design is given. The assumptions of the model are described in Section 4.2. In Section 4.3, the mathematical model is explained. In Section 4.4, the scenarios and their importance are described. In Section 4.5 is described how the proposed solution design works and helps solve the problem by means of a toy example. Lastly, the conclusion for the chapter is provided in Section 4.6.

4.1 Model Description

This research aims to minimize the logistics costs, which include fixed costs (rent), handling costs, shuttle costs, and transportation costs, by optimizing the number and location of warehouses, their storage capacities, and the allocation of customers to these warehouses. The model considers multiple time periods, providing insights into the possibility of short-term contracts for specific warehouse locations, which are contracts lasting for 1 or a few months. Essentially, this research provides the most cost-efficient solution by determining where capacity is needed, how much is needed, and when it is needed.

The mathematical model is based on the Warehouse Location Problem (WLP), which is extensively studied in Chapter 3. We recall that with the traditional WLP, we determine the best locations for warehouses and allocation of customers to these warehouses, to minimize total costs, which include fixed costs of establishing and operating the warehouses, as well as variable costs associated with transportation. Our research maintains the objective of minimizing total logistics costs, while incorporating additional cost parameter shuttle costs. We include the shuttle costs because our WLP includes multiple distribution levels, starting from the Facility Y warehouse where the products are produced. From there, products are transferred either directly to the customer or to external warehouses before reaching the customer, similar to the approach used by Adeleke and Olukanni (2020).

We extended the traditional model by including multiple time periods and dynamic capacity in our research, based on Correia and Melo (2017); Kelly and Marucheck (1984); Brunaud et al. (2017). Including this creates a dynamic warehouse location problem allowing the model to capture fluctuations in demand and storage capacity requirements. In our research, we use capacity levels, where each capacity level has a specific storage capacity and associated fixed costs (rent), which is similar to the modular capacity concept used by Correia and Melo (2017). Additionally, our research focuses on long-term planning, where each time period represents, for example, a week or month, rather than a day.

Different from literature, to the best of our knowledge, is the inclusion of the storage capacity requirement per SKU. In traditional models this is addressed through a day-to-day simulation model (Szczepanski et al. (2019)) from which you learn the storage requirements on a very detailed level. We took a different approach, since the company wanted a more high-level view, requiring less data. By including the storage capacity requirement per SKU per period, the model allocates the necessary storage space for each SKU per period, ensuring we know where, when, and how much capacity is required. Additionally, the demand volume of a SKU can only flow through a warehouse if storage space of a SKU is allocated to that warehouse. To make sure the Turnover Rate at the warehouses is realistic, we included a parameter that specifies the allowable turnover rates per SKU at the Facility Y warehouse. Finally, we incorporated a constraint which assures that if demand volume is less than the storage space requirement for a SKU at an external warehouse, the difference is carried over to the next period. Essentially, this ensures that any unsold or unused inventory in one period continues to occupy storage space in next period.

4.2 Assumptions

This section outlines the foundational assumptions that underpin our problem formulation. These assumptions include:

- All input parameters are deterministic.
- We consider production and demand as a given, from which storage capacity requirements per SKU and turnover rates at Facility Y can be estimated based on historical data. We do not consider production policy changes or any other changes regarding production, which could influence the storage capacity requirements.
- All external warehouses considered are either warehouses owned by the company (facility warehouses) or warehouses that are rented (external warehouses). Only for the latter warehouse type the choice can be made not to open the warehouse.
- The costs for increasing capacity level is based on the costs to store one ton of

storage in a specific location.

- The maximum throughput capacity of Facility Y in period t is assumed to be the actual throughput of Facility Y in period t. For external warehouses this is calculated based on the number of docks and personnel, as shown in Section 2.2.3.
- We assume that if demand volume is less than the storage space requirement for an SKU at an external warehouse, the difference is carried over to the next period. If the demand volume is greater than or equal to the storage space requirement of an SKU at an external warehouse, the remaining storage space required is set to zero.

4.3 Mathematical Model

The model is based on the WLP, described in Chapter 3. The indexes and decision variables of the model are described in Section 4.3.1, and the parameters in Section 4.3.2. The corresponding mathematical model is explained in Section 4.3.3.

4.3.1 Indices and Decision Variables

Indices

- i - Customer (i = 1,...,I)
- j - Warehouse (j = 1,...,J)
- s - SKU (s = 1,...,S)
- t - Time period (t = 1,...,T)
- m - Facility (m = 1,...,M)
- c - Capacity level (c = 1,...,C)

Decision Variables

- Let y_{jct} be a binary variable indicating whether warehouse j, with capacity level c is open or closed in period t.
- Let v_{msjit} be a continuous variable representing the demand volume that warehouse j provides to customer i for SKU s, originating from facility m in period t.
- Let x_{msjt} be a continuous variable representing the storage space of SKU s, originating from facility m, that is required in warehouse j during period t.
- Let p_{msjt} be a binary variable that checks whether storage space of SKU s, originating from facility m, is allocated to warehouse j in period t.

4.3.2 Parameters

- D_{msit}: Demand in tons of SKU s from customer i supplied by facility m in period t.

- S_{mst}: Amount of storage space in tons that is required for SKU s, by facility m, during period t.

- QS_{mst}: Total Demand in tons of SKU s, which is supplied by facility m in period t.

- SC_{jc}: Storage Capacity of warehouse j with capacity level c.

- TC_{jt}: Throughput Capacity of warehouse j in period t.

- TR_{mst}: Turnover Rate at facility m for SKU s in period t.

- F_{jc}: Fixed costs (rent) per period for opening warehouse j with capacity level c.

- H_j: Handling costs of handling 1 ton of product coming in warehouse j (in euros per ton).

- SHC_{mj}: Shuttle cost of moving 1 ton of product from facility m to warehouse j (in euros per ton).

- TSC_{ji}: Transportation costs of moving 1 ton of product from warehouse j to customer i (in euros per ton).

- BM: Big M is a large positive number.

4.3.3 Model Formulation

In this section we describe and explain the mathematical model, which is used to solve the Warehouse Location Problem of Company X.

Mathematical Model

$$\min \sum_{t\in T}\left(\sum_{j\in J}\sum_{c\in C}F_{jc}\cdot y_{jct} + \sum_{m\in M}\sum_{s\in S}\sum_{j\in J}\sum_{i\in I} v_{msjit}\left(\mathrm{SHC}_{mj}+H_j+\mathrm{TSC}_{ji}\right)\right.$$
$$\left. + \sum_{m\in M}\sum_{s\in S}\sum_{j\in J} x_{msjt}\cdot \mathrm{SHC}_{mj}\right) \tag{1}$$

S.t.

$$\sum_{j\in J} x_{msjt} = S_{mst}, \quad \forall m\in M, s\in S, t\in T \tag{2}$$
$$\sum_{j\in J} v_{msjit} = D_{msit}, \quad \forall m\in M, i\in I, s\in S, t\in T \tag{3}$$
$$\sum_{m\in M}\sum_{s\in S} x_{msjt} \le \sum_{c\in C} SC_{jc}\cdot y_{jct}, \quad \forall j\in J, t\in T \tag{4}$$
$$\sum_{i\in I} v_{msjit} \le TR_{mst}\cdot x_{msjt}, \quad \forall j\in J, m\in M, s\in S, t\in T \tag{5}$$
$$x_{msjt} \le p_{msjt}\cdot BM, \quad \forall j\in J, m\in M, s\in S, t\in T \tag{6}$$
$$p_{msjt} \le x_{msjt}, \quad \forall j\in J, m\in M, s\in S, t\in T \tag{7}$$
$$\sum_{i\in I} v_{msjit} \le BM\cdot p_{msjt}, \quad \forall j\in J, m\in M, s\in S, t\in T \tag{8}$$
$$p_{msjt} \le \sum_{i\in I} v_{msjit}, \quad \forall m\in M, i\in I, s\in S, j\in J, t\in T \tag{9}$$
$$x_{msjt} \le \sum_{c\in C} S_{mst}\cdot y_{jct}, \quad \forall m\in M, i\in I, s\in S, j\in J, t\in T \tag{10}$$
$$v_{msjit} \le \sum_{c\in C} D_{msit}\cdot QS_{mst}\cdot y_{jct}, \quad \forall m\in M, i\in I, s\in S, j\in J, t\in T \tag{11}$$
$$\sum_{c\in C} y_{jct} \le 1, \quad \forall j\in J, t\in T \tag{12}$$
$$\sum_{c\in C} y_{mct} = 1, \quad \forall m\in M, t\in T \tag{13}$$
$$\sum_{m\in M}\sum_{s\in S}\sum_{i\in I} v_{msjit} \le \sum_{c\in C} TC_{jt}\cdot y_{jct}, \quad \forall j\in J, t\in T \tag{14}$$
$$x_{msjt} \ge x_{m,s,j,t-1} - \sum_{i\in I} v_{m,s,j,i,t-1}, \quad \forall j\in J, m\in M, j\ne m, s\in S, t\in T, t>1 \tag{15}$$
$$x_{msjt} \ge 0, \quad \forall i\in I, j\in J, t\in T \tag{16}$$
$$v_{msjit} \ge 0, \quad \forall i\in I, j\in J, t\in T \tag{17}$$
$$y_{jct} \in \{0,1\}, \quad \forall j\in J, c\in C, t\in T \tag{18}$$
$$p_{msjt} \in \{0,1\}, \quad \forall j\in J, c\in C, t\in T \tag{19}$$

The objective function (1) is the minimization of first the fixed rent costs of warehouses, followed by the shuttle, handling, and transportation costs, and lastly, we incur costs for moving stock. In constraint (2) we make sure the storage space requirement of each SKU is allocated to warehouses. Constraint (3) makes sure all demand is allocated to the customer. Constraint (4) makes sure the capacity of each warehouse is not exceeded. Constraint (5) makes sure that the storage space of an SKU at a warehouse can at most be turned over the number of times given by the turnover rate. In constraints (6), (7), (8), and (9) we make sure that the decision variable p, controls that volume can only flow through (m,s,j) whenever there is stock at (m,s,j), if there is no stock, no volume can flow through this warehouse for this particular SKU. In constraints (10) and (11) we provide variable upper bounds for decision variable x and v, respectively. Constraint (12) makes sure only 1 capacity level can be chosen for each warehouse. Constraint (13) makes sure that the Facility Y warehouse is always open. In constraint (14) we make sure that the throughput capacity per period of Facility Yis not exceeded. In constraint (15), we ensure that if the demand volume for an SKU in a given period is less than the required storage space, the remaining stock must be carried over to the next period. This means that the storage space allocated in the next period must account for the leftover stock from the previous period. Essentially, this constraint ensures that any unsold or unused inventory continues to occupy warehouse space. And lastly, constraints (16), (17), (18), and (19) define the non-negativity and binary nature of the decision variables.

4.4 The Scenarios

We provide multiple scenarios, with each the same objective, but with slightly different criteria regarding warehouse contracts, for the overview see Table 4.1. By creating multiple scenarios, we gain many useful insights into what is the best option for Facility Y in terms of warehousing. Below the scenarios and their importance are described, these are optimized and in Chapter 6 the results are analyzed and discussed.

Scenario 1: Minimize logistics costs for each time period separately

This scenario is the mathematical model described in Section 4.3, we minimize the logistics costs, where each time period is optimized separately in terms of warehouse choices. This scenario allows a lot of freedom in changing warehouses and their capacities in each period, which provide insights into the optimal warehouse choices per time period.

Scenario 2: Minimize logistics costs where a warehouse must be opened for all periods with a fixed capacity level

In this scenario we minimize the logistics costs, but unlike the previous scenario, the time periods are interdependent regarding warehouse selections and capacity levels, which must remain constant across all periods. This approach is useful when short-term contracts are not feasible, providing valuable insights into the long-term implications of fixed warehouse capacities.

The criteria for this scenario is incorporated in the mathematical model by adding the following constraint:

$$\text{len}(T) \cdot y_{jct} \geq \sum_{t' \in T} y_{jct'}, \quad \forall j \in J, t \in T, c \in C \tag{20a}$$

Constraint (20a) assures that a warehouse must be open for all periods with the same capacity level.

Scenario 3: Minimize logistics costs where a warehouse must be opened for all periods with a variable capacity level

In this scenario we minimize the logistics costs, where time periods are interdependent regarding warehouse choices, but unlike scenario 2, capacities can be adjusted each period. This approach is useful when short-term contracts are feasible, revealing the most cost-efficient warehouse configurations. Although challenging to implement, it provides insights into the flexibility of capacity management.

The criteria for this scenario are incorporated in the mathematical model by adding the following constraint:

$$\sum_{c \in C} \text{len}(T) \cdot y_{jct} \geq \sum_{c \in C} \sum_{t' \in T} y_{jct'}, \quad \forall j \in J, t \in T \tag{20b}$$

Constraint (20b) assures that a warehouse must be open for all periods but it can make different decisions regarding the capacity level.

Criteria/Scenario	Scenario 1	Scenario 2	Scenario 3
Independent Warehouse Choice	✓		
Interdependent Warehouse Choice		✓	✓
Fixed Storage Capacity		✓	
Variable Storage Capacity			✓

Table 4.1: Criteria and Scenarios Overview

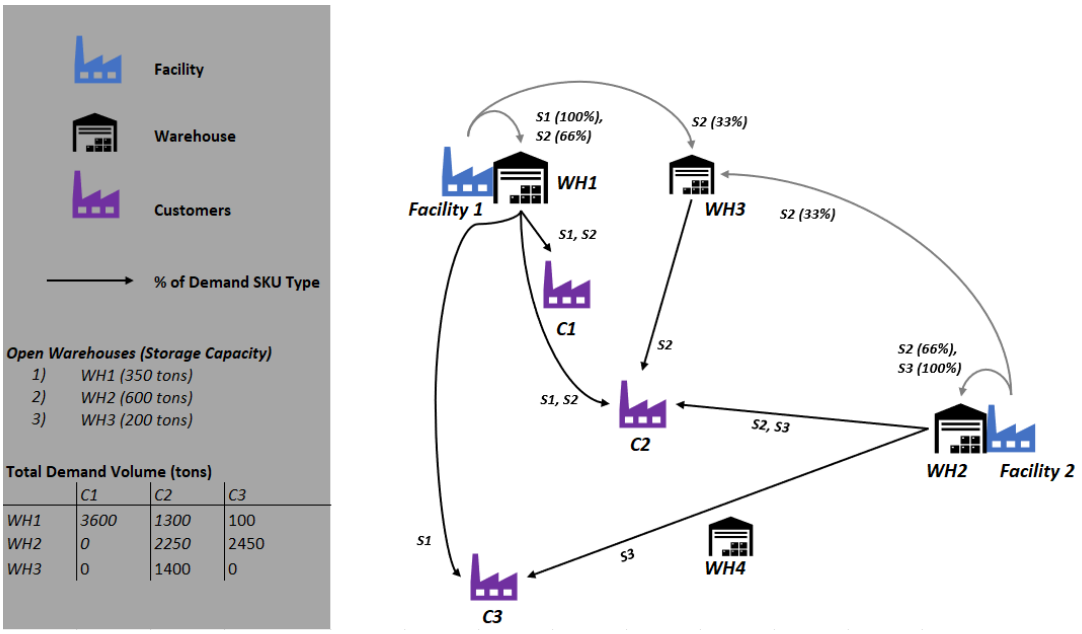
4.5 Toy Example

In this section, we provide an illustrative example to demonstrate the solution approach for the WLP, described in Section 4.3.

For this basic problem we consider a set of facilities M = [Facility 1, Facility 2], a set of warehouses W = [WH1, WH2, WH3, WH4], a set of capacity levels CL = [CL0, CL1, CL2, CL3, CL4, CL5], a set of demand points or customers C = [C1, C2, C3], a set of SKUs S = [S1, S2, S3], and a set of time periods T = [T1, T2, T3]. From the set of warehouses, WH1 and WH2 are the warehouses of Facility 1 and Facility 2, respectively. These Facility warehouses serve as the starting points where products are either shipped directly to customers or to external warehouses, from which they are eventually distributed to the customers. The company wants to find out whether the current warehouse network is optimal in terms of costs, divided into fixed storage, handling, shuttle, and transportation costs. Moreover, the company wants to investigate if short-term contracts would be beneficial and whether potential warehouse 4 would be a good fit for the warehouse network.

The model created in Section 4.3 helps the company solve this problem. The input data for the model is found in Chapter C. First, we need the customer demand data to know how much demand is required where and when. Second, we need the storage space requirements per SKU per period data to determine how much storage space is needed in each period. The turnover rate is used to allow for better comparison against the current way of working, where the turnover rate at the Facility Y warehouses is much higher compared to the external warehouses. Third, the SKU identification data provides insights into the type of SKUs. For each warehouse and capacity level combination, the storage capacity along with the associated fixed costs are needed to make the trade-off between higher fixed costs versus lower transportation costs, and vice versa. Additional costing data required include the handling costs of demand coming in and out of the warehouses, the shuttle costs from Facility warehouse to other warehouses, and the transportation costs to customers from each warehouse. Lastly, the maximum throughput capacity is necessary to ensure the demand allocated to each warehouse is within the capacity of each warehouse.

Consider the setting drawn in Figure 4.1. This figure represents how the current warehouse network looks like and how the customers are supplied. This is the setting for all periods (T1, T2, and T3). What is seen from this setting, is that both Facility warehouses consistently send 33% of the volume to warehouse 3. Warehouses 1, 2, and 3 have a storage capacity of 350 tons, 600 tons, and 200 tons, respectively. Which adds up to a total costs of €18,000 for fixed costs for maintaining this capacity for three periods. Additionally, there are €48,600 in handling costs, €8,500 in shuttle costs, and €82,250 in transportation costs. Summing these costs, the total costs for the current situation is €157,350.



Open Warehouses (Storage Capacity)
1) WH1 (350 tons)
2) WH2 (600 tons)
3) WH3 (200 tons)

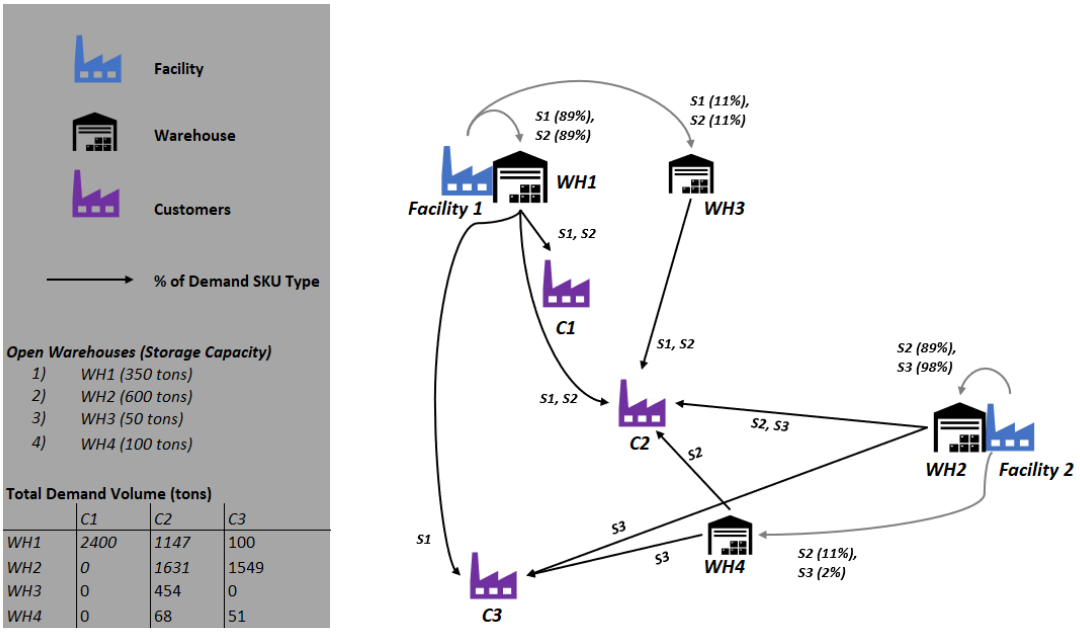
Total Demand Volume (tons)

	C1	C2	C3
WH1	3600	1300	100
WH2	0	2250	2450
WH3	0	1400	0

Figure 4.1: Toy Example: Current warehouse network structure.

To optimize the current situation, the decisions for this WLP include selecting the warehouses, determining the number of warehouses, specifying the storage capacity per warehouse per period, and allocating customers to warehouses. The output of the model are the most cost-efficient warehouse locations and capacities for each time period, identifying the potential for short-term contracts and when they are needed. Additionally, it provides the optimal customer allocation to these warehouses and outlines the costs associated with this proposed solution.

Depicted in Figure 4.2, the optimal configuration for periods T1 and T3 involves using warehouses 1, 2, 3, and 4 with a storage capacity of 350 tons, 600 tons, 50 tons, and 100 tons, respectively. The main difference with the current situation is that warehouse 4 is used and that the external storage capacity is divided over warehouses 3 and 4, rather than only warehouse 3. Depicted in Figure 4.3, the optimal configuration for period T2 also includes warehouses 1, 2, 3, and 4, but here warehouses 3 requires a storage capacity of 100 tons, rather than 50 tons. In this period, the optimal solution suggests to use a short-term contract to increase storage to 100 tons in period T2. This solution results in €15,000 in fixed (rent) costs, €47,244 in handling costs, €4,740 in shuttle costs, and €80,490 in transportation costs. Adding up to a total costs of €147,474, resulting in a cost saving between 6% and 7%. From these optimizations, the company gains insights into how to adjust capacity over time, either by increasing the rented storage space of existing warehouses or by opening new ones for a short-term. Overall, the company can learn the optimal warehouse usage, capacity levels, and customer allocations to minimize delivery costs effectively.



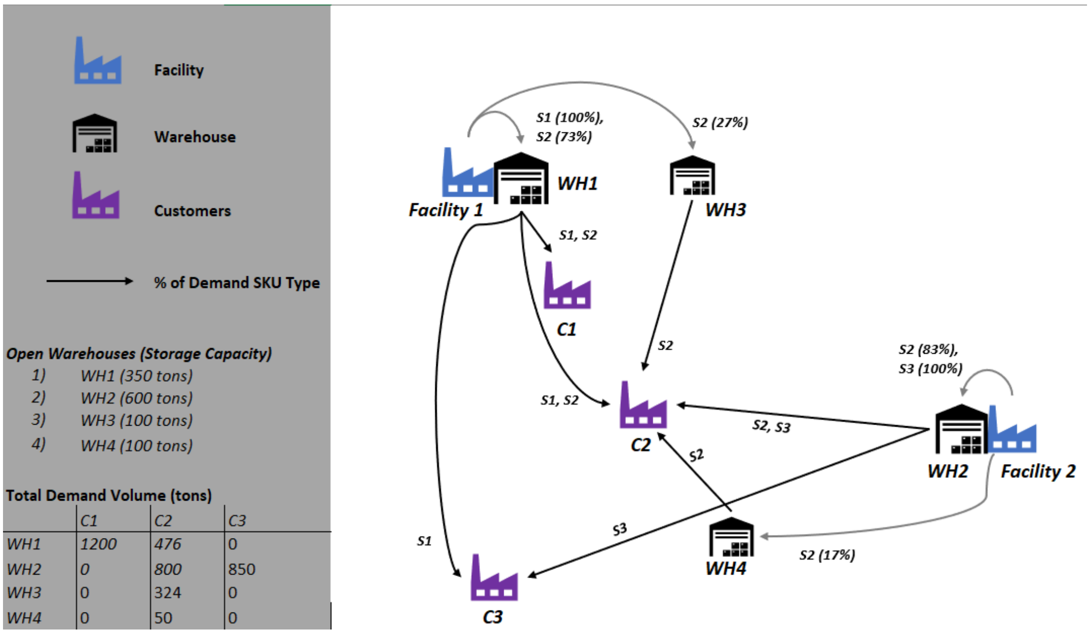
Open Warehouses (Storage Capacity)

1) *WH1 (350 tons)*
2) *WH2 (600 tons)*
3) *WH3 (50 tons)*
4) *WH4 (100 tons)*

Total Demand Volume (tons)

	C1	C2	C3
WH1	2400	1147	100
WH2	0	1631	1549
WH3	0	454	0
WH4	0	68	51

Figure 4.2: Toy Example: The optimized situation for T1 and T3.



Total Demand Volume (tons)

	C1	C2	C3
WH1	1200	476	0
WH2	0	800	850
WH3	0	324	0
WH4	0	50	0

Figure 4.3: Toy Example: The optimized situation for T2.

4.6 Conclusion

In this chapter, we answered the research question ”What are the most suited algorithms or methodologies to solve Company X’s Warehouse Location Problem?”. Based on literature, we presented a detailed description of the solution design for solving the WLP variant faced by Company X. Scenarios are created to simulate different criteria that could be faced by Company X, which are incorporated in the experiments in Chapter 5. Last, this chapter presented a toy example of the inputs, outputs, and model functionality. In the next chapter, Chapter 5, the experimental setup is discussed in which the experiments and the experimental settings are explained.

Chapter 5

Experimental Setup

This chapter presents the experimental setup of this research, starting with Section 5.1, in which the experiments are explained including the solving approach. In Section 5.2 and Section 5.3, the experimental settings and computer specifications used for experimentation are described. Furthermore, in Section 5.4 is explained how the model input data is acquired. Last, the conclusion of this chapter is given in Section 5.5.

5.1 The Experiments

To assess the proposed solution, we define a set of experiments that represent different operational conditions and challenges faced by Company X. The scenarios, described in Section 4.4, serve as the basis for our experimentation and performance evaluation. In Table 5.1, the experiments performed to find useful insights for solving the problem at Facility Y are listed.

Exp.	Scenario	Criteria	Storage Requirement	Utilization Rate
1-3	1	Independent Warehouse Choice	Average Average Peak	90% 80% 90%
4-6	2	Interdependent Warehouse Choice Fixed Storage Capacity	Average Average Peak	90% 80% 90%
7-9	3	Interdependent Warehouse Choice Variable Storage Capacity	Average Average Peak	90% 80% 90%

Table 5.1: Experimental Setup

We include experiments using both average and peak storage space requirements to determine the storage capacity requirements under average and peak conditions. For average storage space requirements, we assess capacity requirements at utilization rates of 80% (a common practice based on Derhami et al. (2016)) and 90% (as requested by the company). This means that these percentages of the storage capacity may be utilized. For peak storage space requirements, we experiment with 90% utilization to account for fluctuations during peak conditions. The model is solved using two solvers: CBC (Coin-or Branch and Cut) and Gurobi. CBC is a free solver with limited advanced features, while Gurobi is a commercial solver with advanced capabilities like presolve techniques, cutting planes, branching strategies, heuristics, and parameter tuning. Gurobi is expected to solve the problem faster than CBC, but it requires an investment from Company X. In Chapter 6, we investigated which solver is recommended for Company X based on performance requirements. A total of 18 runs are conducted, with 9 experiments performed twice, once for each solver.

5.2 Experimental Settings

The models used in this study were developed in Python, utilizing the MIP library for optimization. The parameters used for the experiments are summarized in Table 5.2. One facility is used in the experiments, namely Facility Y. The existing warehouses are the Facility Y warehouse, external warehouse WH1, and external warehouse WH2. Three potential warehouses are used and are identified in Section 5.4. Last, the time periods represent the months of the year.

Parameter	**Value**
Customers	200
SKUs	158
Facilities	1
Existing Warehouses	3
Potential Warehouses	3
Time Periods	12
Capacity Levels	6

Table 5.2: Experimental Settings

5.3 Computer Specifications

The computer on which these models are optimized has the specifications mentioned in Table 5.3.

Type:	MacBook Pro (Retina, 15-inch, Mid 2015)
Processor:	2.2 GHz Quad-Core Intel Core i7
Memory:	16 GB 1600 MHz DDR3
Graphics:	Intel Iris Pro 1536 MB

Table 5.3: Specification of the computer on which the experiments were executed.

5.4 Input Data Acquisition

We analyzed and explained in Chapters 2 and 4 the data required for solving the WLP. In this chapter, we explain the acquisition of this data.

Determining potential warehouses

To find applicable locations for warehouses, we employed the center of gravity approach (K-means), using the demand volume and customer coordinates as input. We selected this approach for its proven effectiveness in finding potential warehouse locations. Besides, it provides a straightforward and efficient algorithm for clustering data based on the geographic location of customer and their demand, allowing for fast and simple scans. The code used for the K-means approach is found in Appendix A. We executed the K-means approach to find 1, 2, and 3 centers based on the demand volume. See figure 5.1 for the result with 3 centers, for the results with 1 and 2 centers, refer to Chapter A. Based on the analysis and expert insights, we identified three interesting warehouse locations to incorporate into the model. External warehouse WH3 at location A is chosen for its strategic proximity to Facility Y and logistic advantages. The second potential external warehouse WH4 at location B is selected due to its favorable position relative to Facility Y. And lastly, the third potential external warehouse WH5 at location C is preferred over location D (results from the k-means approach) to avoid traffic congestion.

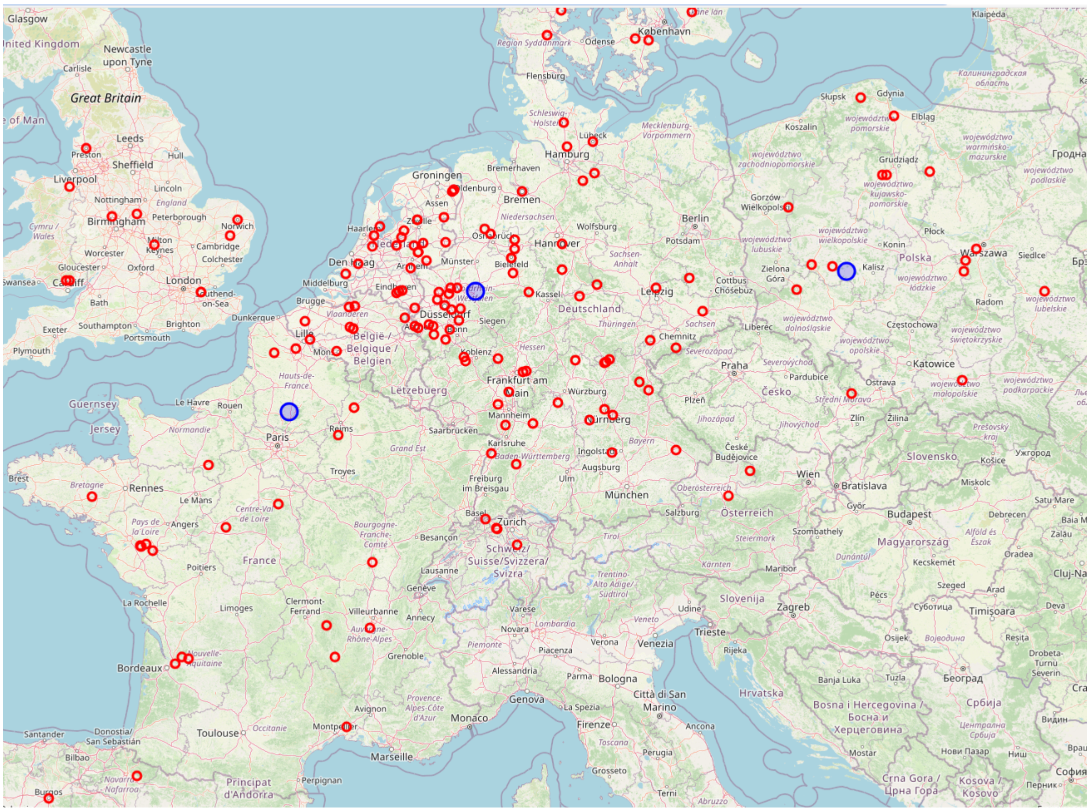


Figure 5.1: The output of the K-means approach with k = 3, where the blue circle represent the center and the red circle the customer locations.

Cost Parameters

In Section 2.2.1 is explained how the fixed and handling costs are calculated for external warehouses WH1 and WH2. For external warehouse WH1 the handling is done by Facility Y and for external warehouse WH2 the handling is outsourced. For the remaining external warehouses, the handling must also be outsourced, therefore the same handling costs are used for the external warehouses WH3, WH4, and WH5. The fixed costs are dependent on the amount of storage capacity that is rented, the higher the storage capacity the higher the fixed costs. Based on the data base of all warehouses which are rented by Company X, we found that the costs of storing 1 ton of product is similar to the fixed costs per ton of external warehouse WH2. Therefore, we applied the same fixed costs per ton for the external warehouses WH3, WH4, and WH5 as we did for external warehouse WH2.

We modeled the shuttle and transportation costs, to estimate the costs for the three potential warehouses without existing transportation cost data. To estimate these costs accurately, we divided each country that Facility Y supplies to into regions. For example, we divided the Netherlands into NL North, NL South, NL West, and NL East. Each warehouse and customer at Company X is allocated to a region based on their geographic location.

Based on the transportation data base of Company X, we extracted the shipments that have occurred between regions, with their associated costs and travelled distance. With this information, we created regression models for transportation costs between all regions. From this regression we extracted the base cost rate and a variable cost rate dependent on the distance in kilometers. Take for instance a customer in region NL East and a warehouse in region NL South, with a distance of 100 kilometers. The regression model between region NL East and NL South is a base rate of €180 plus a variable rate of €1.20 per kilometer (€180 + €1.20 * KMs). Based on this regression model, we calculate the transportation costs as follows: €180 + €1.20 * 100 KMs = €300. To remain consistent, we not only calculated the shuttle and transportation costs for the three potential warehouses but also for the existing warehouses and customers involved in the experiments.

Storage Space Requirements

The storage space requirements per SKU per time period is determined by analyzing the historical data of inventory levels per SKU per time period. From Section 2.2.2, we observed that peak inventory levels occur after weekends or holidays, which allowed us to pinpoint the peak periods for each month. We used the identified peak inventory levels to estimate the storage space requirements per SKU per time period. We consulted with the warehouse manager of Facility Y, capacity planners, and logistics employees who validated our findings and ensured that the data accurately reflects peak conditions.

Remaining Data

The customer demand, SKU identification, turnover rate at the facility, and the maximum throughput capacity data are extracted from the data base of Company X. The maximum throughput capacity of the facility per time period, used for optimization, equals the total demand volume handled by Facility Y in that period. The storage capacity per capacity level are determined in consultation with Company X.

5.5 Conclusion

In this chapter, we explained the experimental setup to solve the WLP of Company X. We started by outlining the experiments we will conduct, detailing the experimental settings, and specifying the computer specifications. Furthermore, we explained the process of acquiring the input data required for the model. This chapter forms the basis for the subsequent analysis and evaluation of results, which we discuss in the following chapter, Chapter 6.

Chapter 6

Results and Discussions

This chapter presents the results of the experiments conducted to assess the proposed solution for addressing the Warehouse Location Problem at Company X. The results are presented and explained by answering the following research question:

> *"How does the proposed solution perform compared to the current situation?"*

In Section 6.1, we establish the benchmark for our proposed solution. The results of the experiments with average stock level and peak stock level are presented in Sections 6.3 and 6.3, respectively. Moreover, we explore a situation in which we combine scenarios 1 and 3 in Section 6.4. We explore the effect on the results when throughput efficiency would increase in section 6.5. Last, we conclude the findings in Section 6.6.

6.1 Baseline Performance

To benchmark our proposed solution, we evaluated the current situation in Chapter 2. The discrepancy between the base case and reality is 5%, which is acceptable and attributed solely to estimated shuttle and transportation costs because these costs are estimated using regression models and not exact. This assessment aims to compare the relative difference between our solution and Company X's current situation. The following sections compare the calculated base case with the results from the experiments.

6.2 Optimizing Scenarios with Average Stock

In this section, we delve into the outcomes of experiments where the input is based on the average stock level and we explore the differences between having a maximum utilization of 80% and 90%. For the results, we are interested in the warehouse location the model recommends to open to minimize costs, when the model recommends opening these warehouses, how much savings are made with that setting, the warehouse capacity in each month, the utilization of the warehouses, the customer allocation towards the warehouses and with that the SKU allocation.

We start of by analyzing the differences in the costs. In Figure 6.1, we see the costs for each scenario divided into each component (see Table 4.1 for the criteria of each sce-

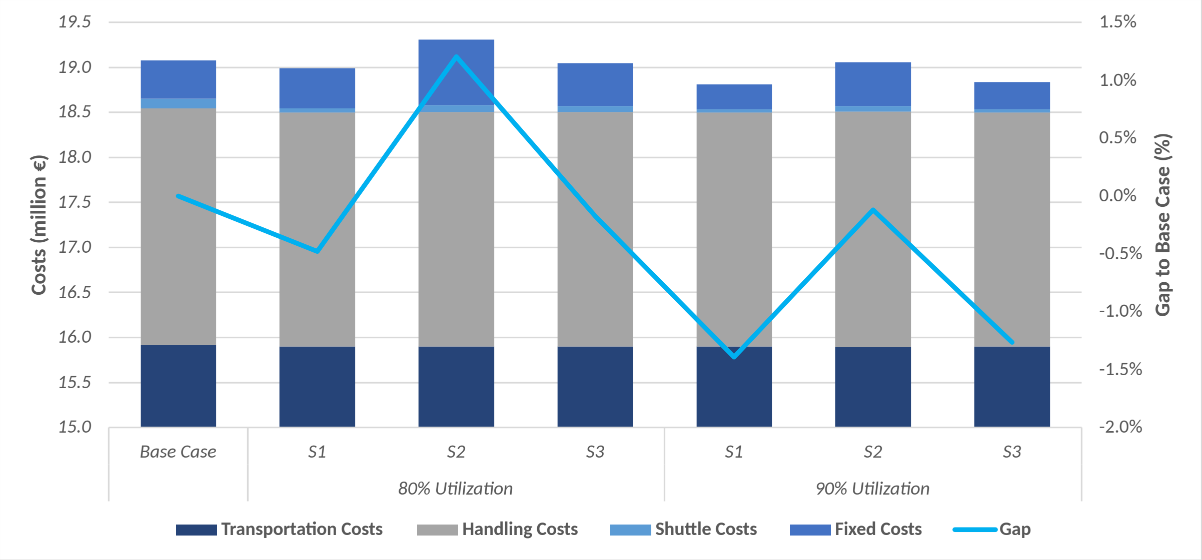


Figure 6.1: Cost savings per scenario with a maximum utilization rate of 80% and 90%, and with average stock level.

nario). From the figure, we see that relatively minimal cost savings are made for the scenarios, indicating that based on the volume of Facility Y the current performance is quite efficient. The savings primarily come from fixed costs and shuttle costs, while transportation and handling costs remain nearly identical to the base case, highlighting the significant impact of transportation costs, which constitute more than 80% of the total costs. Scenario 1 yields the most savings; however, this scenario is challenging to implement due to the need for highly flexible warehouse usage, including varying storage capacities and potentially changing warehouse locations. Moreover, we see that scenario 2 with an utilization rate of 80% requires investments in storage space, adding to the costs. Last, we see that the cost savings are higher for the scenarios when the utilization rate is 90%. This is logical, since more storage space may be used and thus less external storage space is required, resulting in lower fixed costs.

To further understand these results, we look into the capacity and utilization of each warehouse. As explained in Section 4.4, in scenarios 1 and 3 the model has the freedom to pick whatever capacity level for each external warehouse and for scenario 2 this freedom is removed, so only 1 capacity level must be chosen for all periods. From the output of the model, we found that in scenarios 1 and 2 the external warehouses WH1 and WH3 are open and in scenario 3 the external warehouse WH1 is open. For all scenarios the maximum capacity requirement is 7,500 tons, if a maximum utilization rate allowed is 90%. From Figure 6.2, we see the capacity evolution of scenario 1. From this figure we see how the capacity level of external warehouse WH1 fluctuates over the full year and we see that external warehouse WH3 is only required in 2 months. The average utilization of external warehouse WH1 is 68%, with a minimum utilization of 17% and maximum utilization of 90%. The average utilization of external warehouse WH3 is 5%, with a minimum utilization of 3% and a maximum utilization of 7%. This suggests even lower capacity is required than the lowest capacity level available for external warehouse WH3.

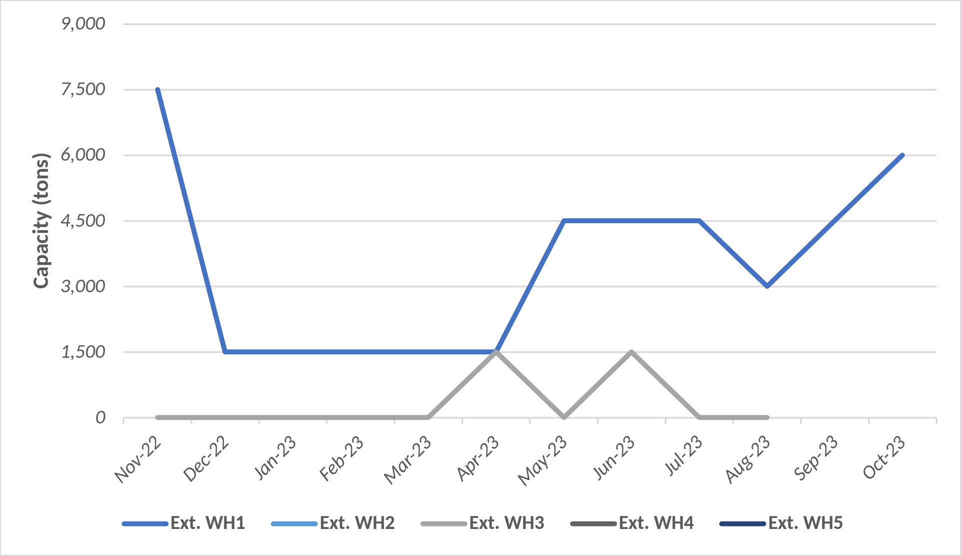


Figure 6.2: Capacity evolution over the time periods for the 2 open warehouses in scenario 1, with a maximum utilization rate of 90% and the average stock level.

For scenario 2 the fixed capacity level for external warehouses WH1 and WH3 is 4,500 and 3,000 tons, respectively. This results in an average utilization of 53% and 26%, for external warehouses WH1 and WH3, respectively. External warehouse WH1 is utilized in each period, whereas external warehouse WH3 is only being utilized for 3 periods, in which the 3,000 tons capacity is required only once in the period November 2022. From Figure 6.3, we see the capacity evolution of scenario 3. From this figure we see that only external warehouse WH1 is open and all other external warehouse are closed (including external warehouse WH3). In these scenario the average utilization of external warehouse WH1 is 63% with a minimum utilization rate of 17% and maximum of 90%. This also suggests lower capacity is required than the lowest capacity level possible for some periods.

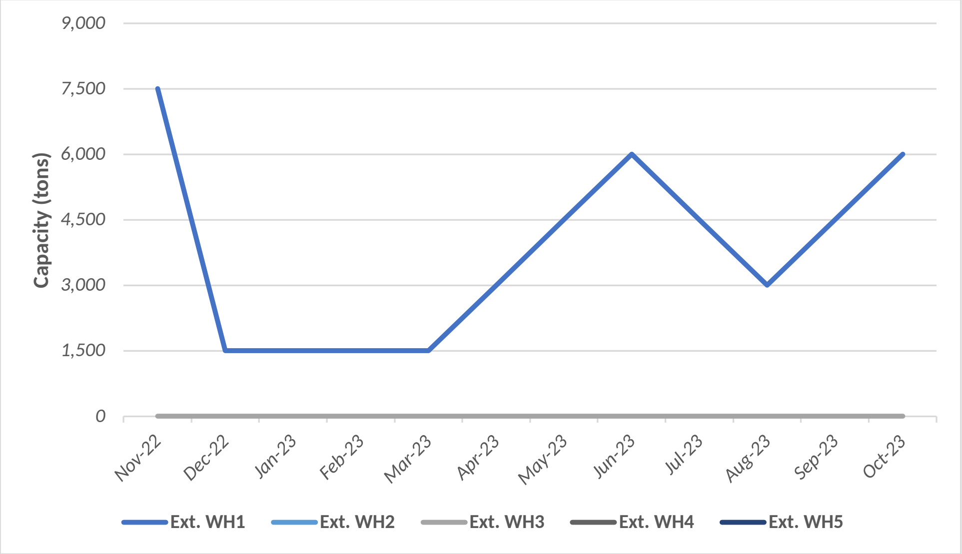


Figure 6.3: Capacity evolution over the time periods for the open warehouse in scenario 3, with a maximum utilization rate of 90% and the average stock level.

For the experiments in which 80% of the warehouses may be utilized, more storage capacity is required. For all scenarios the maximum storage requirement is 10,500 tons. In Figure 6.4, we see that in scenario 1 external warehouse WH1 is open in all periods and external warehouse WH3 is open in 3 periods. Moreover, the utilization rate at these external warehouses is higher in scenario 1. For external warehouses WH1 and WH3 the average utilization rates are 75% and 35%, respectively.

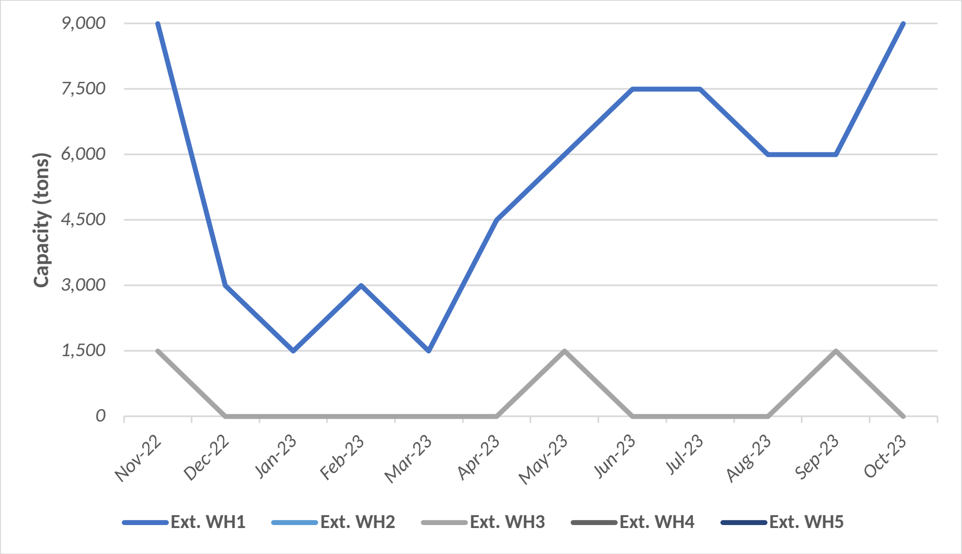


Figure 6.4: Capacity evolution over the time periods for the open warehouses in scenario 1, with a maximum utilization rate of 80%.

For scenario 2, with a maximum utilization rate of 80%, we see a difference in the warehouse capacity decisions. Scenario 2 requires a capacity of 7,500 tons for external warehouse WH1 for all periods and 3,000 tons for external warehouse WH3 in all periods, of which WH3 is utilized in only two periods. For external warehouses WH1 and WH3 the average utilization rates are of 53% and 8%, respectively.

Last, in Figure 6.5, we have the capacity evolution of scenario 3. In this scenario external warehouses WH1 and WH3 are open. In these scenarios the average utilization of external warehouse WH1 is 76% with a minimum utilization rate of 66% and maximum of 80%. External warehouse WH3, on the other hand, has an average utilization of only 14%, as it is not being utilized in 7 periods.

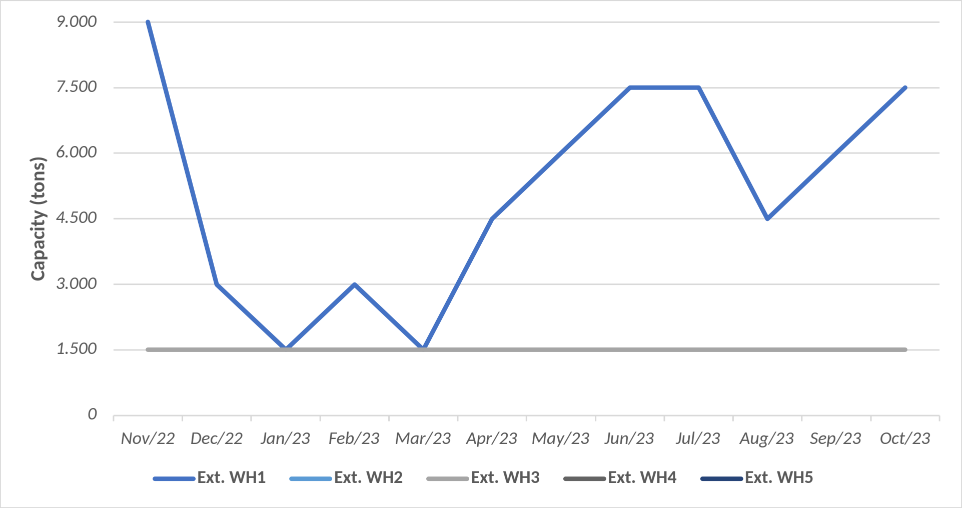


Figure 6.5: Capacity evolution over the time periods for the open warehouses in scenario 3, with a maximum utilization rate of 80%.

Furthermore, we are interested in the customer allocation towards external warehouses. In general, for the external warehouse WH1, there are no typical customers that have to be allocated here, since the transportation costs from the Facility Y warehouse and external warehouse WH1 are identical for each customer. However, for external warehouses like WH3, the transportation costs vary, leading to differences in the costs associated with supplying customers from these warehouses. From Figure 6.6, we see the number of distinct customers that are supplied from external warehouses, excluding external warehouse WH1. For the base case, there are 27 customers that were supplied from external warehouse WH2. Comparing the number of customers supplied from external warehouses, excluding external warehouse WH1, we see no extreme difference between the base case and scenarios 1, 2, and 3. We do see a difference in the specific customers that are supplied from these external warehouses, since this is very location dependent. Also notice the difference for each scenario between a maximum utilization rate of 80% and 90%.

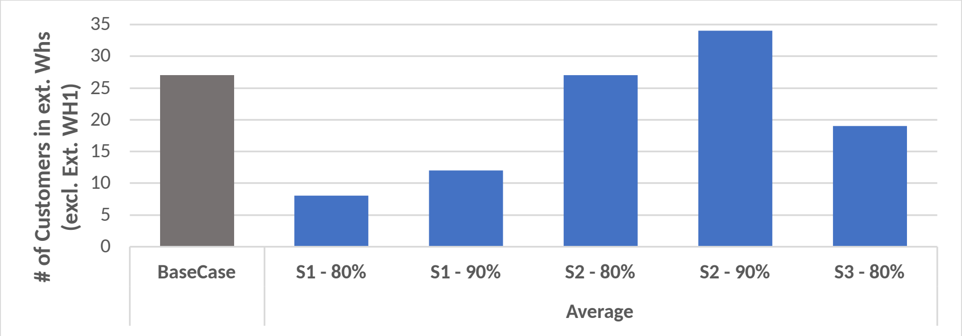


Figure 6.6: The number of customers in external warehouses, excluding external warehouse WH1, for each experiment with average stock level.

To gain the most useful insights into what type of SKUs are send to external warehouses, we look into scenarios 2 and 3, as these provide the most realistic picture for this matter. In Figure 6.7, we see the turnover rates per month per warehouse per SKU class of scenario 2. Based on this figure, what stands out is that the turnover rate at the Facility Y warehouse seems to be quite stable. Moreover, we see that the turnover rate at external warehouse WH1 is high from December 2022 until March 2023, indicates that fast moving SKUs are allocated to external warehouse WH1. Because the stock level is rather low in these months (all could fit in the Facility Y warehouse) and the model reaches its throughput capacity, it is forced to supply a certain amount via external warehouses. The model does this in the most cost efficient way, which is with SKUs that require a low amount of stock (because more stock results in higher fixed costs), but with a reasonable demand volume, or in other words SKUs with a high turnover rate.

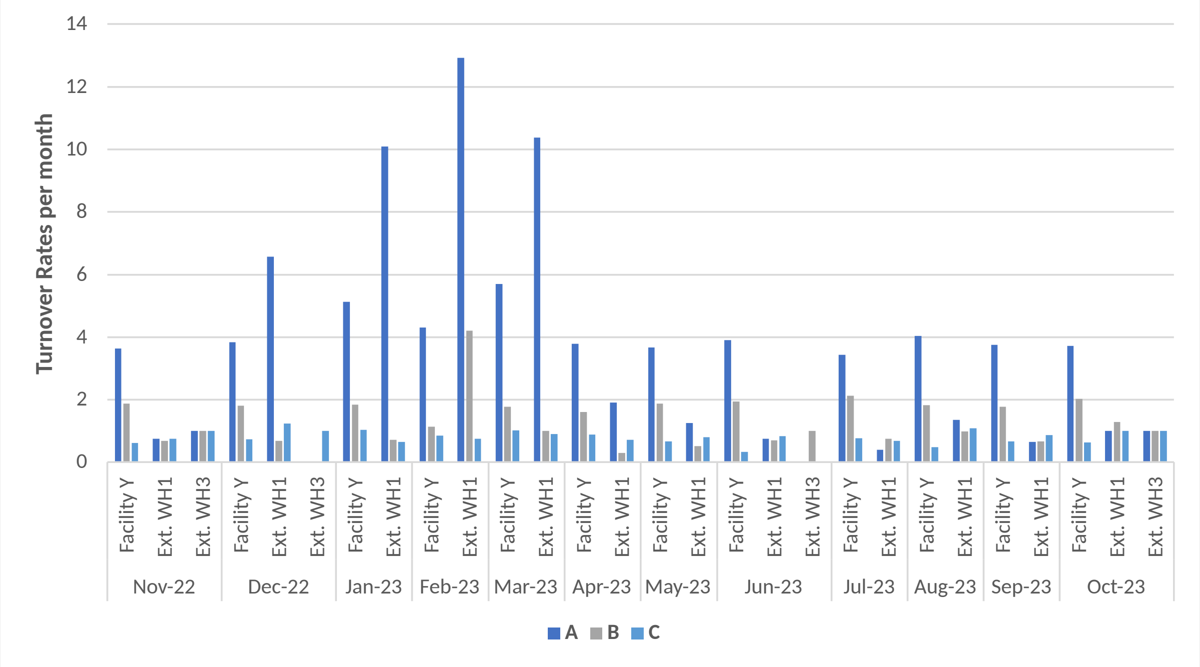


Figure 6.7: The turnover rates per month (period) per warehouse per SKU class for scenario 2 with a utilization rate of 90% and average stock level.

If we compare the turnover rates of scenario 2, with the turnover rates of scenario 3 from Figure F.1, we see that these are nearly identical. The same goes for all other scenarios using the average stock level. For each we find that the turnover rates are quite stable for the Facility Y warehouse and that mostly fast moving SKUs are allocated to external warehouse WH1 from December 2022 until March 2023.

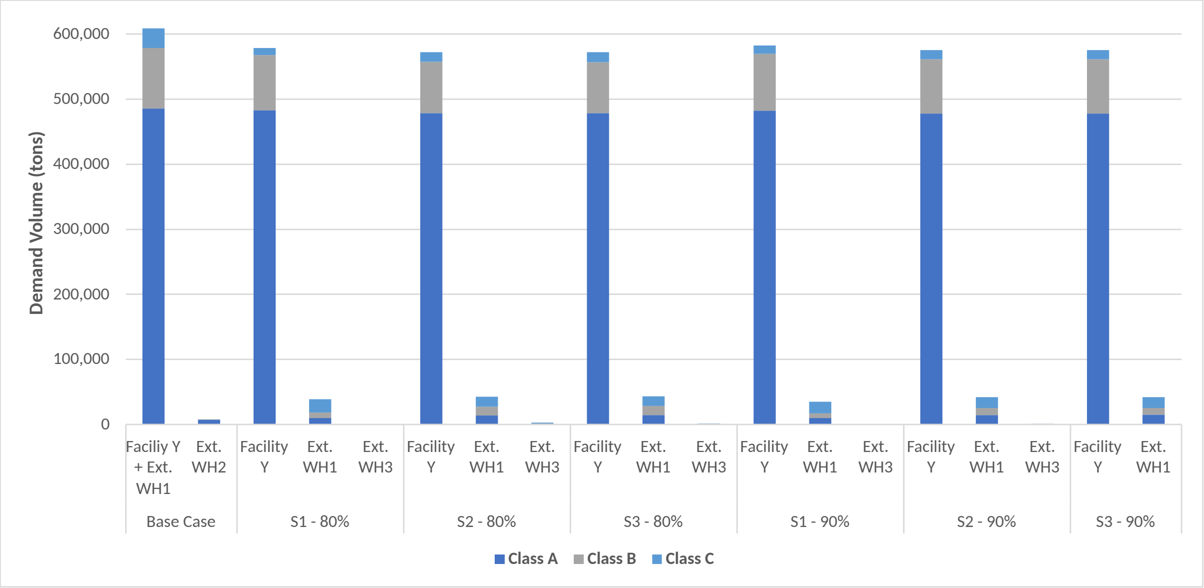


Figure 6.8: The demand volume over the year per SKU class per warehouse per experiment.

In Figure 6.8, we see the total demand per SKU class per warehouse for each experiment. What stands out is that a very low amount of volume goes via external warehouse WH3. Moreover, we see that when the utilization rate increases to 90%, the total demand volume through external warehouses slightly decreases, but the demand volume of A-class SKUs increases. The reason for this is that with a 90% utilization rate, more stock is kept at the Facility Y warehouse. But for the solution to still satisfy the throughput capacity constraint, the model allocates SKUs with a low stock level and relatively high demand volume (A-class SKUs), to minimize costs.

6.3 Optimizing Scenarios with Peak Stock

In this section, we delve into the outcomes of experiments where the input is based on the peak stock level and a maximum utilization rate of 90%. We are mainly interested in the warehouse choices to capture these peak periods.

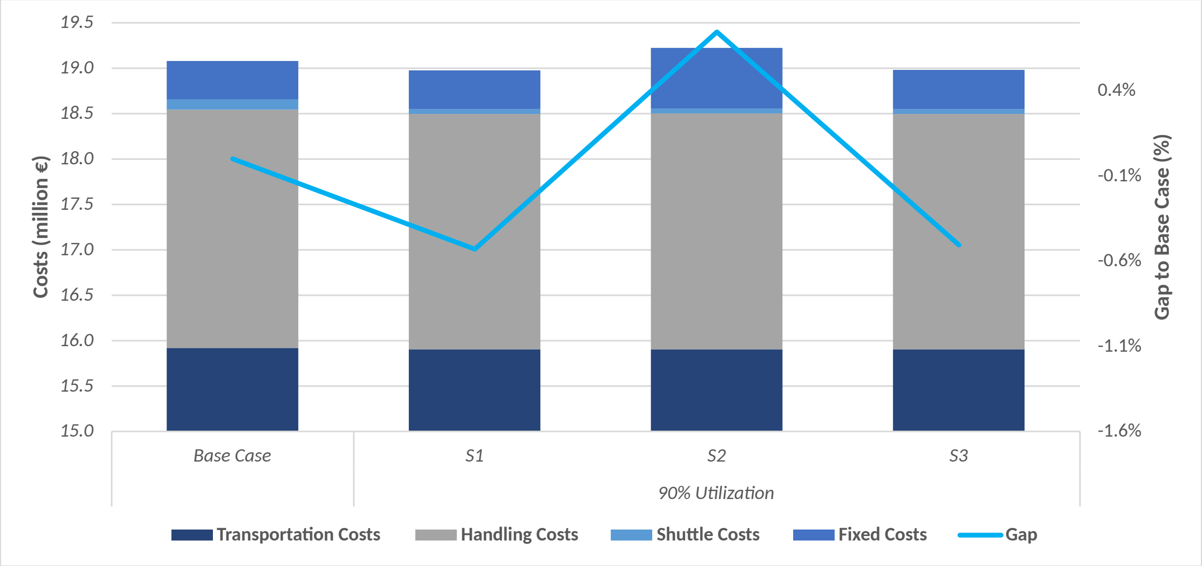


Figure 6.9: Cost savings per scenario with a maximum utilization rate of 90% to deal with peak stock scenarios.

We start of by analyzing the differences in the costs. In Figure 6.9, we see the costs for each scenario divided into each component. From the figure, we that the costs savings are rather minimal, which suggests that based on the volumes of only Facility Y the performance is quite well. The savings are coming from the fixed costs, handling costs, and the shuttle costs. The handling and shuttle costs are lower because mainly external warehouse WH1 is being used, which is the cheapest option for both the handling and shuttle costs. The savings in the fixed costs are there because for only the scenarios for which the capacity levels may be altered in each period. The most is saved according to scenario 1 and 3. With these scenarios the costs are reduced with at most 0.5%. Realizing these scenarios might be difficult due to the fact the capacity levels need to be altered many times.

From the output of the model, we found that in scenario 1 and 2 the external warehouses WH1 and WH3 are open and in scenario 3 the external warehouse WH1 is open. Since in these scenarios 90% of the warehouses may be utilized during peak conditions, this results in a storage capacity requirement of in total 9,000 tons, as seen from the figures. Moreover, we see from Figure 6.10 that external warehouse WH3 is open, but only for 1 period. The model chooses to increase capacity of external warehouse WH1 rather than increasing the capacity of external warehouse WH3. The average utilization of external warehouses WH1 and WH3 are 80% and 2%, respectively.

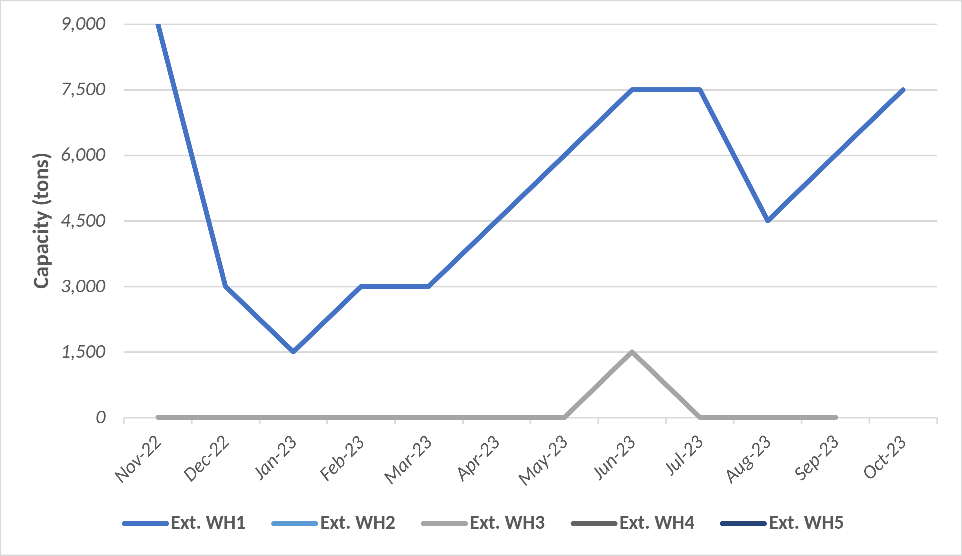


Figure 6.10: Capacity evolution over the time periods for the open warehouses in scenario 1, with a maximum utilization rate of 90% and peak stock level.

For scenario 2, with a maximum utilization rate of 90%, there is a difference in the warehouse capacity decisions. In scenario 2, external warehouse WH1 is chosen for all periods, with a capacity of 7,500 tons, and external warehouse WH3 is chosen, with a capacity of 1,500 tons which is only utilized in 2 periods. Last, in Figure 6.11, the capacity evolution of scenario 3. In these scenarios only external warehouse WH1 is open with an average utilization of 79% with a minimum utilization rate of 63% and maximum of 86%.

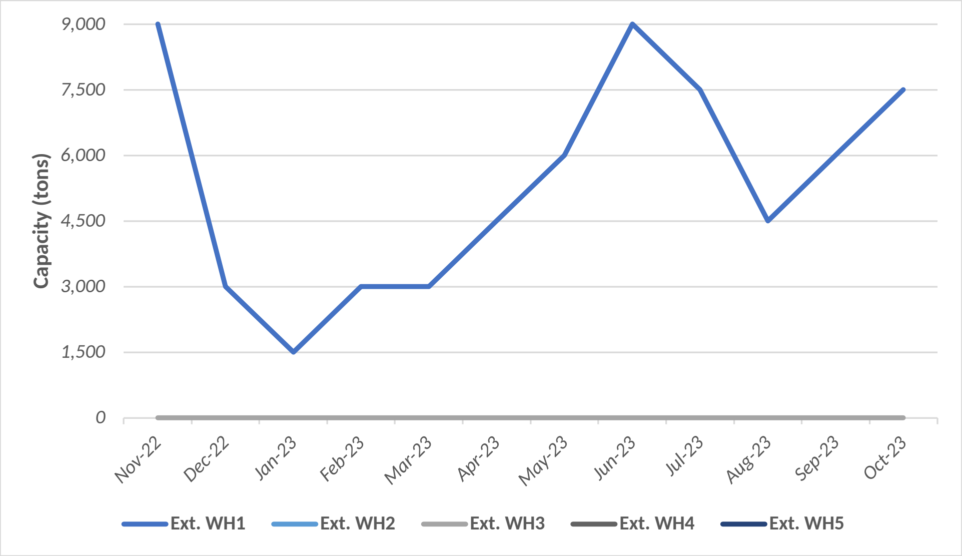


Figure 6.11: Capacity evolution over the time periods for the open warehouses in scenario 3, with a maximum utilization rate of 90% and peak stock level.

In Figure 6.12, we see the turnover rates per month per warehouse per SKU class for scenario 2 with an allowed utilization rate of 90% and peak stock level. Comparing this figure with Figure 6.7, we see that the turnover rate at the Facility Y warehouse remains the same, but the turnover rate at the external warehouses are much lower. This is because the stock is higher and the demand volume remains the same, resulting in a lower turnover rate. Also among the scenarios with peak stock level, see Figure F.2, we do not see major differences in the turnover rates at the warehouses. For each we find that the turnover rates are quite stable for the Facility Y warehouse and that mostly fast moving SKUs are allocated to external warehouse WH1 from December 2022 until March 2023.

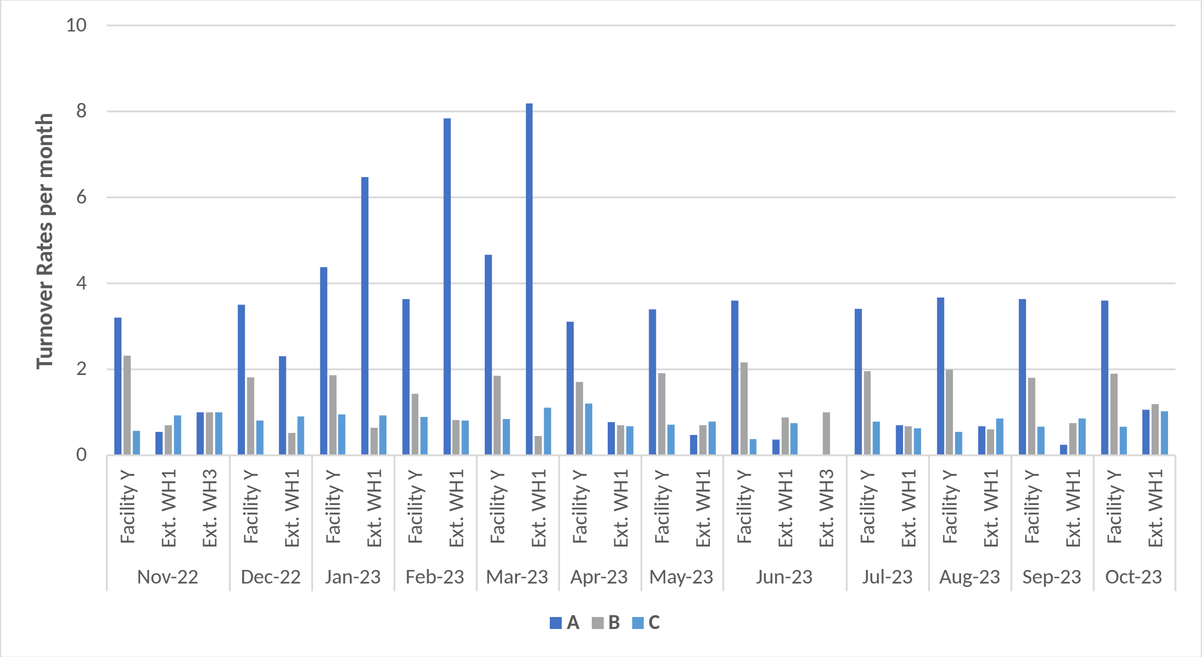


Figure 6.12: The turnover rates per month (period) per warehouse per SKU class for scenario 2 with a utilization rate of 90% and peak stock level.

6.4 Combined Optimization Scenarios 1 and 2

In Sections 6.2 and 6.3, we found the solutions for all experiments and analyzed the results. From these analyses, we extract that external warehouse WH1 is open in all periods for each experiment, which suggests this warehouse is the most cost efficient based on the volume of Facility Y. From the results of the experiments with scenario 3, we found that to minimize the costs it is best to increase the capacity of external warehouse WH1. However, this may not be a suitable option in reality, because there may not be the possibility of increasing warehouse storage space in certain periods. Therefore, in this section, we run experiments to find the optimal warehouse choice if this were to be the case. In this experiment we give external warehouse WH1 the constraint set in scenario 2, where the model can pick only 1 capacity level. All other warehouses have the same criteria as in scenario 1.

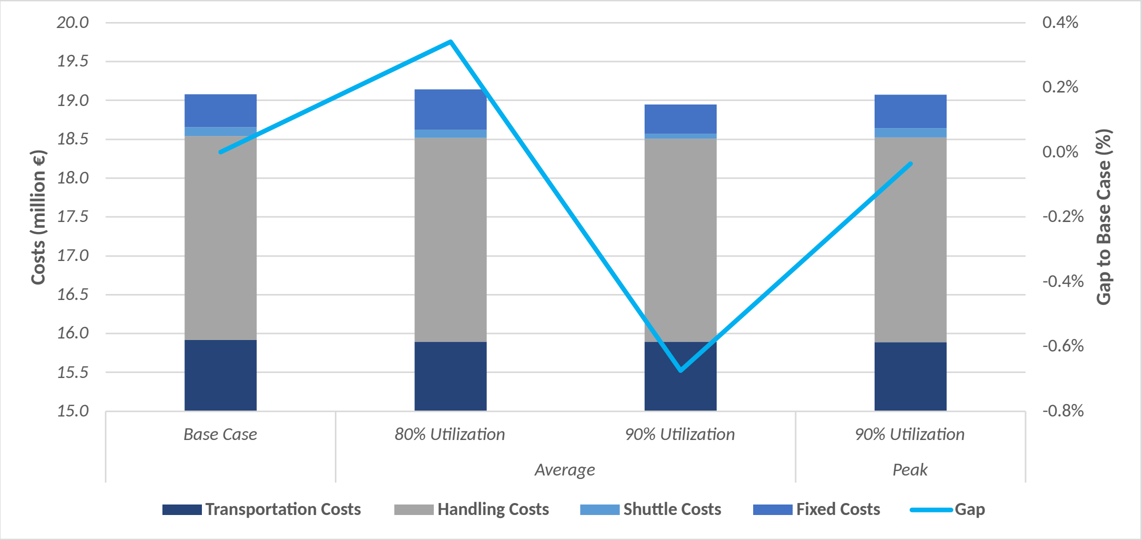


Figure 6.13: Cost savings of experiments in which we combine scenario 1 and 2.

From Figure 6.13, we see the cost savings per experiment compared to the base case. Based on the figure, the total costs can be decreased with at most 0.8%, if the capacity of external warehouse WH1 cannot be increased. The most savings are found in the fixed costs by using short-term contracts and in the shuttle costs because external warehouse WH1 is much closer. If Company X prefers to realize an utilization rate of 80% during an average period or an utilization rate of 90% during a peak period then a slight investment in the fixed costs is necessary. What stands out is that more capacity is required for the experiment with average storage requirement and 80% utilization rate compared to the experiment with peak storage requirement and 90% utilization rate.

In Figure 6.14, we show the capacity requirement during the year for the experiments with average storage requirements. For the external warehouse WH1, the capacity is 6,000 tons with an 80% maximum utilization rate and 4,500 tons with a 90% maximum utilization rate. For the external warehouse WH3, short-term contracts are required. With a 90% utilization rate, external warehouse WH3 needs a capacity of 3,000 tons in November 2022 and 1,500 tons in October 2023. With an 80% utilization rate, external warehouse WH3 requires short-term contracts for 4,500 tons in November 2022, 1,500 tons in June and July 2023, and 3,000 tons in October 2023.

Figure 6.14: Capacity evolution over the time periods for the 2 open warehouses, with the average stock level.

In Figure 6.15, shows the capacity evolution with peak storage requirement and a 90% utilization rate. From this figure, we see that again a capacity of 4,500 tons is required for external warehouse WH1 for the whole year. When utilizing 90% of the storage capacity, we require short-term contracts with external warehouse WH3 in the months November, May, June, July, September, and October.

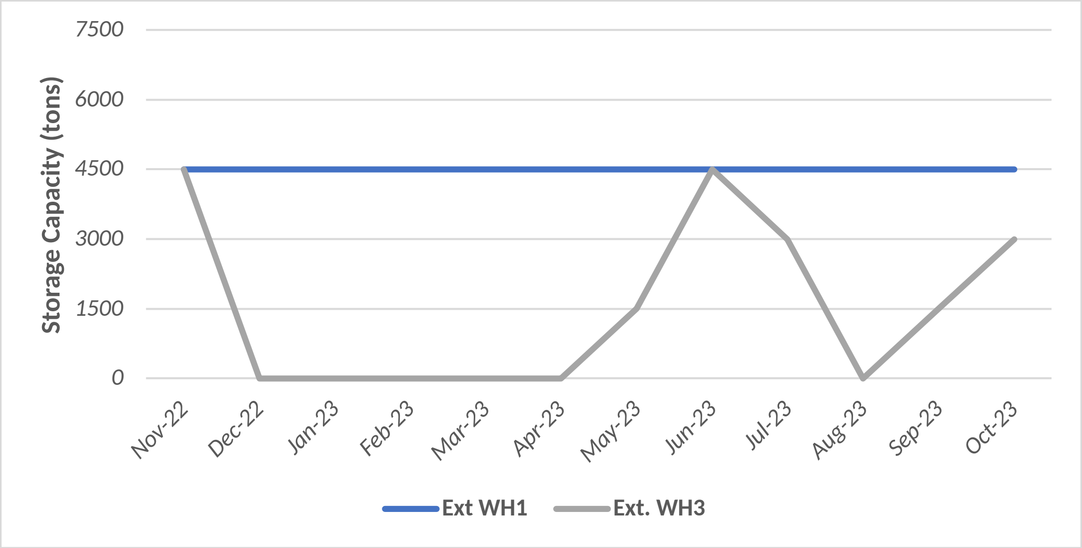


Figure 6.15: Capacity evolution over the time periods for the 2 open warehouses, with the peak stock level.

6.5 Optimizing while Increasing Facility Y Throughput Capacity

From Sections 6.2 and 6.3, we learned that the throughput capacity has a big influence on which SKUs to allocate to external warehouses. To show how the model responds to this constraint and how the company could decrease costs even more, some experiments are set out in which we increase the throughput capacity of the Facility Y warehouse with scenario 3. This means the company has found ways to increase operational efficiency or increase operational capacity, to be able to handle more volume in a month.

In figure 6.16, we see the cost savings are made when increasing the throughput capacity of the Facility Y warehouse with 2% and 5%. What we see is that between the experiments, the fixed, handling, and transportation costs remain the same, however minor savings are made in the shuttle costs, since less demand volume has to go through external warehouses. No savings are made in handling costs between the experiments, because only external warehouse WH1 is open, which has the same handling costs as Facility Y.

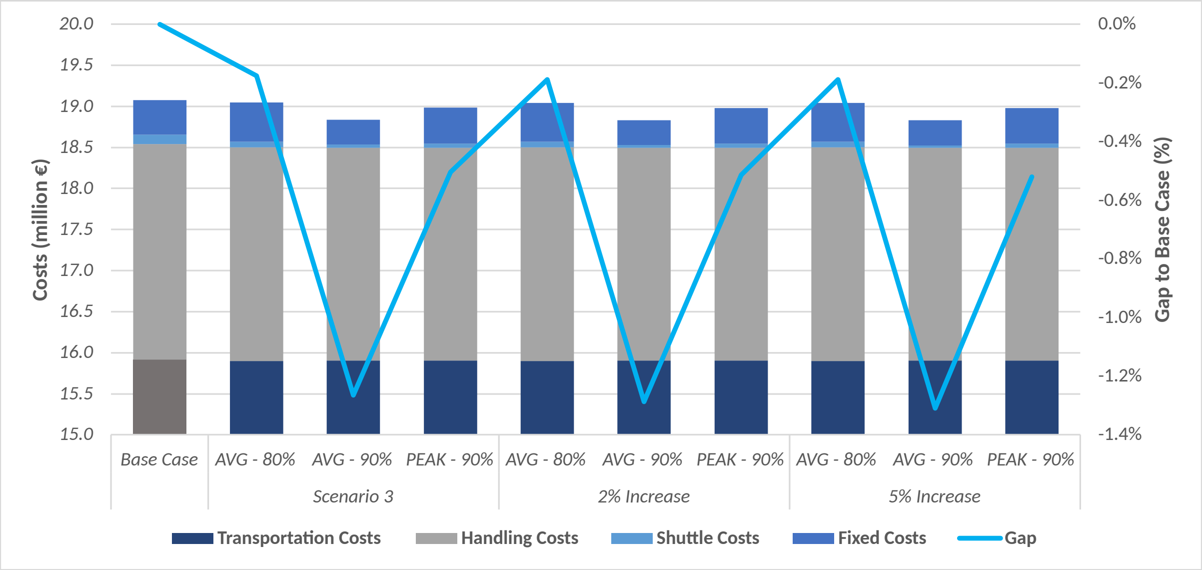


Figure 6.16: Cost savings of scenario 3 experiments, when increasing the throughput capacity to 2% and 5%.

From figure 6.17, we see the turnover rates per warehouse for scenario 3 with an utilization rate of 90%, average storage requirement, and an increased throughput capacity with 5%. From this figure we see that the turnover rate at external warehouse WH1 becomes much lower, compared to the turnover rates from Figure F.1. When the throughput capacity is increased at Facility Y, the model prefers to send SKUs to external warehouse WH1 with a low turnover rate. This is because the throughput capacity is not the constraint that is not satisfied, but the storage capacity constraint is not satisfied. This means the solution prefers to send SKUs with a low demand volume and high stock level, or in other words slow moving SKUs.

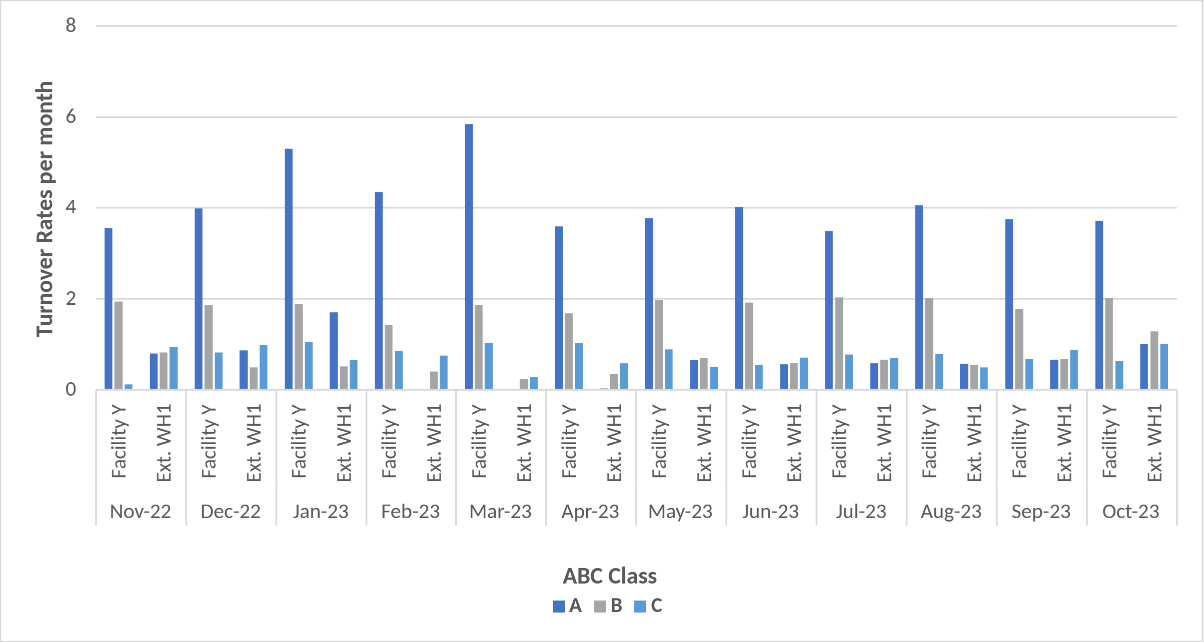


Figure 6.17: The turnover rates per month (period) per warehouse per SKU class for scenario 3 with an utilization rate of 90% and average stock level when increasing the throughput capacity with 5%.

6.6 Conclusion

Results of experiments using average stock

The cost savings of the experiments compared to the base case are minimal, suggesting that the current warehouse operations are already quite efficient solely based on the volume of Facility Y. Savings primarily come from fixed costs and shuttle costs, while transportation and handling costs remain largely unchanged. Transportation costs constitute over 80% of the total costs, highlighting their significant impact on overall expenses.

Scenarios with a 90% utilization rate show greater cost savings compared to those with a 80% utilization rate. This is due to the increased storage capacity utilization, reducing the need for additional external storage space. Specifically, the total capacity requirement is 7,500 tons for 90% utilization scenarios and 10,500 tons for 80% utilization scenarios. In scenarios 1 and 2, external warehouses WH1 and WH3 are utilized. In scenario 3, only external warehouse WH1 is used for 90% utilization scenarios, whereas for 80% utilization scenarios both external warehouses WH1 and WH3 are utilized. External warehouse WH1 is open in each period, with an average utilization rate of 60%, whereas the average utilization for external warehouse WH3 is around 26%. The number of customers supplied from external warehouses (excluding external warehouse WH1) varies slightly across scenarios but does not show extreme differences from the base case. The customers supplied from external warehouses depend significantly on the warehouse locations.

The turnover rates at the Facility Y warehouse are stable and do not fluctuate much, whereas the turnover rates at external warehouses are high during specific periods. Scenarios 2 and 3 show that fast-moving SKUs are often allocated to external warehouses during periods in which the throughput capacity is reached and stock level is rather low (December to March) to minimize costs. The total demand volume through external warehouses decreases when the utilization rate increases to 90%, but the proportion of A-class SKUs handled by external warehouses increases. This is because higher utilization rates at Facility Y allow for more stock to be kept there, and to manage throughput constraints, the model allocates high-demand, low-stock SKUs to external warehouses.

A summary of the findings of the experiments with average stock are found in Tables G.1, G.2, G.3, and G.4.

Results of experiments using peak stock

For the experiments using the peak stock level, the most significant savings are observed in fixed costs, handling costs, and shuttle costs, primarily because of the use of the external warehouse WH1, which has the lowest handling and shuttle costs. Experiments with a 90% utilization rate in peak conditions show potential cost reductions of up to 0.5%.

Across all experiments executed with peak stock level, external warehouse WH1 is open in all periods, indicating its the most cost-efficient warehouse. The other external warehouse that is picked in scenarios 1 and 2 is external warehouse WH3. For scenarios with 90% utilization, a storage capacity of 9,000 tons is required. The results also demonstrate a preference for using external warehouse WH1's capacity over increasing external warehouse WH3's capacity due to cost efficiency. The number of customers served by external warehouses (excluding external warehouse WH1) remains relatively consistent across scenarios, although specific customers and SKUs vary due to location dependencies.

The turnover rates at the Facility Y warehouse remain stable across scenarios. External warehouses show lower turnover rates under peak stock conditions, reflecting higher stock levels and consistent demand. Mostly fast-moving SKUs are allocated to external warehouse WH1, particularly from December 2022 to March 2023. Implementing scenarios with dynamic capacity changes (scenario 1 and 3) might be challenging in reality due to the need for frequent capacity adjustments.

A summary of the findings of the experiments with peak stock are found in Tables G.5 and G.6.

Combined Optimization Scenarios 1 and 2

When we consider the scenario where increasing the capacity of external warehouse WH1 is not feasible, the results show this leads to costs savings ranging of at most 0.6%. If it is desired to utilize a maximum of 90% of the storage capacity during peak stock levels, these costs are nearly similar to those of the current situation. The most significant savings are obtained through use of short-term contracts, resulting in a decrease in fixed costs, and in shuttle costs due to the closer proximity of external warehouse WH1. From the experiments is observed that external warehouse WH1 requires a capacity of 4,500 tons (6,000 tons for an utilization rate of 80%) throughout the year, while additional short-term contracts are needed for warehouse WH3 during specific months, depending on the utilization level.

Increasing Facility Y Throughput Capacity

If we increase the throughput capacity of the Facility Y warehouse, the total costs slightly decrease in terms of the shuttle costs. However, there are no savings in handling costs as only external warehouse WH1 remains open, which has the same handling costs as Facility Y. There is a slight difference in the total costs when comparing a 2% increase in throughput capacity with a 5% increase. The main difference found is in terms of the turnover rate at the external warehouses, which substantially decreased, where the turnover at the Facility Y warehouses increased. This is because the storage capacity constraint, rather than the throughput capacity, becomes the limiting factor.

Solver Computation Time (Gurobi vs. CBC)

Based on the computation times of the Gurobi and CBC solver, provided in Tables G.1 and G.2, we conclude that the computation time of the CBC solver is not suitable for the current model given the input data used. However, if less input data (fewer SKUs, customers, or warehouses) is to be used by the company, this decreases the complexity and therefore the computation time.

Chapter 7

Conclusions and Recommendations

In this chapter, we summarize the research findings, draw conclusions, and provide recommendations to Company X. This is done by answering the final research question:

> *"What conclusions are obtained from the results, and what recommendations can be made to Company X?"*

The conclusions and recommendations are given in Section 7.1 and Section 7.2, respectively. Section 7.3 outlines the contribution to theory and practice. Lastly, the recommendations for future research are provided in Section 7.4.

7.1 Conclusions

In this section, we draw the conclusions from our study of Company X's WLP variant. From the analysis in Chapter 6, the following conclusions can be stated:

Experiments using average and peak stock

The cost savings from the experiments are minimal, between 0.1% and 1.4% of the total costs, indicating that the current warehouse operations are already quite efficient. The savings are from fixed costs and shuttle costs, with transportation and handling costs remaining largely unchanged. Experiments with higher utilization rates show greater cost savings, due to increased storage capacity utilization.

Overall, the capacity requirement is around 6,000 tons when utilizing 90% of the capacity in average storage requirements. External warehouse WH1 is consistently used in all scenarios and periods and external warehouse WH3 is used in scenarios 1 and 2 and utilized in 2 to 4 periods. Scenario 2 suggests that if short-term contracts are not possible the best solution is to use both external warehouses WH1 and WH3 with a storage capacity of 4,500 tons and 3,000 tons, respectively. Scenario 3, on the other hand, suggests that using external warehouse WH1 is the most cost-efficient solution, however constant changes in capacity might be challenging to realize in practice.

The customer allocation towards external warehouse WH1 is not of importance, as the costs of allocating a customer to external warehouse WH1 is the same for each customer. Moreover, from December to March mostly SKUs with a high turnover rate are allocated to external warehouses to manage throughput capacity at Facility Y. Last, we found that the demand volume via external warehouses remains nearly the same compared to the base case.

Experiments with fixed capacity level for external warehouse WH1

Fixing the condition that the external warehouse WH1 can only choose one capacity level (meaning no short-term contracts are possible there), but for other warehouses short-term contracts are allowed, we found cost savings of at most 0.6%. This solution requires a fixed storage capacity of 4,500 tons at the external warehouse WH1 and a variable storage capacity at the external warehouse WH3.

General Conclusions

Increasing throughput capacity at Facility Y slightly decreases shuttle costs for scenario 3, but the main difference observed is the turnover rate at external warehouses, which decreases as storage capacity becomes the limiting factor rather than the throughput capacity. Moreover, we found that the Gurobi solver has a much faster computation time compared to the CBC solver. Using less input data (fewer SKUs, customers, or warehouses) decreases complexity and computation time, which makes the CBC solver suitable for solving the model. Last, the tool evaluation results, presented in Appendix G, demonstrate that the tool is well-received and regarded as highly useful for Company X.

7.2 Recommendations

This section outlines the recommendations based on our research findings and insights. We propose the following recommendations for Company X and Facility Y:

Recommendation for Warehouse Location

We recommend Company X to use the optimization tool every year, to check, based on the portfolio, whether the external warehouse locations are still the most optimal in terms of costs. Furthermore, we recommend to use the tool when considering a potential new warehouse location or when considering closing an external warehouse.

Based on the results and conclusions, we recommend Facility Y the following, if an utilization rate of 90% is desired during average and peak periods:

- If short-term contracts are no option whatsoever, we recommend using external warehouse WH1 with a storage capacity of 4,500 tons and external warehouse WH3 with a storage capacity of 3,000 tons. This is recommended since only in 3 months, this storage capacity at external warehouse WH3 is required, against lower fixed costs compared to external warehouse WH1. This decreases costs by around 0.1% and 0.3%.

- If short-term contracts are an option, we recommend using a fixed storage capacity of 4,500 at external warehouse WH1 and a variable storage capacity of 3,000 tons or lower at external warehouse WH1 as well, depending on the period. This decreases costs by around 0.8%.

- If short-term contracts are not an option at external warehouse WH1, we recommend using a fixed storage capacity of 4,500 at external warehouse WH1 and a variable storage capacity of 3,000 tons or lower at external warehouse WH3, depending on the period. This decreases costs by around 0.6%.

Recommendation for Customer and SKU allocation to external warehouses

We recommend Facility Y to use the results of the customer allocation as a guideline for which customers to assign to which external warehouses (excluding external warehouse WH1) in which periods. The tool presents the optimal solution taking into account the customer demand on SKU level, the storage requirements on SKU level, the proximity of the customers, and multiple time periods. The model should be used as a supporting tool in understanding why specific customers or SKUs are supplied via external warehouses in certain periods.

General Recommendations

We recommend Company X to adopt the established guidelines, which offer comprehensive descriptions of the model and its functionalities. Furthermore, we recommend integrating the output generated by the newly designed inventory optimization tool by Company X into this framework. This alignment ensures that operational requirements complement warehousing management practices. Moreover, we recommend Company X to use the Gurobi solver over the CBC solver, as this reduces the computation time substantially. Lastly, we recommend Company X to use the tool as a scenario analysis tool by disabling the criteria of scenario 1. This ensures that each time period becomes a separate scenario, that is optimized independent of the other periods (or scenarios in this case).

7.3 Contributions to Theory and Practice

Contribution to Theory

This research contributes to the theory by applying the basics of the Warehouse Location Problem. Based on the literature review, we found that traditional models typically address WLPs by either focusing solely on demand volume, neglecting the incorporation of storage capacity constraints, or by incorporating detailed operational parameters such as production input and demand output to determine the storage space requirements, leading to complex and computationally intensive models. To the best of our knowledge, we introduced a slightly different approach by creating a model that on a strategic and tactical level includes both the demand volume and storage space requirement considerations as input to find the optimal warehouse location. Our model provides on a strategic and tactical level where, when, and how much storage capacity is required, this is useful for finding the potential first and then move on to a very detailed analysis, rather than the other way around.

Contribution to Practice

This research makes a contribution to practice for businesses seeking to optimize their warehouse locations. Using the model, companies can make informed decisions regarding warehouse choices, capacity requirements, and customer allocations in different time periods, leading to cost savings. Furthermore, the model allows for scenario analysis and experimentation, allowing businesses to evaluate different scenarios efficiently. From Chapter H, this practical contribution is supported by Company X.

7.4 Future Research Directions

In this section, we identify promising avenues for further research in the realm of Company X's WLP variant. Our study has highlighted areas that merit continued investigation:

- For future research, we recommend to extend the scope of the problem at Company X to find a global optimum. The current research is based solely on the volume of Facility Y, which may give a sub-optimal solution for the whole network, therefore we recommend Company X to use utilize this model for a larger scope.
- We also recommend to create a model on the operational level, which uses the output of the model of this research regarding warehouse location and simulate the optimal operational requirements at these warehouses in terms of staff, docks required, how to combine orders in trucks, etc.
- For future research, we recommend to extend the model to incorporate multiple objectives, if this were to be required in the future by Company X or any other company.
- To improve operational efficiency, we recommend investigating the other challenges mentioned in Section 2.2.4 and the other core problems mentioned in Section 1.3.

Appendix A

Process Flow Chart: Storing and Loading Processes

In this Appendix, the process flow charts of the storing and loading processes at Facility Y can be seen:

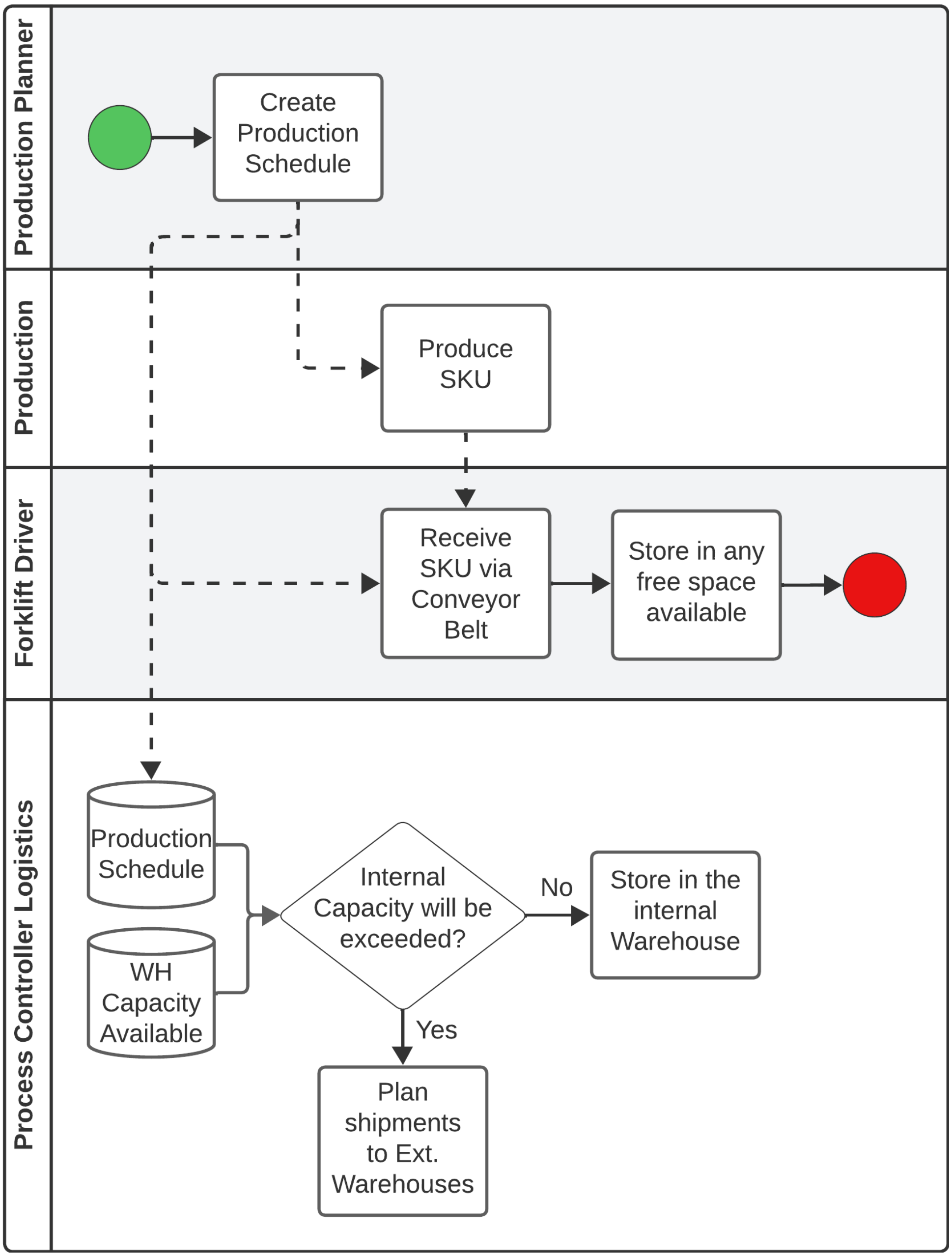


Figure A.1: The Process flow chart of the storing process at Facility Y

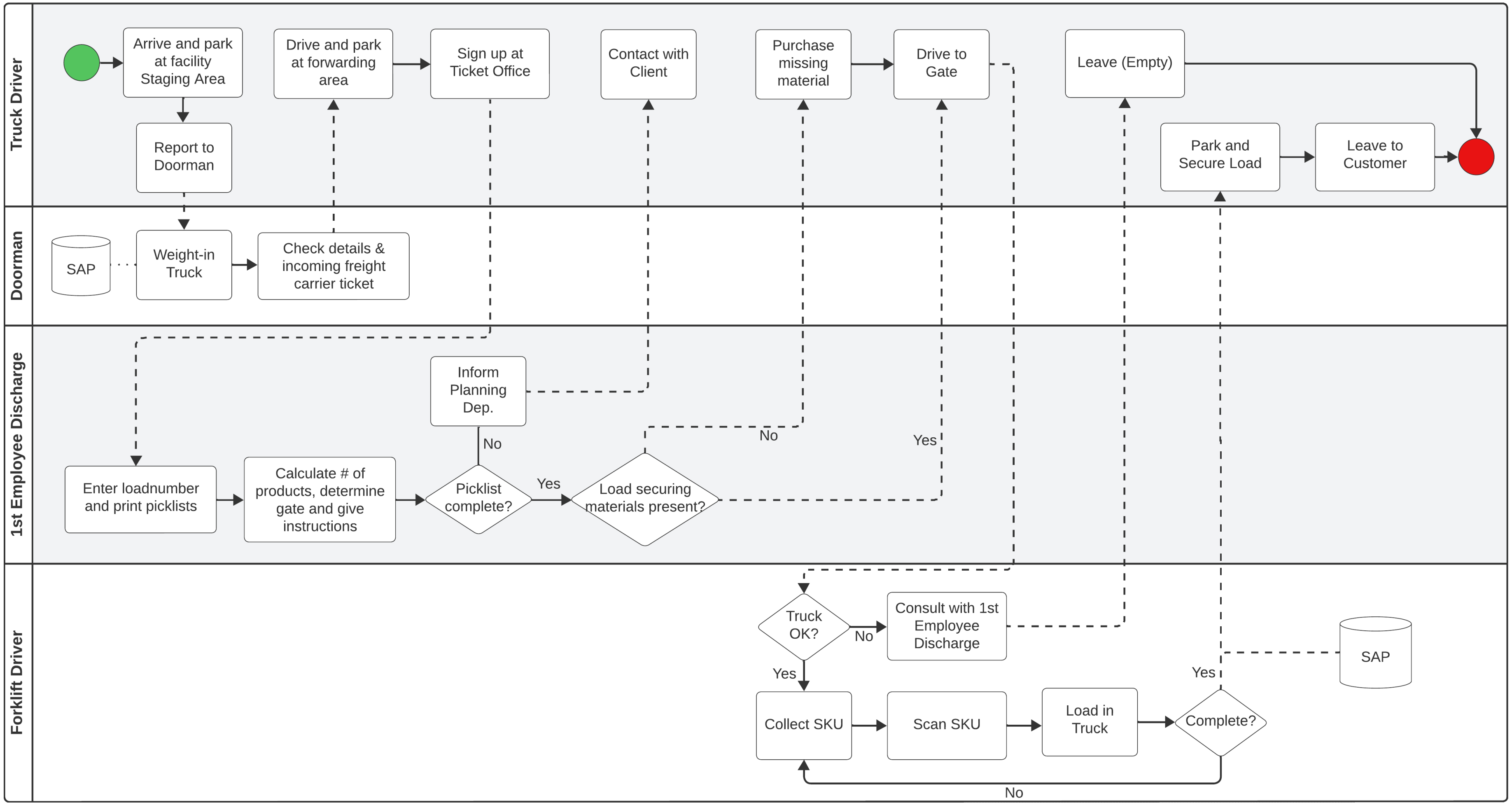


Figure A.2: The process flow chart of the loading process at Facility Y

Appendix B

Operational Activities and Challenges at Facility Y

In this appendix, we give a thorough overview of the picking activity within the warehouses of Facility Y.

To get a picture of the movement activity within the warehouse, a heatmap is created in Figure B.1. The darker the color of the location the more activity or the more picks at this location. In general, we see that the activity is dispersed over the warehouse. We see that a lot of the activity is centered around docks 5 and 6. The main reason for this is that currently much of the newly produced SKUs are stored in the S-section on the left. On contrast, the activity around docks 1 and 2 is low. The main reason for this is that in the left hand A-section the SKUs are stored that come from the SKU edit area, where side-run SKUs are converted to a product desired by the customer. However, as these are in low demand, there is not a lot of activity.

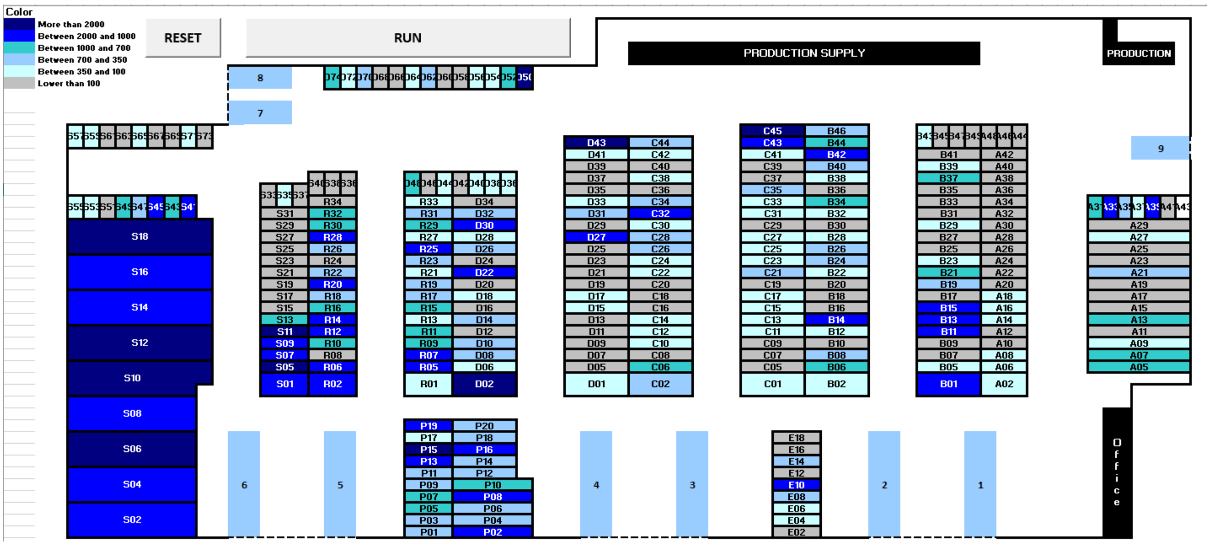


Figure B.1: Heatmap of the picking activity in the main warehouse Hal 14/15

The decision to let a truck come to a dock is based on what SKUs are in the order, meaning that a truck is placed at a dock which is close to at least 1 The decision to let a truck come to a dock is based on what SKUs are in the order, meaning that a truck is placed at a dock which is close to at least 1 SKU in the warehouse. The forklift driver can only move 3 tons at a time, which often is 1 SKU, depending on the size. This means that the forklift driver has to drive back and forth every time only 1 SKU is collected. This results in a lot of driving activity. An example of such a picking path is given in Figure B.2. In this example is seen that when the forklift driver has collected an SKU at a certain location, he comes back to load it into the truck, and moves to the next SKU. in the warehouse. The forklift driver can only move 3 tons at a time, which often is 1 SKU, depending on the size. This means that the forklift driver has to drive back and forth every time only 1 SKU is collected. This results in a lot of driving activity. An example of such a picking path is given in Figure B.2. In this example is seen that when the forklift driver has collected an SKU at a certain location, he comes back to load it into the truck, and moves to the next SKU.

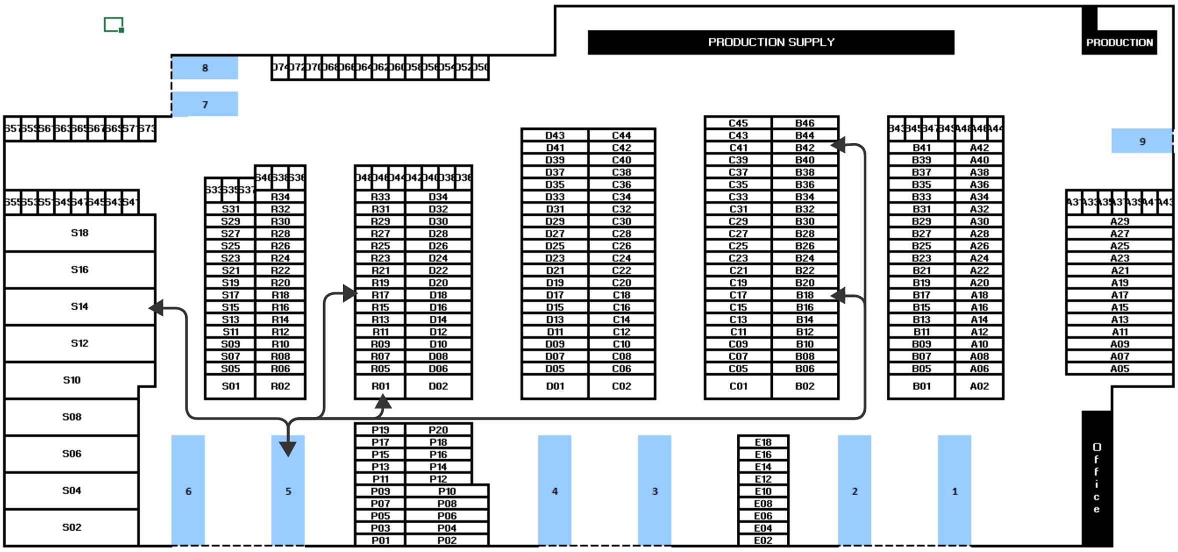


Figure B.2: Picking path example showing a picker has to drive back and forth for picking only 1 SKU

In the main warehouse Hal 14 and 15, the stacking of SKUs can go up to 7.60 m. SKUs can only be stacked if the bottom product has a bigger diameter, else the products are damaged. A forklift driver always want to move a hand with a weight of 3 tons. Most of the times 1 product is around this weight, however with side runs (products smaller than 1.60 m) the forklift driver first has to stack multiple products to come close to a weight of 3 tons. Thus, side runs require extra handling when being picked. Other complications with the picking of the products is that in many locations more than 1 type of SKU is stored and SKUs are stacked. Both result in more picking time, as in both you have to move SKUs before the SKU can be picked. In Table B.1 is seen how many locations consist of 1 or more SKUs. From this we see that more than 50% of the locations have more than 1 SKU, which results in inefficient picking.

The decision to let a truck come to a dock is based on what SKUs are in the order, meaning that a truck is placed at a dock which is close to at least 1 SKU in the order. This results in a dispersion in activity per dock as well, since more trucks are loaded where the fast movers are located. Figure B.3 shows the dispersion of loading activity per dock and hal. From the figure we see that especially in Hal 8 there is a lot of loading activity. The reason for this is that the side runs can only be transported to

# of distinct SKUs on the location	**# of Locations**
1 SKU	113
Between 1 and 5 SKUs	121
Between 5 and 10 SKUs	27
More than 10 SKUs	8
Total	269

Table B.1: An Overview of the occupation of distinct SKUs per location in the storage location Hal 14/15

Hal 8, since this is on the property of Facility Y. To reach the other warehouses (Hal 7 and ext. WH1) the shuttle truck has to go on the road, however this is not allowed with side runs as these cannot be secured on the shuttle truck, the larger products can be transported to Hal 7 and external warehouse WH1. Moreover, the products produced on machine 3, must be stored within the main warehouse, since there is no shuttle truck on this side of the warehouse. This also results in more products from the machine 2 and machine 2 to be stored in the external warehouses. All these complications currently result in around 17% of all loads per week to be loaded at multiple warehouses.

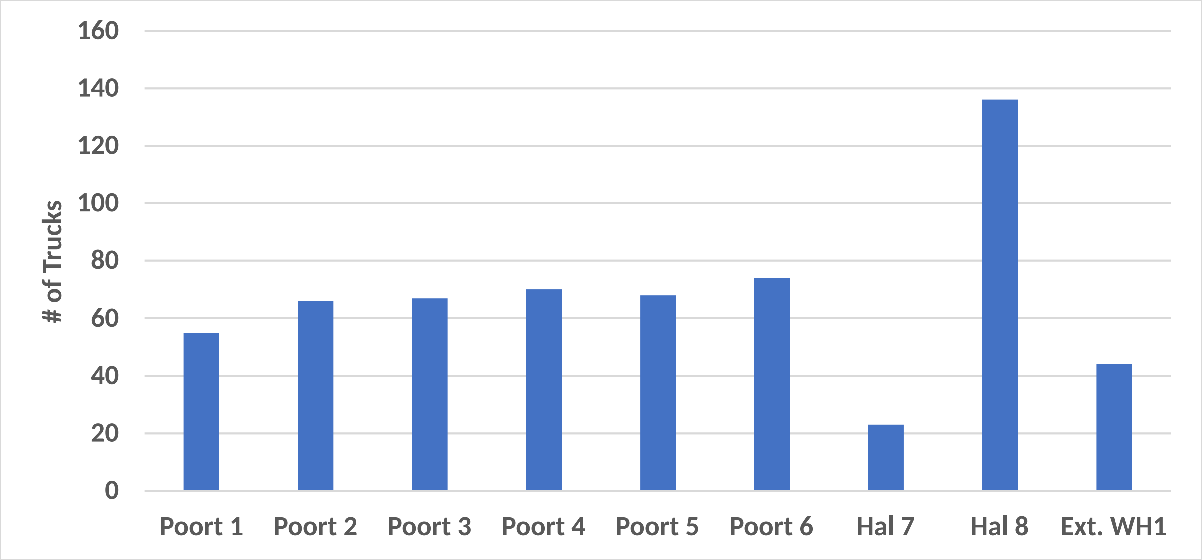


Figure B.3: Overview of dispersion of loading activity per dock and hal of a random week

The decision to let a truck come to a dock is based on what SKUs are in the order, currently this sometimes results in trucks having to wait to dock, even though there is a dock available, because the docks close to SKUs in the order of those trucks are occupied. In Figure B.4 an overview is given of the average waiting time per truck, average loading time per truck, and average number of trucks per day for each week of the year. We see that the loading time per truck is quite stable over the year and is around 21 minutes on average. The number of trucks per day also is quite stable between 80 to 100 trucks per day, with one outlier in week 52 and 53. This is because of the Christmas holidays.

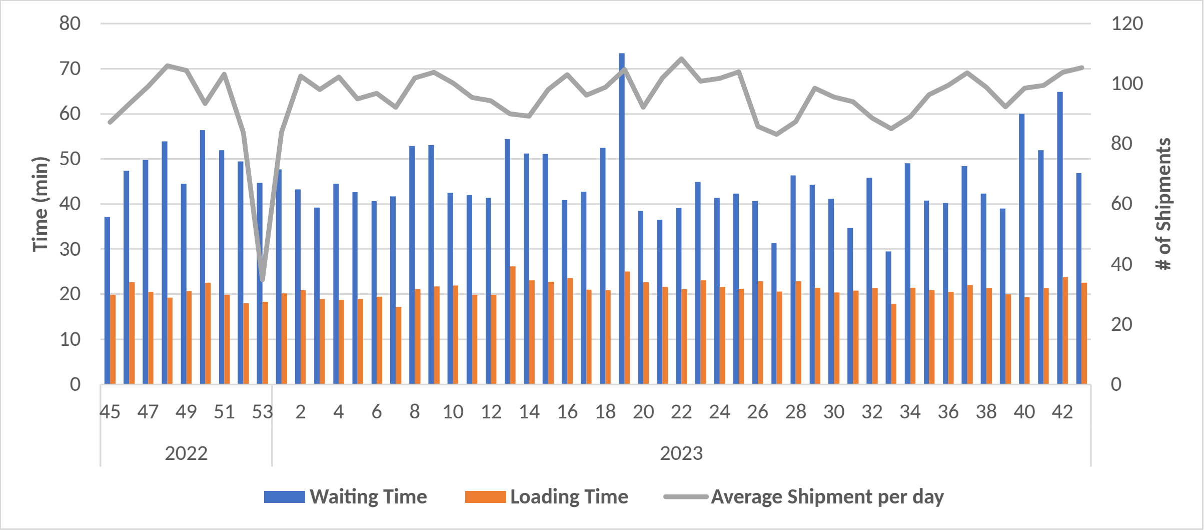


Figure B.4: Overview of the average waiting time per truck, average loading time per truck, and average number of trucks per day for each week of the year

We see that for the waiting time per truck there is a lot of deviation, which is dependent on multiple factors, such as dock availability, forklift availability, skill of truck drivers themselves (regarding docking and preparation), loading time, and peaks in arrival hours. In Figure B.5, we show the truck arrivals per time slot, the waiting time, loading time, gate-out time, and total throughput time. From this we see that peaks in arrivals are between 06:00 and 07:00, but especially between 10:00 and 13:00 there are many trucks. With the current process of having no strategy on where to place, in combination with high peaks in arrivals, this leads to high waiting times during these peak hours.

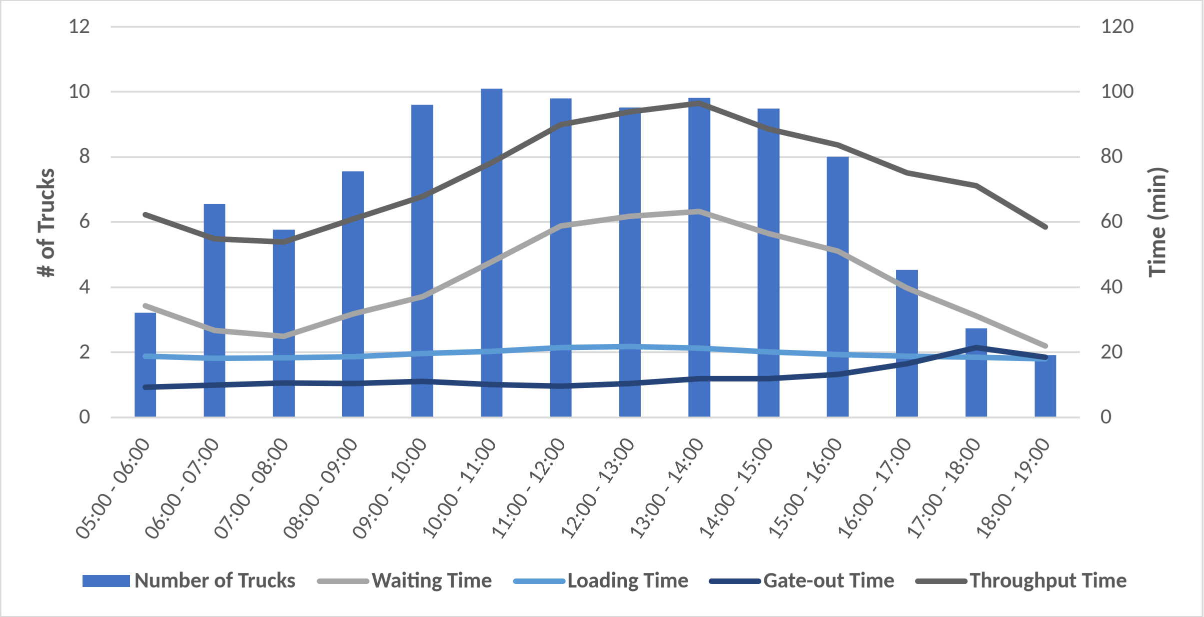


Figure B.5: Distribution Trucks per hour against the throughput time elements

If the waiting time is too long, this can lead to waiting money. Waiting money can be asked for by truck drivers when they have a throughput larger than 120 minutes.

The price of 1 hour Overtime is equal to €40.00. The past 12 months this has resulted in €117,864.677 with an average of 12% of the trucks that arrive result in overtime, as seen from Table B.2.

Total Overtime (hours)	2947
Total Overtime Costs	€117,864.67
Average Trucks Overtime % per day	12%

Table B.2: An Overview of the Overtime and costs associated with the Overtime from the period 1/11/2022 - 1/11/2023

Appendix C

Toy Example Data

Below all required data for the Warehouse Location Problem of the toy example is found.

Period	Facility	SKU	Demand (tons)	Storage Requirement (tons)	Turnover Rate Facility
1	1	1	900	150	6.50
1	1	2	1000	250	4.00
1	2	2	250	300	0.84
1	2	3	1250	350	4.00
2	1	1	900	150	6.50
2	1	2	1100	300	3.67
2	2	2	300	300	1.00
2	2	3	1400	400	4.00
3	1	1	1000	150	6.67
3	1	2	1200	250	4.80
3	2	2	350	300	1.17
3	2	3	1450	400	4.00

Table C.1: Storage Requirement and Turnover Rate Data

Period	**Facility**	**Customer**	**SKU**	**Demand (tons)**
1	1	1	1	500
1	1	2	1	300
1	1	3	1	100
1	1	1	2	600
1	1	2	2	400
1	1	3	2	0
1	2	1	2	0
1	2	2	2	250
1	2	3	2	0
1	2	1	3	0
1	2	2	3	500
1	2	3	3	750
2	1	1	1	550
2	1	2	1	350
2	1	3	1	0
2	1	1	2	650
2	1	2	2	450
2	1	3	2	0
2	2	1	2	0
2	2	2	2	300
2	2	3	2	0
2	2	1	3	0
2	2	2	3	550
2	2	3	3	850
3	1	1	1	600
3	1	2	1	400
3	1	3	1	0
3	1	1	2	700
3	1	2	2	500
3	1	3	2	0
3	2	1	2	0
3	2	2	2	350
3	2	3	2	0
3	2	1	3	0
3	2	2	3	600
3	2	3	3	850

Table C.2: Customer Demand Data

SKU	**ABC Class**	**Siderun**	**B-Grade**
1	A	False	False
2	B	False	True
3	C	True	False

Table C.3: SKU Identification table including ABC class, Siderun and B-grade.

Warehouse	CL 0	CL 1	CL 2	CL 3	CL 4	CL 5
1	350	350	350	350	350	350
2	600	600	600	600	600	600
3	50	100	150	200	250	300
4	50	100	150	200	250	300

Table C.4: Warehouse Capacity in tons per Capacity Level (CL)

Warehouse	CL 0	CL 1	CL 2	CL 3	CL 4	CL 5
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	1500	3000	4500	6000	7500	9000
4	1500	3000	4500	6000	7500	9000

Table C.5: Warehouse Fixed Costs in Euros per Capacity Level (CL) per time period

Warehouse	Handling Cost
1	4
2	4
3	7
4	7

Table C.6: Handling Costs per warehouse in euros

Facility	WH1	WH2	WH3	WH4
1	0	20	5	20
2	20	0	10	5

Table C.7: Shuttle Costs in euros

Warehouse	C1	C2	C3
1	5	10	15
2	10	5	10
3	5	10	20
4	10	5	5

Table C.8: Transportation Costs in euros

Warehouse	Period	Max Throughput (tons)
1	1	1900
1	2	1900
1	3	1900
2	1	1700
2	2	1700
2	3	1700
3	1	1000
3	2	1000
3	3	1000
4	1	1000
4	2	1000
4	3	1000

Table C.9: Maximum Warehouse Throughput per warehouse

Appendix D

K-means Code

Below the code used for the Center of Gravity approach (K-means) can be seen:

```
# Import libraries
import pandas as pd
import folium
from sklearn.cluster import KMeans

# Load data
data = pd.read_excel('c:/FileLocation.xlsx',
                     dtype={'Location Name': str,
                            'Location Type': str})

# Color options
color_options = {'demand': 'red',
                 'supply': 'yellow',
                 'flow': 'black',
                 'cog': 'blue',
                 'candidate': 'black',
                 'other': 'gray'}

# Instantiate map
m = folium.Map(location=data[['Latitude', 'Longitude']].mean(),
               fit_bounds=[[data['Latitude'].min(),
                            data['Longitude'].min()],
                           [data['Latitude'].max(),
                            data['Longitude'].max()]])

# Add volume points
for _, row in data.iterrows():
    folium.CircleMarker(location=[row['Latitude'], row['Longitude']],
                        radius=5,
                        color=color_options.get(str(row['Location Type'])
                        tooltip=f"{row['Location Name']} {row['Volume']}"
```

```
# Zoom based on volume points
m.fit_bounds(data[['Latitude', 'Longitude']].values.tolist())

# Fit K-means for 3 centroids
kmeans = KMeans(n_clusters=3, random_state=0).fit(
    data.loc[data['Volume'] > 0, ['Latitude', 'Longitude']],
    sample_weight=data.loc[data['Volume'] > 0, 'Volume'])

# Get centers of gravity from K-means
cogs = kmeans.cluster_centers_
cogs = pd.DataFrame(cogs, columns=['Latitude', 'Longitude'])

# Get volume assigned to each cluster
data['Cluster'] = kmeans.predict(data[['Latitude', 'Longitude']])
cogs['Volume'] = data.groupby('Cluster')['Volume'].sum().values

# Add centers of gravity to map
for _, row in cogs.iterrows():
    folium.CircleMarker(location=[row['Latitude'], row['Longitude']],
                        radius=10, # Increase radius for better visibili
                        color=color_options['cog'],
                        fill=True,
                        fill_color=color_options['cog'],
                        tooltip=f"COG Volume: {row['Volume']}").add_to(m)

# Show map
m.save("c:OutputLocationName.html")

# Show the map in the notebook
m
```

Appendix E

K-means Output

In figures E.1 and E.2 we see the output of center of gravity approach (K-means) on a map, with 1, and 2 centers, respectively.

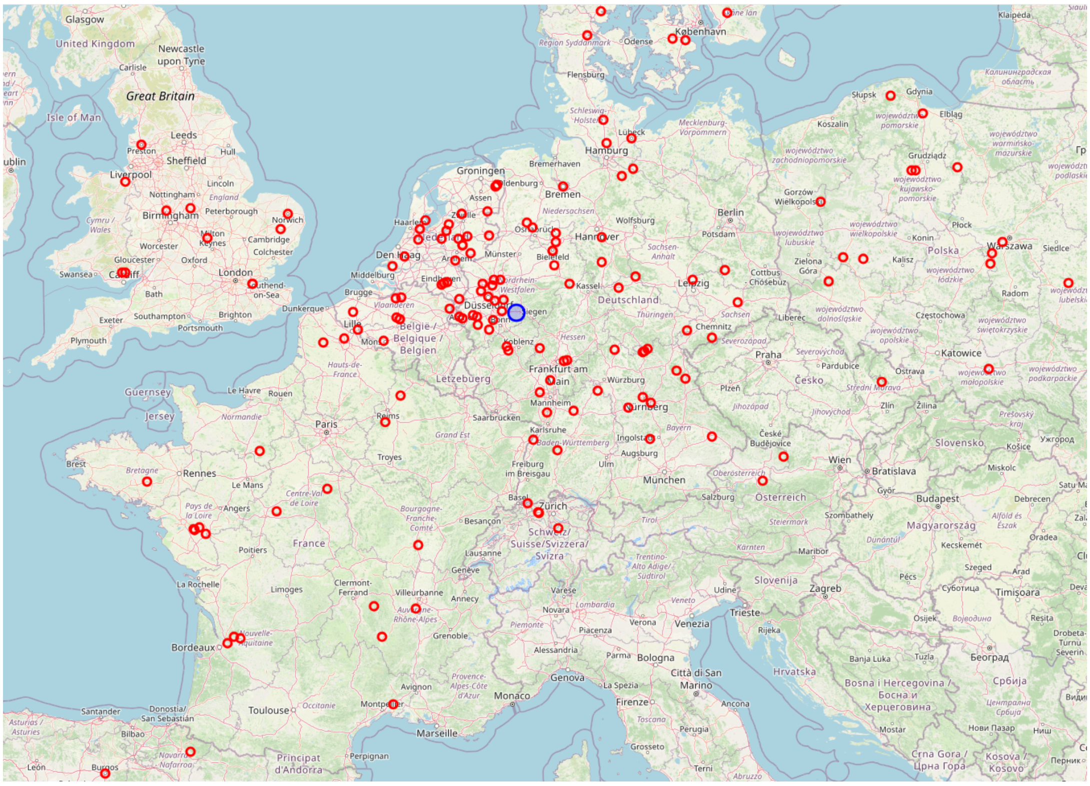


Figure E.1: The output of the K-means approach with k = 1, where the blue circle represent the center and the red circle the customer locations.

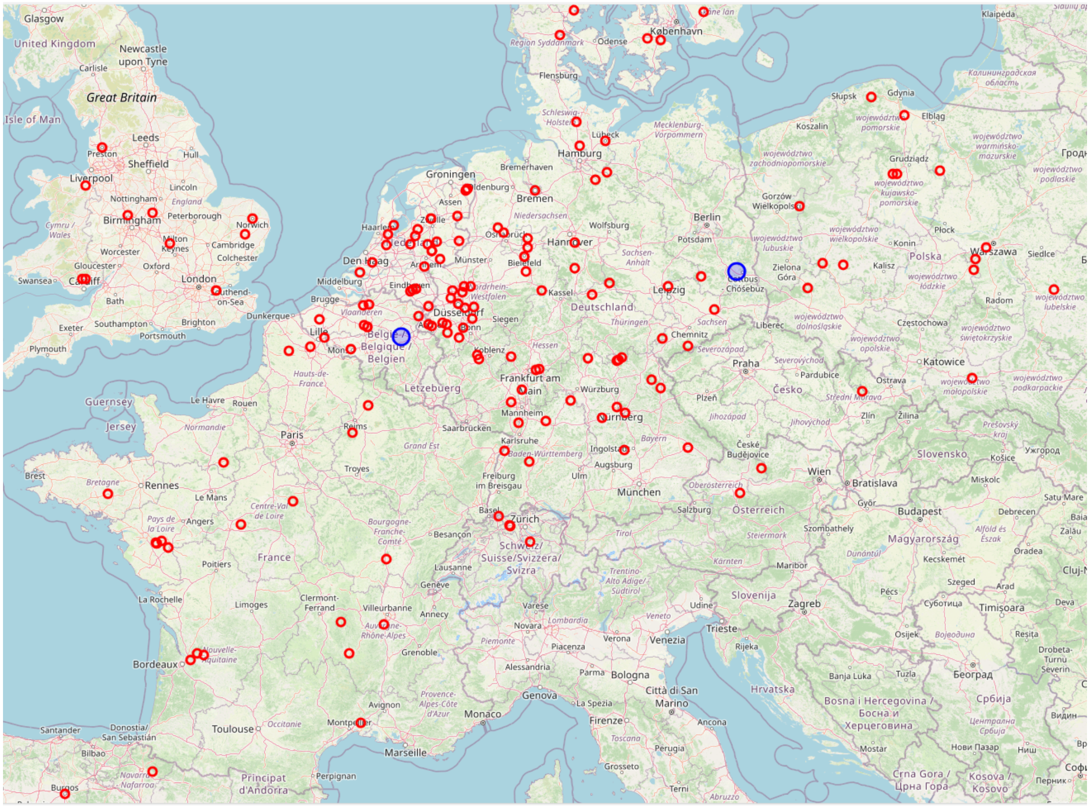


Figure E.2: The output of the K-means approach with k = 2, where the blue circle represent the center and the red circle the customer locations.

Appendix F

Turnover Rates per month

We see the turnover rates per month per warehouse per period of scenario 3 with average stock level and peak stock level, in figures F.1 and F.2, respectively. All results are with a maximum utilization rate of 90%.

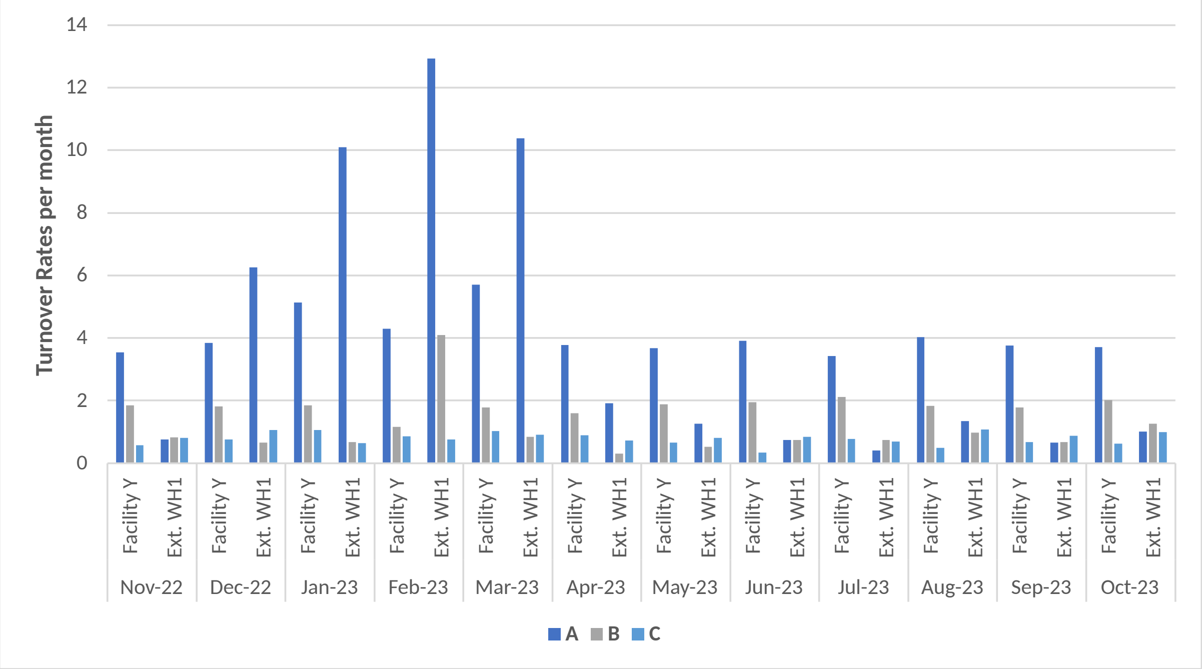


Figure F.1: The turnover rates per month (period) per warehouse per SKU class for scenario 3 with a utilization rate of 90% and average stock level.

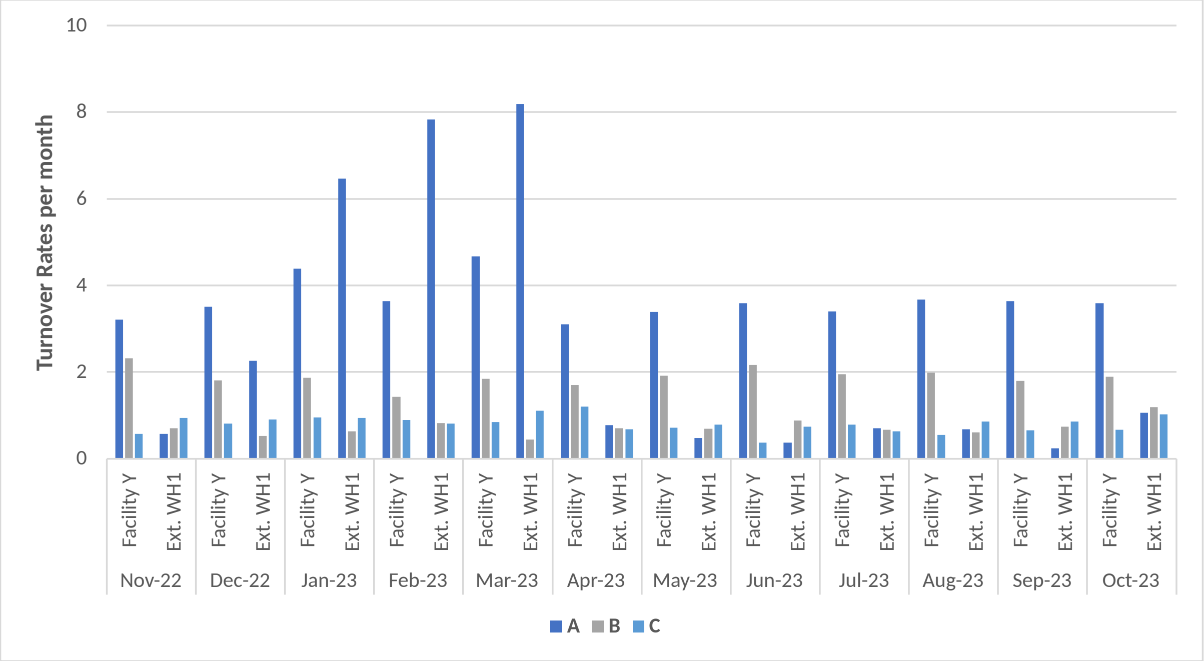


Figure F.2: The turnover rates per month (period) per warehouse per SKU class for scenario 3 with a utilization rate of 90% and peak stock level.

Appendix G

Summary Table of Experiment Results

Table G.1: Summary of the experiments with the average stock level and 90% utilization rate.

	Base Case	**Scenario 1**	**Scenario 2**
Open Warehouses	1: Facility WH 2: Ext. WH1 3: Ext. WH2	1: Facility WH 2: Ext. WH1 3: Ext. WH3	1: Facility WH 2: Ext. WH1 3: Ext. WH3
# of Periods utilized	1: 12 2: 12 3: 12	1: 12 2: 12 3: 5	1: 12 2: 12 3: 4
Max External Capacity (tons)	2: 3,000 3: 4,500	7,500	2: 4,500 3: 3,000
		Total: 7,500	
Average Utilization Rate (%)	1: 90 2: 74 3: 61	1: 89 2: 66 3: 22	1: 89 2: 53 3: 26
# of Customers served (external)	2: NO DATA 3: 27	2: 81 3: 6	2: 82 3: 34
Cost Decrease (%)	-	-1.4%	-0.1%
Euro per Ton (€ / ton)	€30.87 / ton	€30.44 / ton	€30.83 / ton
Computation Time (GRB // CBC)	-	180 s // 1999 s	239 s // 1449 s

Table G.2: Continued: Summary of the experiments with the average stock level and 90% utilization rate.

	Base Case	**Scenario 3**
Open Warehouses	1: Facility WH 2: Ext. WH1 3: Ext. WH2	1: Facility WH 2: Ext. WH1
# of Periods utilized	1: 12 2: 12 3: 12	1: 12 2: 12
Max External Capacity (tons)	2: 3,000 3: 4,500	7,500
	Total: 7,500	
Average Utilization Rate (%)	1: 90 2: 74 3: 61	1: 88 2: 63
# of Customers served (external)	2: NO DATA 3: 27	2: 97 3: 6
Cost Decrease (%)	-	-1.3%
Euro per Ton (€ / ton)	€30.87 / ton	€30.48 / ton
Computation Time (GRB // CBC)	-	337 s // 1999 s

Table G.3: Summary of the experiments with the average stock level and 80% utilization rate.

	Base Case	**Scenario 1**	**Scenario 2**
Open Warehouses	1: Facility WH 2: Ext. WH1 3: Ext. WH2	1: Facility WH 2: Ext. WH1 3: Ext. WH3	1: Facility WH 2: Ext. WH1 3: Ext. WH3
# of Periods utilized	1: 12 2: 12 3: 12	1: 12 2: 12 3: 3	1: 12 2: 12 3: 2
Max External Capacity required (tons)	2: 3,000 3: 4,500	10,500 **Total: 10,500**	2: 7,500 3: 3,000
Average Utilization rate (%)	1: 90 2: 74 3: 61	1: 80 2: 77 3: 33	1: 80 2: 53 3: 8
# of Customers served (external)	2: NO DATA 3: 27	2: 121 3: 5	2: 135 3: 29
Costs Decrease (%)	-	-0.3%	1.2%
Euro per Ton (€ / ton)	€30.87 / ton	€30.72 / ton	€31.24 / ton
Computation time (GRB)	-	170 s	239 s

Table G.4: Continued: Summary of the experiments with the average stock level and 80% utilization rate.

	Base Case	**Scenario 3**
Open Warehouses	1: Facility WH 2: Ext. WH1 3: Ext. WH2	1: Facility WH 2: Ext. WH1 3: Ext. WH3
# of Periods utilized	1: 12 2: 12 3: 12	1: 12 2: 12 3: 2
Max External Capacity (tons)	2: 3,000 3: 4,500	10,500
	Total: 10,500	
Average Utilization Rate (%)	1: 90 2: 74 3: 61	1: 80 2: 77 3: 15
# of Customers served (external)	2: NO DATA 3: 27	2: 132 3: 17
Cost Decrease (%)	-	-0.2%
Euro per Ton (€ / ton)	€30.87 / ton	€30.81 / ton
Computation Time (GRB)	-	337 s

Table G.5: Summary of the experiments with the peak stock level and 90% utilization rate.

	Base Case	Scenario 1	Scenario 2
Open Warehouses	1: Facility WH 2: Ext. WH1 3: Ext. WH2	1: Facility WH 2: Ext. WH1 3: Ext. WH3	1: Facility WH 2: Ext. WH1 3: Ext. WH3
# of Periods utilized	1: 12 2: 12 3: 12	1: 12 2: 12 3: 3	1: 12 2: 12 3: 2
Max External Capacity required (tons)	2: 3,000 3: 4,500	2: 9,000 **Total: 9,000**	2: 7,500 3: 1,500
Average Utilization rate (%)	1: 90 2: 74 3: 61	1: 90 2: 82 3: 16	1: 90 2: 56 3: 16
# of Customers served (external)	2: NO DATA 3: 27	2: 116 3: 2	2: 116 3: 9
Costs Decrease (%)	-	-0.5%	0.7%
Euro per Ton (€ / ton)	€30.87 / ton	€30.69 / ton	€31.02 / ton
Computation time (GRB)	-	176 s	235 s

Table G.6: Continued: Summary of the experiments with the peak stock level and 90% utilization rate.

	Base Case	Scenario 3
Open Warehouses	1: Facility WH 2: Ext. WH1 3: Ext. WH2	1: Facility WH 2: Ext. WH1
# of Periods utilized	1: 12 2: 12 3: 12	1: 12 2: 12
Max External Capacity (tons)	2: 3,000 3: 4,500	9,000
	Total: 9,000	
Average Utilization Rate (%)	1: 90 2: 74 3: 61	1: 90 2: 79
# of Customers served (external)	2: NO DATA 3: 27	2: 116
Cost Decrease (%)	-	-0.5%
Euro per Ton (€ / ton)	€30.87 / ton	€30.71 / ton
Computation Time (GRB)	-	239 s

Appendix H

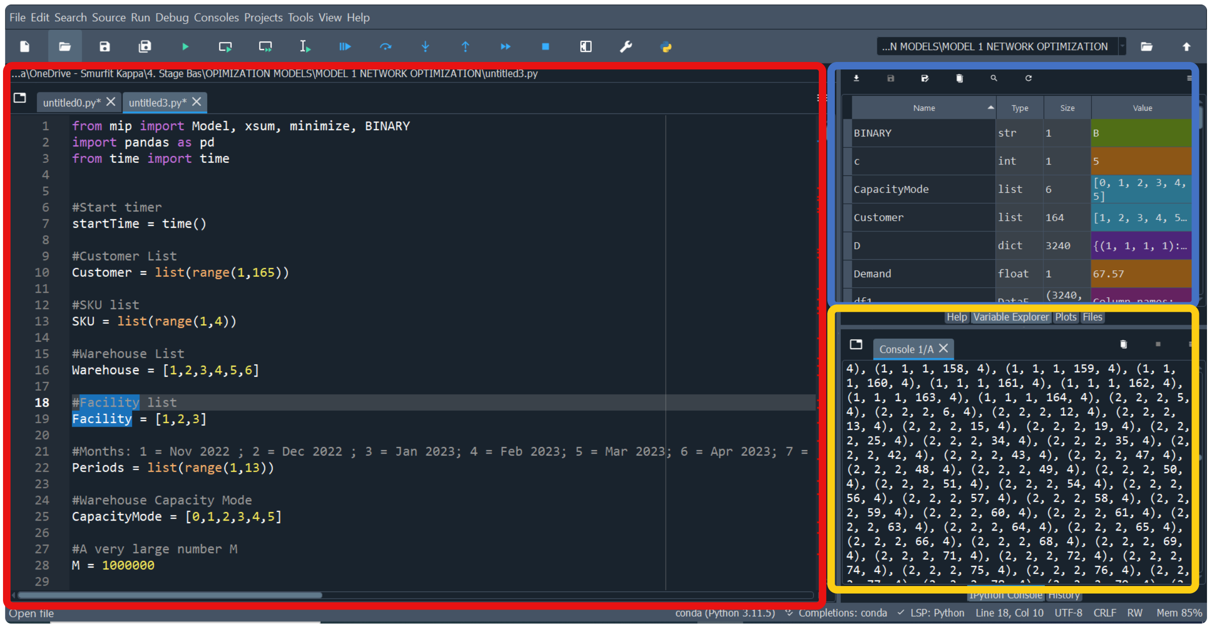
Tool Evaluation

In this chapter, we provide an evaluation of the solution approach implemented for Company X. The solution approach consists the programmed model in Python and the file to which the output is written. For Company X to have a good understanding of the tool and make use of it appropriately and efficiently, this evaluation is executed.

In Section H.1, we describe the tool briefly. Before the solution approach could be reviewed, a literature review is conducted to get more insights on how to evaluate the solution approach and design. In Section H.2, the method of evaluation is explained. In Section H.3, the survey is explained, and the results are presented. Lastly, in Section H.4 the conclusion of the evaluation results is given.

H.1 Tool Design

This section explains the design of the tool, beginning with a brief overview of the Python environment in which the model can be run. The environment is seen in Figure H.1, the red part is the interaction part, here code is presented which is divided into three parts, namely the input data, mathematical model, and output writing part. Python gathers the required input data from specific excel files, this excel data can be altered for experiments. More experiments can be done, by enabling or disabling specific constraints (e.g., maximum utilization rate). The blue part is the information part, here the output of the created variables can be checked. In the yellow part we have the outcome, here output information of the optimal solution can be attained from the created scenario in the red part, to get a quick overview of the results.



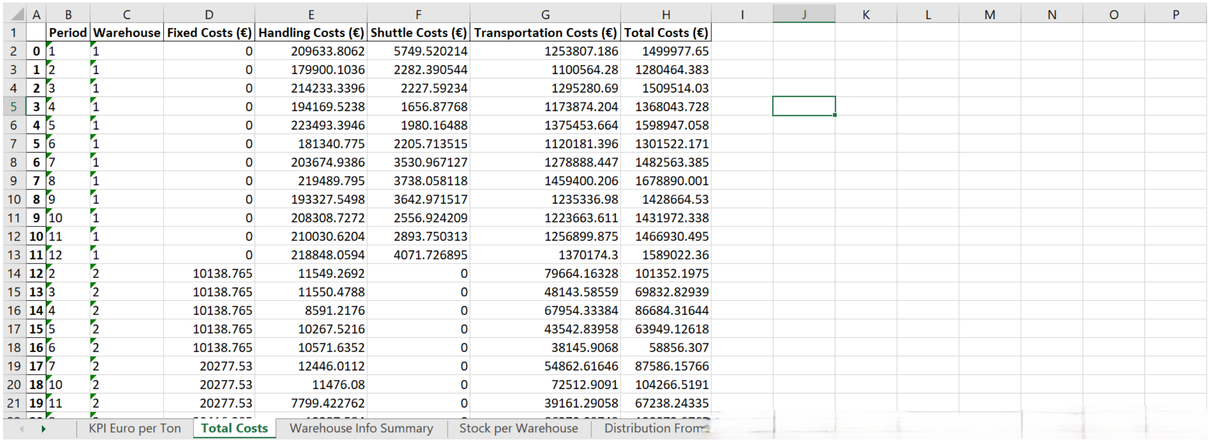
```python
from mip import Model, xsum, minimize, BINARY
import pandas as pd
from time import time


#Start timer
startTime = time()

#Customer List
Customer = list(range(1,165))

#SKU list
SKU = list(range(1,4))

#Warehouse List
Warehouse = [1,2,3,4,5,6]

#Facility list
Facility = [1,2,3]

#Months: 1 = Nov 2022 ; 2 = Dec 2022 ; 3 = Jan 2023; 4 = Feb 2023; 5 = Mar 2023; 6 = Apr 2023; 7 =
Periods = list(range(1,13))

#Warehouse Capacity Mode
CapacityMode = [0,1,2,3,4,5]

#A very large number M
M = 1000000

```

Name	Type	Size	Value
BINARY	str	1	B
c	int	1	5
CapacityMode	list	6	[0, 1, 2, 3, 4, 5]
Customer	list	164	[1, 2, 3, 4, 5…
D	dict	3240	{(1, 1, 1, 1):…
Demand	float	1	67.57

```
4), (1, 1, 1, 158, 4), (1, 1, 1, 159, 4), (1, 1,
1, 160, 4), (1, 1, 1, 161, 4), (1, 1, 1, 162, 4),
(1, 1, 1, 163, 4), (1, 1, 1, 164, 4), (2, 2, 2, 5,
4), (2, 2, 2, 6, 4), (2, 2, 2, 12, 4), (2, 2, 2,
13, 4), (2, 2, 2, 15, 4), (2, 2, 2, 19, 4), (2, 2,
2, 25, 4), (2, 2, 2, 34, 4), (2, 2, 2, 35, 4), (2,
2, 2, 42, 4), (2, 2, 2, 43, 4), (2, 2, 2, 47, 4),
(2, 2, 2, 48, 4), (2, 2, 2, 49, 4), (2, 2, 2, 50,
4), (2, 2, 2, 51, 4), (2, 2, 2, 54, 4), (2, 2, 2,
56, 4), (2, 2, 2, 57, 4), (2, 2, 2, 58, 4), (2, 2,
2, 59, 4), (2, 2, 2, 60, 4), (2, 2, 2, 61, 4), (2,
2, 2, 63, 4), (2, 2, 2, 64, 4), (2, 2, 2, 65, 4),
(2, 2, 2, 66, 4), (2, 2, 2, 68, 4), (2, 2, 2, 69,
4), (2, 2, 2, 71, 4), (2, 2, 2, 72, 4), (2, 2, 2,
74, 4), (2, 2, 2, 75, 4), (2, 2, 2, 76, 4), (2, 2,
```

Figure H.1: Environment Optimization Tool in Python.

To get a more thorough view of the result from the model, an Excel file is create to which all output information is written and can be analyzed in more detail. All information that is written to this Excel file is according to the wishes of Company X. An overview of the Excel file is seen in Figure H.2.



	Period	Warehouse	Fixed Costs (€)	Handling Costs (€)	Shuttle Costs (€)	Transportation Costs (€)	Total Costs (€)
0	1	1	0	209633.8062	5749.520214	1253807.186	1499977.65
1	2	1	0	179900.1036	2282.390544	1100564.28	1280464.383
2	3	1	0	214233.3396	2227.59234	1295280.69	1509514.03
3	4	1	0	194169.5238	1656.87768	1173874.204	1368043.728
4	5	1	0	223493.3946	1980.16488	1375453.664	1598947.058
5	6	1	0	181340.775	2205.713515	1120181.396	1301522.171
6	7	1	0	203674.9386	3530.967127	1278888.447	1482563.385
7	8	1	0	219489.795	3738.058118	1459400.206	1678890.001
8	9	1	0	193327.5498	3642.971517	1235336.98	1428664.53
9	10	1	0	208308.7272	2556.924209	1223663.611	1431972.338
10	11	1	0	210030.6204	2893.750313	1256899.875	1466930.495
11	12	1	0	218848.0594	4071.726895	1370174.3	1589022.36
12	2	2	10138.765	11549.2692	0	79664.16328	101352.1975
13	3	2	10138.765	11550.4788	0	48143.58559	69832.82939
14	4	2	10138.765	8591.2176	0	67954.33384	86684.31644
15	5	2	10138.765	10267.5216	0	43542.83958	63949.12618
16	6	2	10138.765	10571.6352	0	38145.9068	58856.307
17	7	2	20277.53	12446.0112	0	54862.61646	87586.15766
18	10	2	20277.53	11476.08	0	72512.9091	104266.5191
19	11	2	20277.53	7799.422762	0	39161.29058	67238.24335

Figure H.2: Overview of the Excel output file containing detailed information of the solution.

H.2 Unified Theory of Acceptance and Use of Technology

The Unified Theory of Acceptance and Use of Technology (UTAUT), from Venkatesh et al. (2003), is employed to validate the solution approach of this thesis. This method is particularly suitable as it evaluates the likelihood of success for new technological artifacts, such as models, dashboards, or tools developed in Python, which are introduced to Company X. The UTAUT model, depicted in Figure H.3, assesses these artifacts through a questionnaire based on six constructs:

1. **Performance expectancy**: The degree to which the user believes that using the technical artifact will help in improving their job performance.
2. **Effort expectancy**: The degree to which the sure thinks the artifact is easy to use.
3. **Social influence**: The extent to which the user perceives that important others believe they should use the system. This may be less relevant in this context as usage is ultimately the user's decision..
4. **Facilitating conditions**: The degree to which the user believes that an organizational and technical infrastructure exists to support use of the system
5. **Behavioural intention**: The intention of the user to work with the artifact and integrate it into their daily or yearly operations.
6. **Use behaviour**: The actual usage behavior of the users when interacting with the artifact.

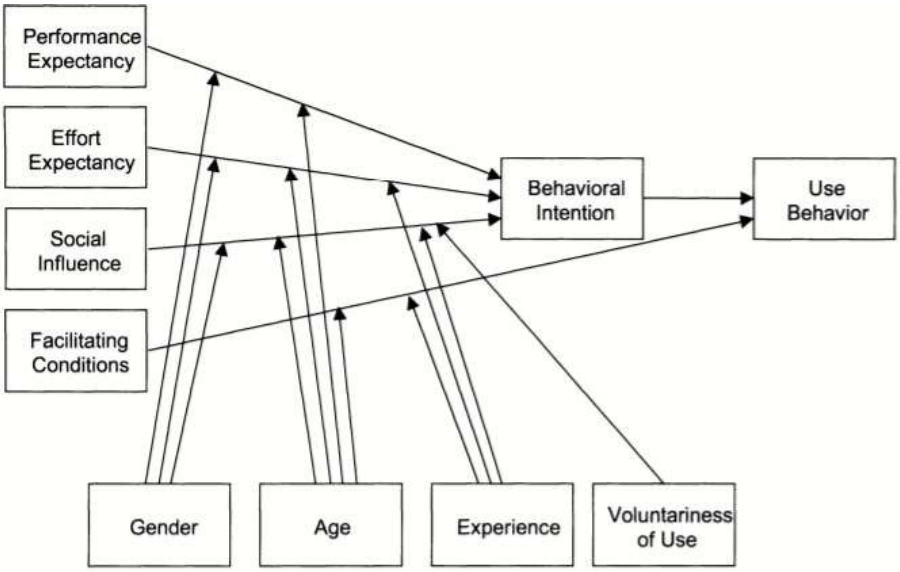


Figure H.3: The UTUAT Research Model.

The UTAUT model, illustrated in Figure H.3, also considers four additional variables that influence these six constructs. These variables help to understand the perspective of the interviewees. These variables are gender, age, experience, and voluntariness of use. By analyzing these constructs and variables, we can better understand the factors that contribute to the acceptance and use of the new technological tools introduced at

Company X. This holistic approach ensures that the tools are user-friendly and well-integrated into the existing organizational infrastructure.

H.3 The Survey

The evaluation is done by means of multiple interviews and a presentation in which the guidelines on how to the model can be used were described. After the presentation the interviews were conducted. The questions from this interview can be found in appendix I. There were three participants for this interview, all working in the logistics department.

For the interview, a five-level Likert scale is used. The answers the participant could be rated a strongly disagree, disagree, neutral, agree, strongly agree. The strongly disagree has a score of 1 and the strongly agree a score of 5. Thus, values between 1 and 2 reflect negative feedback, the value 3 reflect neutral feedback, and 4 till 5 reflect positive feedback.

Table H.1 shows the results of the survey. From this table, no negative feedback is seen, because no score lower than 3 is given. Therefore, we conclude that there is a positive opinion about both tools created for Company X and that these are generally accepted. We also see that the Behavioural Intention of Use is very high for both tools, which suggests that Company X finds the tools useful for their activities.

H.4 Summary

In summary, this chapter provided a brief overview of the tool design and discussed the evaluation approach for Company X. Based on a literature review, we identified the Unified Theory of Acceptance and Use of Technology (UTAUT) as a suitable method for evaluating the tool. This method helped us formulate the survey questions by focusing on specific constructs. We presented the evaluation results, which indicated that the tool is well-received and considered highly useful for Company X.

Nr.	**Type of Question**	**Score (1 - 5)**
1	PE-1	4
2	PE-2	5
3	PE-3	5
4	PE-4	5
5	EE-1	4
6	EE-2	4
7	EE-3	4
8	EE-4	2 (= 4 reversed question)
9	ATT-1	4
10	ATT-2	3
11	ATT-3	3
12	ATT-4	4
13	FC-1	4
14	FC-2	4
15	FC-3	3
16	FC-4	3
17	SE-1	4
18	SE-2	4
19	SE-3	4
20	BIU-1	5
21	BIU-2	5
22	BIU-3	5
Average Performance Expectancy		4.75
Average Effort Expectancy		4.00
Average Attitude Towards Technology		3.50
Average Facilitating Conditions		3.50
Average Self-Efficacy		4.00
Average Behavioural Intention of Use		5.00

Table H.1: Survey Results for Optimization Tool

Appendix I

Survey Questions

#	Category	Question (Q)
1	PE-1	I find the tool in Python useful for my job
2	PE-2	Using the tool in Python increases the effectiveness of my tasks
3	PE-3	Using the tool in Python improves the quality of my work
4	PE-4	Using the tool in Python improves the quality of the output of my work
5	EE-1	The interaction with the tool in Python is clear and understandable using the guidelines
6	EE-2	It's easy for me to get experienced with the tool in Python using the guidelines
7	EE-3	I find the tool in Python easy to use using the guidelines
8	EE-4	It takes too long to learn how to use the tool in Python, it's not worth it
9	ATT-1	Using the tool (in Python) is a good idea
10	ATT-2	The tool in Python makes work more interesting
11	ATT-3	Using the tool in Python is fun
12	ATT-4	I like working with a tool in Python
13	FC-1	I have the resources needed to use the tool in Python
14	FC-2	I have special and specific instructions for using the tool in Python
15	FC-3	A specific person or group can be reached for help with problems of the tool in Python
16	FC-4	Using the tool in Python is compatible with other aspects of my job
17	SE-1	I can complete a task if: no one is there to tell me what to do step by step
18	SE-2	I can complete a task if: I can call someone when I get stuck
19	SE-3	I can complete a task if: I get a lot of time to complete my task for which the tool was created in Python
20	BIU-1	I intend to use the tool in Python every time a new warehouse location problem comes up in at least the next 6 months

21	BIU-2	I predict to start using the tool in Python every time a new warehouse location problem comes up in at least the next 6 months
22	BIU-3	I plan to use the tool in Python every time a new warehouse location problem comes up in at least the next 6 months

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