Optimizing the transportation and external warehousing process of Euroma

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Master Thesis

Industrial Engineering and Management
Specialization: Production and Logistics Management

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Preface

This thesis marks the end of my master Industrial Engineering and Management at the University of Twente. During the master's, I followed the track Production and Logistics Management with the orientations (i) Supply Chain and Transportation Management, (ii) Manufacturing Logistics, and (iii) Operations Management in Healthcare. Prior to this master's, I followed the bachelor Industrial Engineering and Management at the University of Twente. During my time as a student, I acquired a lot of knowledge that I can now implement in practice. Furthermore, I have worked as a teaching assistant for 5 years, in which I could develop my explanation skills; I want to thank all lecturers for giving me this opportunity. I also published a paper[1] with Martijn Mes and Tim van Benthem, of which I am very proud. Finally, I have had a wonderful time as a student and enjoyed every second of it!

First of all, I would like to thank everyone at Euroma for their help and input regarding this research. Especially, I would like to thank my supervisor at Euroma, Pim Bax, for his guidance and trust in me; during my time of graduating at Euroma, I was already involved in several projects at Euroma to provide input using my research.

Second, I would like to thank my supervisors Martijn Mes and Marco Schutten for providing me with useful feedback to develop myself and improve the quality of this research. Furthermore, I would like to thank my fellow students and friends Tim van Benthem and Fabian Akkerman for the useful brainstorm sessions and for proofreading my research.

As of 1 March 2021, I am working for Euroma as a Logistics Engineer in which I am responsible for optimizing the transportation and external warehousing process and the implementation of the corresponding logistical changes.

I hope that you enjoy reading this research and I hope that this research can contribute to new research projects.

Mark Bergman
Enschede, August 18, 2021

[1] T.S. Van Benthem, M.M.G. Bergman, & M.R.K. Mes (2020). Solving a Bi-Objective Rich Vehicle Routing Problem with Customer Prioritization. In: Lalla-Ruiz E., Mes M., Voß S. (eds) Computational Logistics. ICCL 2020. Lecture Notes in Computer Science, vol 12433. Springer, Cham. https://doi.org/10.1007/978-3-030-59747-4_12

Management summary

Please note that pallet volumes and financial data are indexed. Currently, the configuration of the transportation and external warehousing process of Euroma consists of using 6 transportation companies and 7 external warehouses, leading to sub-optimal values for the KPIs "total costs", "sustainability", and "supply chain complexity". Production volumes of Euroma are expected to increase in the near future, i.e., in the coming three to five years, especially because of potential takeovers and the growth opportunities of Euroma. Therefore, the transportation and external warehousing process should be reconfigured to accommodate these increasing volumes. This results in the following main research question:

"What is the optimal configuration of the transportation and external warehousing process for the near future?"

To answer the main research question, we first conducted a literature review to identify similar problems in the literature. We found that the core of our problem is similar to the traditional fixed charge facility location problem. Inspired by this problem, we created a mathematical model that optimizes the transportation and external warehousing process. This mathematical model optimizes a multi-objective objective function with the KPIs "total costs", "sustainability", and "supply chain complexity". It decides on which transportation companies and external warehouses should be used and how the transportation movements between production locations and external warehouses should be configured. Furthermore, it decides on inventory levels of raw materials and finished goods in external warehouses, the delivery of raw materials to external warehouses, and the delivery of finished goods to external customers.

We performed several experiments with our mathematical model to determine the optimal configuration of the transportation and external warehousing process on different problem instances. First, the performance of the current configuration of the transportation and external warehousing process on the main problem instance was investigated. We conclude that this performance has the values €6,980,586, 162,971 kilometers, and 13 contracts on the KPIs "total costs", "sustainability", and "supply chain complexity", respectively. The optimal configuration of the transportation and external warehousing process found from our mathematical model comprises the values €5,303,098, 67,912 kilometers, and 6 contracts on the KPIs "total costs", "sustainability", and "supply chain complexity", respectively. This is an improvement of (i) at least €1,677,488 (31.6%) on the KPI "total costs", based on the conservative estimation of the storage costs of the initial inventory of raw materials and finished goods, (ii) 95,059 kilometers (58.3%) on the KPI "sustainability" and, (iii) 7 contracts (53.8%) on the KPI "supply chain complexity". Only 2 transportation companies are used; TC_3 and TC_6. Besides that, only 4 external warehouses are used; EW_5, EW_6, EW_7, and EW_10. Finally, we conclude that the main solution (i) is optimal from a total cost perspective, (ii) has a value of 11,511 kilometers higher than the optimal solution from a sustainability perspective, and (iii) has a value of 1 contract higher than the optimal solution from a supply chain complexity perspective.

We also performed several sensitivity analyses. First, we conclude that the impact of varying the number of time periods that a raw material or finished product is stored in an external warehouse on the KPIs "total costs", "sustainability", and "supply chain complexity" is minimal. Second, we conclude that the largest part of the solution configuration remains constant when varying (i) the demand for raw materials and finished goods, (ii) the number of occupied pallet locations, and (iii) the maximum number of trips per day with each transportation company. In case of capacity issues at transportation companies or external warehouses, additional transportation companies and external warehouses were used; TC_2 and EW_10. Third, we conclude that the main solution is fairly robust to changes in transportation costs of the corresponding transportation companies since a transportation costs decrease of at least 24% (in the case of TC_2) is required to change the solution configuration. The main solution is completely robust to changes in warehousing costs of these external warehouses, as a decrease of 100% in warehousing costs does not change the solution configuration. Finally, we conclude that the impact of product-related storage restrictions is relatively small with regard to the KPI "total costs" and there is no impact on the KPIs "sustainability" and "supply chain complexity" and that the solution configuration remains unaltered.

We first recommend investigating the possibilities of only using the transportation companies TC_3 and TC_6, while using the external warehouses EW_5, EW_6, EW_7, and EW_10. We advise Euroma to make customer-specific analyses to determine whether it is beneficial to make these proposed logistics switches, e.g., storing the products of this customer in the external warehouse EW_5 instead of in the external warehouse EW_1. Of course, the KPIs "total costs", "sustainability", and "supply chain complexity" should be examined, but practical KPIs such as customer preferences, product-related storage and transportation constraints, and IT configuration constraints should also be taken into account. After a switch between transportation companies or external warehouses has been made, we advise Euroma to organize periodical meetings, e.g., twice per week, with their new partners for the first couple of weeks to ensure that operational issues, that logically arise after these logistical switches, are tackled directly to optimally benefit from the logistical switch. Finally, Euroma should run our model at least once a year, preferably at a fixed date after (i) the yearly demand and production forecasts are made and (ii) transportation companies and external warehouses updated their cost and capacity information, to determine whether the configuration of the transportation and external warehousing process is still optimal. In case a change in (i) production quantities, (ii) demand, or (iii) cost and capacity information of transportation companies and external warehouses is detected, Euroma should directly run the model again to determine whether a direct change in the configuration of the transportation and external warehousing process is necessary.

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1. Introduction

Please note that pallet volumes and financial data are indexed. This chapter introduces the research and the context that this research takes place in. Section 1.1 introduces Euroma, the company at which the research is conducted. Section 1.2 gives a brief introduction to the logistical processes at Euroma. Section 1.3 presents the case description and the corresponding problem context. Section 1.4 presents the problem approach and the corresponding research questions. Finally, Section 1.5 provides a summary of the studied problem and problem approach and an overview of the chapters of this thesis.

1.1. Introduction to Euroma

Euroma was founded in 1899 by Antonij ten Doesschate (Euroma, 2021d). The company was located in Zwolle and the company produced herbs and spices. The name Euroma was first used in 1966 and kept on being used from that point in time. An important milestone in the history of Euroma is the start of using the Prima Pura treatment in 1991, which is a unique steam treatment where the herbs and spices are disinfected in a natural manner.

To improve Euroma's market position, Euroma took over Intertaste, which resulted in Euroma having a top position in the European herbs and spices market and a number one position in the Dutch herbs and spices market. Figure 1.1 shows the new state-of-the-art production location in Zwolle, which Euroma started using at the beginning of 2019.

At this production location, dry products are produced and packaged, such as seasonings, single herbs and spices, and dry sauces (Euroma, 2021a). The second production location is based in Schijndel, where ambient liquids are produced and packaged, such as ambient dressings, mayonnaises, and satay sauces. The third production location is based in Nijkerk, where fresh liquids are produced and packaged, such as fresh dressings and fresh sauces. The final production location is based in Wapenveld, where dry products are produced and packaged, such as seasonings, single herbs and spices, and dry sauces.

Currently, Euroma has around 500 employees and is able to generate a turnover of around 220 million euros per year (Euroma, 2021b). Euroma's mission is to retain a top 3 position in the European herbs and spices market and to deliver their products to all the big food companies.

Figure 1.1 | The new state-of-the-art production location of Euroma in Zwolle

1.2. Introduction to the logistical processes at Euroma

The logistical operations of Euroma can be divided into six sequential logistical processes. These logistical processes are the following: (i) external warehousing of raw materials, (ii) transportation of raw materials, (iii) internal warehousing of raw materials, (iv) producing the products, (v) transportation of finished goods, and (vi) external warehousing of finished goods. These logistical processes are further elaborated upon below.

The first logistical process comprises the external warehousing of raw materials. Raw materials are either stored in external warehouses that are in the external warehouses' portfolio of Euroma or in internal warehouses of the suppliers. The second logistical process comprises the transportation of these raw materials to the production locations of Euroma. When raw materials arrive by truck, the load, as well as the truck, is inspected, for example by investigating whether pests are present. The third logistical process comprises the internal storage of the raw materials. When the inspection of both the load and trucks are completed and approved, the load is registered in the warehouse management system and the ERP system of Euroma, which is called LN. After that, the load is stored in the high-rise warehouse, which uses an automated storage system. Figure 1.2 shows the high-rise warehouse (in the building process).

Figure 1.2 | The building process of the high-rise warehouse

The fourth logistical process comprises the production of the products. When the raw materials are requested for production, the automated storage system transports the raw materials to the production hall. In this production hall, several production lines are used to produce all kinds of products. When production is finished, the automated storage system transports the products to the (i) expedition hall where the finished products are placed that will be transported or (ii) to the high-rise warehouse. The fifth logistical process comprises the transportation of the finished products. Products that are sent to the expedition hall are transported to external warehouses by trucks of contracted transportation companies. The products are then stored in these external warehouses, which is the sixth logistical process of Euroma. At the current production locations, there is not enough storage space for the finished products. Therefore, external warehouses are used.

1.3. Case description and problem context

Figure 1.3 shows a schematic overview of the logistical processes at Euroma, which are described in Section 1.2. The focus area of this research is highlighted in blue.

Figure 1.3 | Schematic overview of the logistic processes and the focus area

As depicted in Figure 1.3, this study is positioned in the transportation process and external warehousing process of both the raw materials and finished goods. The configuration of the transportation and external warehousing process consists of two main decisions. When raw materials or finished goods should be stored in an external warehouse, decisions should be made (i) in which external warehouse these are stored and (ii) which transportation company transports these to the production location or external warehouse. Only external warehouses in the Netherlands that are not linked to suppliers of raw materials are considered in this research. This means that suppliers that produce raw materials for Euroma and store these raw materials in their own warehouse are excluded from this study. Furthermore, optimal inventory levels, including safety stocks, at external warehouses are not considered. Finally, we use the production planning of the production locations as input data for our research, i.e., we do not determine the production planning in our research.

Currently, the decisions regarding (i) which external warehouses are used to store raw materials and finished goods and (ii) the corresponding transportation process configuration are not based on a structured analysis of the transportation and external warehousing process, taking into account KPIs such as costs and sustainability. Furthermore, there are no overviews of the transportation and external warehousing process regarding the (i) decision rules, (ii) cost agreements with transportation companies and external warehouses, (iii) volumes that are transported between production locations and external warehouses by transportation companies, and (iv) total costs. Because there is no overview of the transportation and external warehousing process, it is not possible to measure the performance of this process and it is also hard to identify improvement opportunities.

In the near future, i.e., in the coming three to five years, Euroma expects that their production volumes increase, especially because of potential takeovers and their growth opportunities. Therefore, the transportation and external warehousing process should be reconfigured to accommodate these increasing volumes. We use a structured approach that optimizes the transportation and external warehousing process and include the KPIs total costs and sustainability in this optimization study. The results of the optimization study prescribe the configuration of the transportation and external warehousing process. This includes (i) strategic decisions, indicating which external warehouses and transportation companies should be used, (ii) tactical decisions, indicating how many trucks of the transportation companies should be included in the portfolio for a certain time period and how many pallets locations should be reserved at external warehouses, and (iii) operational decisions, indicating the transportation movements of transportation companies between production locations and external warehouses for both the raw materials and finished goods.

Table 1.1 shows an overview of the strategic, tactical, and operational decisions in this study.

Decision	Transportation companies	External warehouses
Strategic	Which transportation companies should be used?	Which external warehouses should be used?
Tactical	How many trucks should be used in each time period?	How many pallet locations should be reserved in each time period?
Operational	Which transportation movements should be made by transportation companies between production locations and external warehouses?	

Table 1.1 | Strategic, tactical, and operational decisions

Regarding the strategic decisions, it is possible to (i) change the external warehouses' portfolio, and (ii) to change the portfolio of the contracted transportation companies. For the tactical decisions, it is important to indicate the number of trucks that should be used for a certain time period, as the number of trucks to be reserved cannot always be changed in a small time period. For the operational decisions, it is important to differentiate between transportation movements, i.e., which transportation movements have priority over other transportation movements.

The research has the following aim:

"Optimize the transportation and external warehousing process for the near future, considering possible changes in the current portfolio of external warehouses and transportation companies"

Conducting this research gives Euroma an overview of how the current transportation and external warehousing process is configured and an overview of the strategic, tactical, and operational decisions that optimize the transportation and external warehousing process in the near future.

1.4. Problem approach and research questions

The problem approach is divided into four phases. Each phase answers several research questions. The answers to these research questions are used to answer the main research question, which is formulated as follows:

"What is the optimal configuration of the transportation and external warehousing process for the near future?"

1.4.1. Phase 1 | Analyzing the logistical processes at Euroma

In the first phase, the transportation and external warehousing process of Euroma is analyzed. In our analysis, an overview of the current configuration of the transportation and external warehousing process is created. This overview includes (i) cost overviews of the transportation companies and external warehouses, (ii) a data analysis on the volumes transported between production locations and external warehouses by several transportation companies, and (iii) an overview of the performance on the transportation and external warehousing process which is measured with several KPIs.

To acquire data for this analysis, the production floor is visited and interviews with the employees, of which the daily activities are important to understand the logistical processes, are conducted. Besides that, interviews are conducted with employees from the department that this study takes place in, the logistics department, to understand the current configuration of the transportation and external warehousing process. Furthermore, several data analyses are conducted to create an overview of the current transportation and external warehousing process.

The following research questions are included in this phase:

- Which production locations are used by Euroma?
    - Which volumes of raw materials are transported to these production locations?
    - Which volumes of finished goods are transported from these production locations to external warehouses?
- Which transportation companies are used by Euroma?
    - Which routes are currently driven by these transportation companies?
    - Which costs are incurred for these routes?
    - What is the transportation capacity of these transportation companies?
    - What volumes are transported by these transportation companies?
- Which external warehouses are used by Euroma?
    - Which costs are incurred at these external warehouses?
    - How many pallet spaces are currently occupied by Euroma?
    - What volumes of raw materials are transported from these external warehouses to the production locations of Euroma?
    - What volumes of finished goods are transported to these external warehouses?
- Which KPIs are used to monitor the performance of the transportation and external warehousing process and what is the performance on these KPIs?

1.4.2. Phase 2 | Identifying optimization methods by a literature review

In the second phase, a literature review is conducted to identify how the optimal configuration of the transportation and external warehousing process can be found. First, the translation of (parts of) the studied problem to theoretical problems is investigated and the similarities and gaps between the studied problem and these theoretical problems are identified. Finally, problem-solving approaches for these theoretical problems are studied.

The following research questions are included in this phase:

- To which theoretical problem(s) can (parts of) the studied problem be translated?
- What are the similarities and gaps between the studied problem and theoretical problems?
- Which optimization methods are used to solve these theoretical problems?

1.4.3. Phase 3 | Applying and implementing optimization methods

In the third phase, we design an optimization model to optimize the transportation and external warehousing process. We design (parts of) this optimization model based on the findings from the literature review. We then implement our optimization model and optimize the transportation and external warehousing process regarding the KPIs that are identified in the first phase. After implementing our optimization model, several experiments are conducted, including sensitivity analyses, to provide a reliable advice to Euroma. An overview of the strategic, tactical, and operational decisions that configures the transportation and external warehousing process is created, as well as a dashboard that visualizes the expected performance of the transportation and external warehousing process in the near future.

The following research questions are included in this phase:

- Which experiments should be performed to analyze several future scenarios?
- What performance can be expected from certain strategic, tactical, and operational decisions?

1.4.4. Phase 4 | Writing an implementation plan for Euroma

In the fourth phase, an implementation plan is proposed that should be used for implementing our advice at Euroma. The following research questions are included in this phase:

- How can our advice be implemented at Euroma?
- What are the consequences of our implementation for stakeholders?

1.5. Summary

In our problem, a set of production locations, external warehouses, and transportation companies are considered. Decisions should be made on (i) which transportation companies and which external warehouses should be used, (ii) how the routes for transporting raw materials and finished goods between production locations and external warehouses should be configured, and (iii) which transportation companies should be assigned to these transportation movements.

The transportation and external warehousing process should be optimized on several KPIs and several constraints should be taken into account:

- Finished goods that are produced at the production location should be stored in external warehouses and therefore be transported to these external warehouses.
- Raw materials that are required for the production process should be transported from the external warehouses to the correct production locations.
- The flow of raw materials and finished goods through the external warehouses should be managed in such a way that the warehouse capacity is not exceeded.
- During a certain period, a limited number of pallets can be transported by transportation companies, indicated by the number of trucks that are available during that period.

To optimize the transportation and external warehousing process, a problem approach is divided into four phases. In the first phase, the current transportation and external warehousing process is analyzed. This analysis includes (i) cost overviews of the transportation companies and external warehouses and (ii) a data analysis on the volumes transported between production locations and external warehouses by several transportation companies, and (iii) an overview of the performance on the transportation and external warehousing process which are measured with several KPIs. This phase is discussed in Chapter 2 of this thesis.

In the second phase, a literature review is conducted to identify how the optimal configuration of the transportation and external warehousing process can be found. First, the translation of (parts of) the studied problem to theoretical problems is investigated and the similarities and gaps between the studied problem and these theoretical problems are identified. After that, problem-solving approaches for these theoretical problems are studied. This phase is discussed in Chapter 3 of this thesis.

In the third phase, we design an optimization model to optimize the transportation and external warehousing process. We design (parts of) this optimization model based on the findings from the literature review. We then implement our optimization model and optimize the transportation and external warehousing process regarding several KPIs that are identified in the first phase. This part of the third phase is discussed in Chapter 4 of this thesis.

After our optimization model is implemented, several experiments are conducted, including sensitivity analyses, to provide a reliable advice to Euroma. An overview is presented of the strategic, tactical, and operational decisions that configure the transportation and external warehousing process, as well as a dashboard that visualizes the expected performance of the transportation and external warehousing process in the near future. This part of the third phase is discussed in Chapter 5 of this thesis.

In the fourth phase, we propose an implementation plan that should be used for implementing our advice at Euroma. This phase is discussed in Chapter 6 of this thesis.

Table 1.2 provides an overview of the outline of the thesis and the relation between the phases and the chapters in this thesis.

Phase	**Description**	**Chapter**
1	Analyzing the logistical processes at Euroma	Chapter 2
2	Identifying optimization methods by a literature review	Chapter 3
3a	Applying and implementing optimization methods	Chapter 4
3b	Performing experiments with our optimization model	Chapter 5
4	Proposing an implementation plan to Euroma	Chapter 6

Table 1.2 | Outline of the thesis

2. Context analysis

Please note that pallet volumes and financial data are indexed. In this chapter, a context analysis is conducted to further elaborate upon the transportation and external warehousing process of Euroma. Euroma has four production locations, which are based in Zwolle, Schijndel, Nijkerk, and Wapenveld. The portfolio of external warehouses consists of EW_1, EW_2, EW_3, EW_4, EW_5, EW_6, and EW_7. Transportation movements between the production locations and external warehouses are fulfilled by the transportation companies TC_1, TC_2, TC_3, TC_4, TC_5, and TC_6. Figure 2.1 presents the geographical locations of the production locations of Euroma and the external warehouses that are used by Euroma.

Figure 2.1 | Production locations and external warehouses of Euroma

Section 2.1 discusses the production locations of Euroma. Section 2.2 elaborates upon the portfolio of contracted transportation companies. Section 2.3 elaborates upon the portfolio of external warehouses. Section 2.4 discusses the KPIs that are used to measure the performance of the transportation and external warehousing process. Section 2.5 presents an overview of the transportation and external warehousing process. Finally, Chapter 2 is summarized in Section 2.6.

2.1. The production locations of Euroma

As discussed in Section 1.1, Euroma possesses four production locations that are based in Zwolle, Schijndel, Nijkerk, and Wapenveld. The oldest production location of Euroma is based in Wapenveld. Figure 2.2 depicts this production location. Since 1970, the production location is operational and is now part of the industrial heritage of the Netherlands. However, Euroma experiences two major disadvantages of this production location.

Figure 2.2 | The production location in Wapenveld

The first disadvantage is related to inventory placement (Euroma, 2021c). As the inventory of raw materials for this production location is spread over different warehouses, a lot of transportation movements have to be made to Wapenveld. This production location is difficult to reach, which increases the transportation times, and in combination with a large number of transportation movements, this results in high transportation costs. The second disadvantage is related to the layout of the production location. The current layout limits Euroma to optimally configure internal processes and it is hard to keep satisfying future requirements of the food industry. Due to these disadvantages, most of the production lines in Wapenveld are currently being transferred to the production location in Zwolle. Only two production lines will remain in Wapenveld. This means that most of the demand of the production location in Wapenveld will be covered by the production location in Zwolle in the future.

Figure 2.3 shows the transportation volumes (in europallets) of the raw materials and finished goods per production location. These include transportation movements of (i) raw materials from external warehouses to these production locations and (ii) finished goods from these production locations to external. From now on, we refer to europallets as “pallets”. This data is from the period 01-01-2020 until 05-11-2020. The data is extracted from LN and reports and overviews from transportation companies.

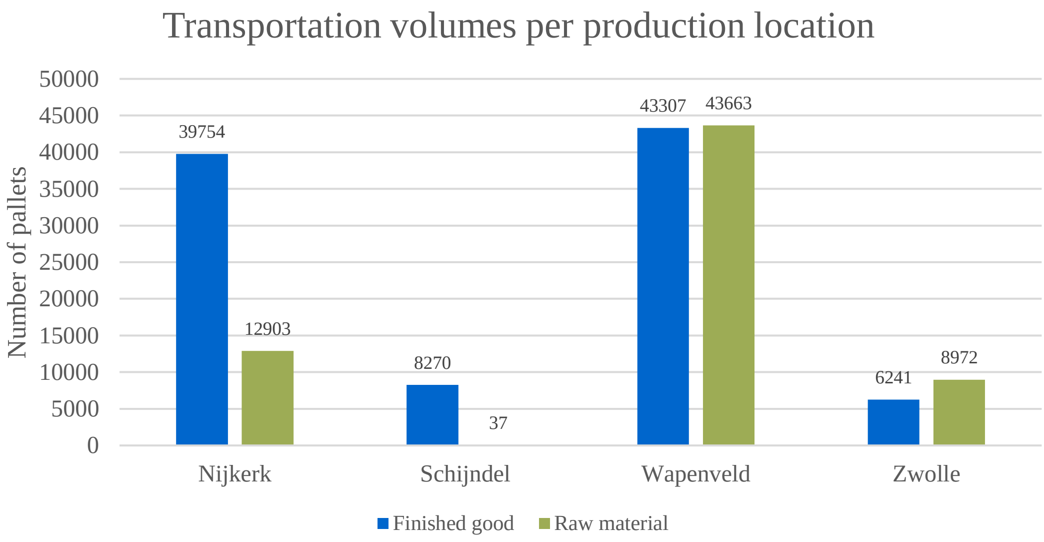

Figure 2.3 | Transportation volumes per production location

We observe that the greatest number of pallets comes from the transportation movements related to the production location in Wapenveld, having a total of around 87,000 pallets. A large part of these transportation movements will be assigned to the production location in Zwolle after most of the production lines of the production location in Wapenveld are transferred to the production location in Zwolle. Furthermore, a lot of the products produced at the production location of Nijkerk are sent to external warehouses. Finally, we observe that a relatively small number of raw materials are sent to the production locations in Nijkerk and Schijndel. Both production locations are mostly delivered directly from the suppliers, without the use of an external warehouse.

2.2. The portfolio of transportation companies

This section further elaborates upon the portfolio of transportation companies. As discussed in Section 1.2, these transportation companies transport raw materials and finished goods between production locations and external warehouses.

There are three types of transportation movements: (i) transporting raw materials from an external warehouse to a production location, (ii) transporting finished goods from a production location to an external warehouse, and (iii) transporting finished goods from an external warehouse to another external warehouse. These transportation movements consist of the following four activities: (i) outbound handling, i.e., loading the pallets from the production location or external warehouse into the truck, (ii) transportation of the pallets, (iii) waiting at the external warehouse or production location for (un)loading the pallets, and (iv) inbound handling, i.e., unloading the pallets from the truck to the production location or external warehouse. Inbound handling and outbound handling both take approximately 45 minutes. Waiting time occurs when trucks have to wait at the dock when (i) the dock is still occupied by another truck or (ii) warehouse or production location personnel is not yet able to (un)load the pallets. This waiting time takes approximately 30 minutes.

The transportation movements are made by 6 different transportation companies, namely (i) TC_1, (ii) TC_2, (iii) TC_3, (iv) TC_4, (v) TC_5, and (vi) TC_6. TC_1, TC_3, TC_4, TC_5, and TC_6 possess their own external warehouses, which are included in their transportation movements. The external warehouses are discussed in Section 2.3.

Three types of cost structures are used for determining the transportation costs related to a transportation movement. The first option is that transportation companies charge fixed costs per trip. For example, TC_1 charges €618.06 for a trip between the production location in Zwolle and their own external warehouse. So, these costs are independent of the load and the transportation time. The second option is that transportation companies charge costs per hour of transportation. For example, TC_2 charges €229.02 per hour of transportation for a transportation movement between the production location in Zwolle and the external warehouse TC_5. The third option is that transportation companies charge costs per pallet. Often, volume-rated prices are used. For example, if the load concerns 15 pallets, TC_5 charges €90.22 per pallet, and if the load concerns 25 pallets, TC_5 charges €74.28 per pallet for a transportation movement between the production location in Schijndel and their own external warehouse. We then calculate the weighted average costs per pallet. In this case, this TC_5 charges on average €82.30 per pallet for this transportation movement. TC_6 does not use volume-related prices; they charge a fixed cost of €16.50 per pallet for transportation movements between the production location in Nijkerk and their own external warehouse.

Table 2.1 shows more information about the transportation companies. It shows the routes that are traveled by the transportation companies and the costs that are charged for these routes. These data are extracted from the contracts between the transportation companies and Euroma.

Transportation company	Route	Costs
TC_1	Zwolle ↔ EW_1	€618.06 / trip
	Wapenveld ↔ EW_1	€618.06 / trip
TC_2	Zwolle ↔ EW_5	€229.02 / hour
	Wapenveld ↔ EW_5	€229.02 / hour
	EW_6 → Zwolle	€46.13 / pallet
	EW_6 → Wapenveld	€46.13 / pallet
TC_3	Zwolle → EW_2	€952.61 / trip
	Schijndel → EW_2	€930.20 / trip
	Wapenveld → EW_2	€60.95 / pallet
	Nijkerk → EW_2	€731.64 / trip
	EW_6 → Nijkerk	€838.20 / trip
TC_4	Zwolle ↔ EW_3	€21.48 / pallet
	Nijkerk ↔ EW_3	€21.48 / pallet
	EW_3 → EW_2	€1069.30 / trip
TC_5	Schijndel ↔ EW_4	€82.30 / pallet
TC_6	Nijkerk ↔ EW_7	€16.50 / pallet

Table 2.1 | Information about transportation companies

The trucks of TC_6 have a capacity of 32 pallets, the trucks of the other transportation companies have a capacity of 33 pallets. The transportation companies TC_2, TC_3, and TC_4 also charge costs for waiting time. These waiting costs are €229.02 per hour, €220.87 per hour, and €148.50 per hour, respectively. The transportation movements coming from the production location in Schijndel are different from other transportation movements in the sense that these concern the transportation of refrigerated and frozen goods, which are also stored in external warehouses where cold stores and freezers are used. Both TC_5 and TC_3 are able to transport refrigerated and frozen goods and store them in their own external warehouse. Besides that, TC_4 transports finished goods from their own external warehouse to the external warehouse EW_2. TC_4 performs additional activities on certain finished goods of Euroma in their own warehouse EW_3, coming from the production locations in Zwolle and Nijkerk. After these additional activities have been completed, they use their own trucks to transport these products to the external warehouse EW_2.

Figure 2.4 shows the transportation volumes (in pallets) of the raw materials and finished goods per transportation company. This data is from the period 01-01-2020 until 05-11-2020. The data is extracted from LN and reports and overviews from transportation companies.

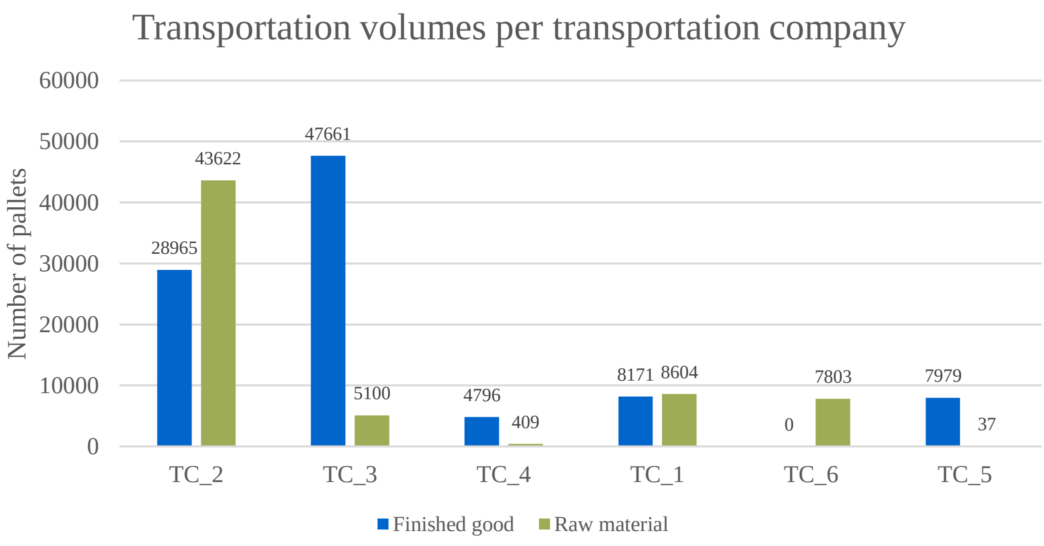

Figure 2.4 | Transportation volumes per transportation company

We observe that TC_2 transports the largest number of pallets, having a total of around 72,000 pallets, followed by TC_3 having a total of around 52,000 pallets. Furthermore, we also observe that transportation volumes are much smaller for the other transportation companies.

Table 2.2 presents a summary of the transportation costs of the transportation companies, where the transportation costs are calculated as the average costs per pallet per hour of transportation. This transportation time also includes inbound handling time, waiting time, and outbound handling time. For each transportation movement, an almost full truckload of 28 pallets is considered, based on the expert opinion of the logistics manager and logistics officers.

Transportation company	Average transportation price (per pallet per hour)
TC_3	€10.43 – €20.72
TC_2	€8.18 – €13.17
TC_1	€6.96 – €7.33
TC_4	€9.01 – €11.35
TC_5	€34.06
TC_6	€8.12

Table 2.2 | Average transportation price per transportation company

We observe that the average transportation prices are fairly constant for TC_1 among different transportation movements. Besides that, TC_1 is, in this case, the cheapest transportation company in the portfolio of Euroma. We identify large differences between the transportation prices within different routes of TC_3 and TC_2, indicating that these transportation companies charge highly varying costs on different routes. TC_5 is very expensive compared to the other transportation companies, although it should be taken into account that TC_5 transports refrigerated and frozen goods.

2.3. The portfolio of external warehouses

This section elaborates on the portfolio of external warehouses. As discussed in Section 1.2, external warehouses are used to store raw materials and finished goods, as storage capacity at the production locations is not sufficient.

In these external warehouses, three activities are performed: inbound handling, storage, and outbound handling. These activities are performed by the following 7 external warehouses: (i) EW_1, (ii) EW_2, (iii) EW_3, (iv) EW_4, (v) EW_5, (vi) EW_6, and (vii) EW_7. EW_1, EW_2, EW_3, EW_4, and EW_7 have their own fleet, while EW_5 and EW_6 do not have their own fleet. Most external warehouses are used to store both raw materials and finished goods, while EW_2 currently only stores finished goods and EW_6 and EW_7 only store raw materials. Regarding storage costs, there are two types of cost structures. In the first cost structure, the external warehouse charges fixed costs per pallet per week, looking at the maximum inventory level of that week. For example, EW_1 charges €4.39 per pallet per week. In the second cost structure, the external warehouse reserves a number of pallet spaces for Euroma and then charges a fixed cost per week. For example, EW_5 charges €7,095 per week for reserving 3,386 pallet spaces for Euroma. We then calculate the average costs per pallet per week, which is €2.10 in this case.

When raw materials are sent from external warehouses to the production locations, outbound handling costs, i.e., costs for loading the pallets into the truck, are charged by the external warehouse. When finished goods are sent from production locations to the external warehouses, inbound handling costs, i.e., costs for unloading the pallets from the truck into the warehouses, are charged by the external warehouse.

Table 2.3 shows more information on these external warehouses. It shows the inbound handling costs, storage costs, outbound handling costs, location, and the approximate number of pallet spaces that are occupied by Euroma in November 2020. Because the inbound handling costs and outbound handling costs are the same for all external warehouses, these costs are grouped as "handling costs" in Table 2.3. These data are extracted from the contracts between the external warehouses and Euroma and reports and overviews of the external warehouses.

External warehouse	Handling costs (per pallet)	Storage costs (per pallet per week)	Location	Pallet spaces
EW_1	€8.25	€4.39	The Netherlands	2,985
EW_2	€9.77	€4.39	The Netherlands	10,120
EW_3	€3.70	€4.85	The Netherlands	823
EW_4	€8.09	€7.62	The Netherlands	836
EW_5	€8.25	€2.10	The Netherlands	8,325
EW_6	€16.50	€5.38	The Netherlands	708
EW_7	€9.90	€3.80	The Netherlands	1,065

Table 2.3 | Information about external warehouses

We observe that EW_3 is very cheap in comparison to other external warehouses, which is caused by the fact that they charge more for performing the additional activities for several products, such as co-packing. Furthermore, we observe that EW_4 and EW_6 are relatively expensive compared to the other external warehouses. Besides that, we observe that a large number of pallets are stored in the warehouses of EW_2 and EW_5 in comparison to other external warehouses.

Figure 2.5 shows the transportation volumes (in pallets) of the raw materials and finished goods per external warehouse that are included in the transportation movements between production locations and external warehouses. This data is from the period 01-01-2020 until 05-11-2020. These data are extracted from LN and reports and overviews from transportation companies.

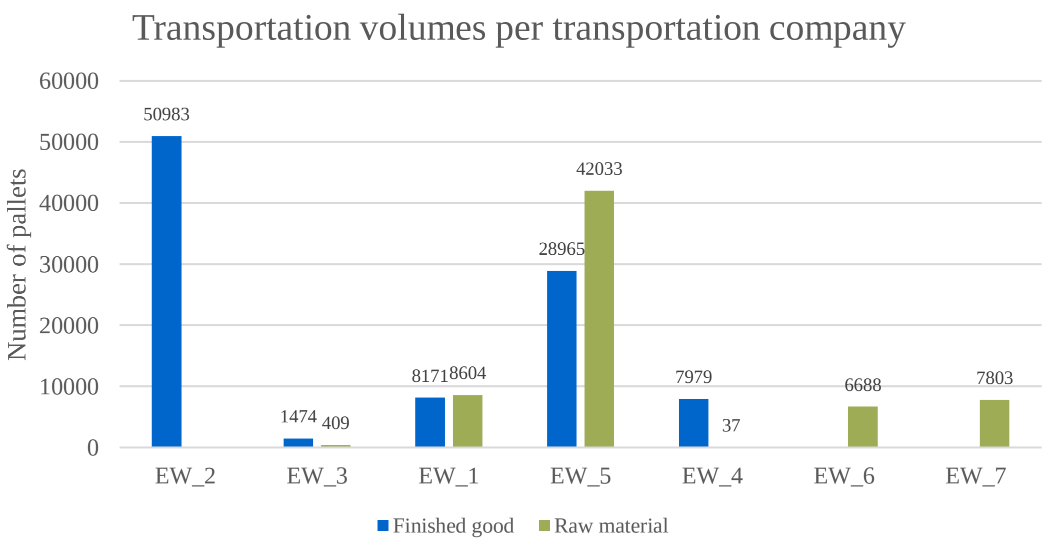

Figure 2.5 | Transportation volumes per external warehouse

We observe that the largest number of pallets are related to the external warehouse of EW_5, namely around 71,000 pallets. Furthermore, around 51,000 pallets with finished goods are stored in the external warehouse EW_2. We also observe that the storage volumes are significantly lower for the other external warehouses.

2.4. The KPIs that are used by Euroma

To measure the performance of the transportation and external warehousing process, Euroma uses three KPIs: total costs, sustainability, and supply chain complexity. The first KPI "total costs" is measured by the total costs involved in the transportation and external warehousing process. It is important for Euroma to minimize the total costs of the transportation and external warehousing process, as long as the agreed service levels and deadlines are met. The second KPI "sustainability" is measured by the number of driven kilometers. Euroma cares about the environment and wants to act in a sustainable manner; therefore, they want to minimize CO_2 emissions by minimizing the number of kilometers traveled by their contracted transportation companies (Euroma, 2021e). The third KPI "supply chain complexity" is measured by the number of contracted transportation companies and external warehouses. Minimizing the supply chain complexity is important for Euroma. When the supply chain complexity is high, there are a lot of contracted transportation companies and external warehouses. This results in having a lot of different contracts, which makes it difficult to manage the supply chain. When the supply chain complexity is low, i.e., fewer contracts are used, it is easier to manage the supply chain and economies of scale can possibly be exploited.

2.5. The transportation and external warehousing process

This section presents an overview of the transportation and external warehousing process. It presents (i) the transportation movements, (ii) cost overviews of the transportation and external warehousing process, (iii) the kilometers traveled by transportation companies, and (iv) the supply chain complexity.

As discussed earlier, several transportation movements occur between production locations and external warehouses. Raw materials are transported from external suppliers to external warehouses 6 weeks prior to when these are used for production, i.e., raw materials are stored in the external warehouse for 6 weeks. These 6 weeks are chosen based on safety stock considerations, i.e., these raw materials can be used for production in case demand is higher than expected or when raw materials are not supplied in time to the external warehouse. After 6 weeks of storing the raw materials, these are transported to the production locations, where these are used for production. These are stored in the internal warehouses of the production locations as short as possible because of limited storage capacity in the internal warehouses at production locations. The same holds for finished goods. The finished goods are produced 6 weeks prior to when these are requested by the external customers. These 6 weeks are based on safety stock considerations, i.e., these finished goods can serve as a backup when Euroma suffers from production failures or when finished goods do not meet quality standards. After 6 weeks of storing the finished goods, these are transported to the external customers. These are stored in the internal warehouses of these customers as short as possible because of limited storage capacity in the internal warehouses at production locations.

There is, however, an exception for the finished goods that are sent from the production locations in Zwolle and Nijkerk to the external warehouse EW_2 after additional activities have been performed and completed at the external warehouse EW_3. In this case, both inbound and outbound handling costs are charged by EW_3, and these products are stored in the external warehouse EW_3 for at most 1 week.

Figure 2.6 shows an overview of the transportation volumes between production locations and external warehouses in the period 01-01-2020 until 05-11-2020. The data are extracted from LN and reports and overviews from transportation companies.

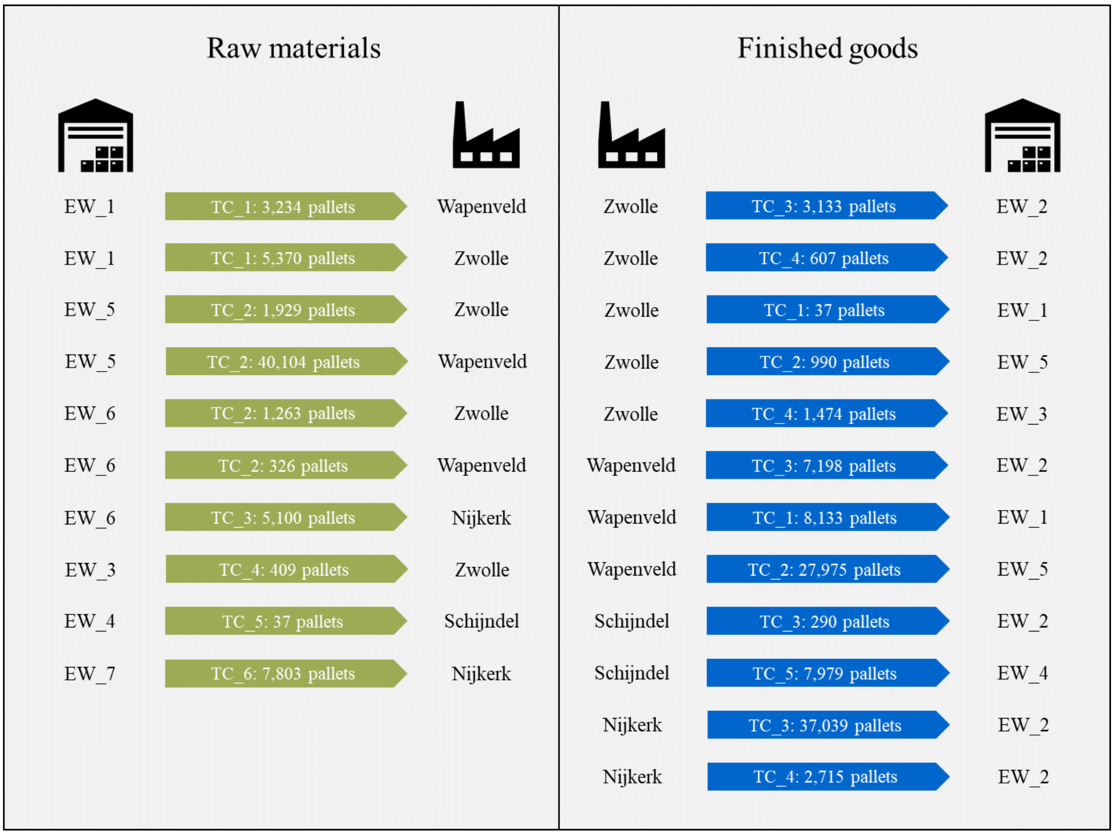

Figure 2.6 | Overview of the transportation movements

In total, these transportation volumes include around 163,000 pallets, of which 66,000 are pallets containing raw materials and 97,000 are pallets containing finished goods. The transportation movements can also be translated into kilometers that are traveled by transportation companies. Table 2.4 shows the number of driven kilometers by each transportation company in the period 01-01-2020 until 05-11-2020.

Transportation company	Kilometers driven
TC_1	79,592
TC_2	11,452
TC_1	25,515
TC_4	10,421
TC_5	4,021
TC_6	64
Total	**131,063**

Table 2.4 | Kilometers driven by transportation companies

The largest number of kilometers are traveled by TC_3 since the transportation movements of TC_3 have long travel distances and a large part of the transportation movements arises from TC_3. However, a large part of the transportation movements also arises from TC_2. Still, the number of kilometers driven by TC_2 is relatively low, since the transportation movements of TC_2 have short travel distances. The total number of kilometers driven is 131,063, which comprises the KPI "sustainability" that Euroma uses to measure the performance of the transportation and external warehousing process. When looking at the CO2 emission, we find that trucks emit approximately 900g of CO2 per kilometer (Ambel, 2021), which in this case comprises a total emission of 117,957 kg of CO2.

The transportation movements can also be translated into transportation costs. Table 2.5 presents the transportation costs in the period 01-01-2020 until 05-11-2020.

Transportation company	Transportation movement	Number of pallets	Costs
TC_3	Zwolle → EW_2	3,133	€ 54,215
	Wapenveld → EW_2	7,198	€ 212,353
	Schijndel → EW_2	290	€ 8,598
	Nijkerk → EW_2	37,039	€ 506,931
	EW_6 → Nijkerk	5,100	€ 78,737
	Total	**52,760**	**€ 860,833**
TC_2	Zwolle → EW_5	990	€ 9,279
	Wapenveld → EW_5	27,975	€ 218,829
	EW_5 → Zwolle	1,929	€ 17,222
	EW_5 → Wapenveld	40,104	€ 311,086
	EW_6 → Zwolle	1,263	€ 28,886
	EW_6 → Wapenveld	326	€ 7,515
	Total	**72,587**	**€ 592,816**
TC_1	Zwolle → EW_1	37	€ 618
	Wapenveld → EW_1	8,133	€ 82,202
	EW_1 → Wapenveld	3,234	€ 32,757
	EW_1 → Zwolle	5,370	€ 54,389
	Total	**16,775**	**€ 169,966**
TC_4	Zwolle → EW_2	607	€ 17,955
	Zwolle → EW_3	1,474	€ 16,176
	Nijkerk → EW_2	2,715	€ 80,318
	EW_3 → Zwolle	409	€ 4,516
	Total	**5,205**	**€ 118,964**
TC_5	Schijndel → EW_4	7,979	€ 298,509
	EW_4 → Schijndel	37	€ 1,399
	Total	**8,017**	**€ 299,908**
TC_6	EW_7 → Nijkerk	7,803	€ 58,526
	Total	**7,803**	**€ 58,526**
		Total	**€ 2,101,013**

Table 2.5 | Transportation costs

The total transportation costs in the period 01-01-2020 until 05-11-2020 comprise €2,101,013. A large part of the transportation costs arises from the transportation movements of TC_3 and TC_2 since these transportation companies transport the most pallets. When investigating the transportation costs of the other transportation companies, we observe that TC_5 has the highest transportation costs while the number of pallets transported is relatively low. This is caused by the high transportation price in comparison to other transportation companies, as depicted in Table 2.2.

The transportation movements can also be translated into external warehousing costs. Table 2.6 presents the external warehousing costs in the period 01-01-2020 until 05-11-2020.

External warehouse	Activity	Number of pallets	Costs
EW_1	Inbound handling	8,171	€ 30,641
	Storage	16,775	€ 200,797
	Outbound handling	86,04	€ 32,266
		Total	**€ 263,703**
EW_2	Inbound handling	50,983	€ 91,004
	Storage	50,983	€ 610,264
	Outbound handling	0	€ 0
		Total	**€ 701,268**
EW_3	Inbound handling	4,796	€ 8,057
	Storage	5,205	€ 32,240
	Outbound handling	3,731	€ 6,268
		Total	**€ 46,565**
EW_4	Inbound handling	7,979	€ 29,324
	Storage	8,017	€ 166,669
	Outbound handling	37	€ 137
		Total	**€ 196,131**
EW_5	Inbound handling	28,965	€ 108,620
	Storage	70,998	€ 312,180
	Outbound handling	42,033	€ 157,625
		Total	**€ 578,424**
EW_6	Inbound handling	0	€ 0
	Storage	6,688	€ 98,113
	Outbound handling	6,688	€ 50,160
		Total	**€ 148,273**
EW_7	Inbound handling	0	€ 0
	Storage	7,803	€ 80,765
	Outbound handling	7,803	€ 35,115
		Total	**€ 115,880**
		Total	**€ 2,050,244**

Table 2.6 | External warehousing costs

The total external warehousing costs in the period 01-01-2020 until 05-11-2020 comprise €2,050,244. A large part of these external warehousing costs arises from the external warehouses EW_2 and EW_5 since a large number of pallets are stored there.

When combining the total costs of transportation and external warehousing, which are €2,101,013 and €2,050,244, respectively, we find that the total costs of the transportation and external warehousing process are €4,151,257 in the period 01-01-2020 until 05-11-2020.

The KPI "supply chain complexity" is measured by the number of contracted transportation companies and external warehouses. Currently, there are 6 contracts with transportation companies and 7 contracts with external warehouses, resulting in 13 contracts in total.

2.6. Summary

Currently, Euroma possesses 4 production locations, which are based in Zwolle, Wapenveld, Schijndel, and Nijkerk. Raw materials and finished goods are often stored in external warehouses, for which Euroma uses 7 external warehouses: (i) EW_1, (ii) EW_2, (iii) EW_3, (iv) EW_4, (v) EW_5, (vi) EW_6, and (vii) EW_7. Euroma has a portfolio of 6 transportation companies that perform transportation movements between these production locations and external warehouses, which are: (i) TC_1, (ii) TC_2, (iii) TC_3, (iv) TC_4, (v) TC_5, and (vi) TC_6.

Regarding production locations, the production location in Wapenveld contributes the most to the transportation movements with a total transportation volume of around 87,000 pallets, of which most will be covered by the production location in Zwolle after the transfer. Regarding external warehouses, the external warehouse EW_5 contributes the most to the transportation movements with a total transportation volume of around 71,000 pallets. Regarding transportation companies, TC_2 contributes the most to the transportation movements with a total transportation volume of around 72,000 pallets.

The performance of the KPIs is calculated in the period 01-01-2020 until 05-11-2020. The transportation costs comprise €2,101,013 and the external warehousing costs comprise €2,050,244. Therefore, the total costs of the transportation and external warehousing process comprise €4,151,257, which is the performance on the KPI "total costs". The total number of kilometers driven is 131,063, which is the performance on the KPI "sustainability". The number of contracts with transportation companies and external warehouses is 6 and 7, respectively, resulting in 13 contracts in total. This is the performance on the KPI "supply chain complexity".

3. Literature review

Please note that pallet volumes and financial data are indexed. This chapter presents the results of our literature review. Section 3.1 discusses theoretical problems that are related to our problem. Section 3.2 compares our problem with the related problems from Section 3.1 and identifies and elaborates upon the gaps between them. Section 3.3 discusses problem-solving approaches for our problem and Section 3.4 summarizes our literature review and discusses the theoretical contribution of our research.

3.1. Facility location problems

Logistic costs consume a large part of the budget of companies. Careful design of the supply chain can reduce these costs substantially (Prodhon & Prins, 2014). Two of the problems that are raised when designing the supply chain are determining where to locate warehouses and how to configure vehicle routes. Facility location decisions are solved at the strategic decision level, while vehicle routes are constructed at tactical or operational decision levels. Studies have shown that tackling these decisions separately may result in excessive overall system costs (Prodhon & Prins, 2014). According to Langevin and Riopel (2005), “inefficient locations for production and assembly plants as well as distribution centers will result in excess costs being incurred throughout the lifetime of facilities, no matter how well the production plans, transportation options, inventory management, and information sharing decisions are optimized in response to changing conditions”. Generally, transportation and inventory decisions are secondary to facility location decisions. However, facility locations that would be made in isolation are different from those that would be made taking into account routing or inventory (Langevin & Riopel, 2005). The idea of combining location problems and routing problems originated around 1965 when inter-dependency of these types of decisions was already highlighted, although optimization approaches and computers were then not yet able to solve these problems (Maranzana, 1964; Von Boventer, 1961; Webb, 1968). Salhi and Rand (1989) were the first to quantify the results of including vehicle routing decisions while locating depots. They showed that the classical strategy consisting of solving a location problem and a routing problem separately often leads to suboptimal solutions.

Problems where decisions have to be made on the location of facilities are generally classified as facility location problems. According to Langevin and Riopel (2005), “the fixed charge facility location problem is a classical location problem and forms the basis of many of the location models that have been used in supply chain design”. In this problem, decisions should be made on locations of facilities and the shipment pattern that minimizes the combined facility location costs and shipment costs, constrained by meeting customer demand. Section 3.1.1 discusses the fixed charge facility location problem. Several extensions of this model are discussed in Section 3.1.2 until Section 3.1.5.

3.1.1. The fixed charge facility location problem

In the fixed charge facility location problem, decisions should be made on locations of facilities and the shipment pattern that minimizes the combined facility location costs and shipment costs, constrained by meeting customer demand. This problem can be mathematically modeled as follows (Balinski, 1965):

Set	**Definition**
I	Set of customer locations
J	Set of candidate facility locations

Parameter	**Definition**
h_i	Demand at customer location $i \in I$
f_j	Fixed cost of locating a facility at candidate site $j \in J$
$c_{i,j}$	Unit cost of shipping between candidate facility site $j \in J$ and customer location $i \in I$

Variable	**Definition**
X_j	1, if we locate at candidate site $j \in J$; 0, otherwise
$Y_{i,j}$	Fraction of the demand at customer location $i \in I$ that is served by a facility at site $j \in J$

Objective function

Minimize $\sum_{j \in J} f_j X_j + \sum_{j \in J} \sum_{i \in I} h_i c_{i,j} Y_{i,j}$ (3a.1)

Constraints

$\sum_{j \in J} Y_{i,j} = 1$	$\forall i \in I$	(3a.2)
$Y_{i,j} \leq X_j$	$\forall i \in I, \forall j \in J$	(3a.3)
$X_j \in \{0,1\}$	$\forall j \in J$	(3a.4)
$Y_{i,j} \geq 0$	$\forall i \in I, \forall j \in J$	(3a.5).

The objective function (3a.1) minimizes the sum of fixed facility location costs and transportation costs. Constraint (3a.2) ensures that the demand of all customers is fulfilled. Constraint (3a.3) states that a facility should be opened if that facility would be used to serve customers. Constraints (3a.4) and (3a.5) are the domain restrictions.

This mathematical model includes assumptions that capacity at the facilities is unlimited and this causes that at least one optimal solution to this problem involves assigning all the demand of each customer location $i \in I$ fully to a single facility site $j \in J$ (Langevin & Riopel, 2005). According to Langevin and Riopel (2005), many firms prefer such single-sourcing solutions because this makes the supply considerably more manageable. This is also in line with the KPI “supply chain complexity” of Euroma, as discussed in Section 2.4. In fixed charged facility location problems, single sourcing can also be enforced by adding an additional constraint. Furthermore, if we define b_j as the maximum demand that can be assigned to the facility at candidate site $j \in J$, we can add a constraint that ensures that the inventory level at a facility $j \in J$ is limited (Langevin & Riopel, 2005):

$$\sum_{i \in I} h_i Y_{i,j} \leq b_j X_j \qquad \forall j \in J \qquad (3a.6).$$

Another possibility to model the traditional fixed charge facility location problem is to change the decision variable related to the transportation movements between facilities $j \in J$ and customers locations $i \in I$. This can be realized by replacing $h_i Y_{i,j}$ by $Z_{i,j}$, which can be defined by the quantity shipped from facility $j \in J$ to customer location $i \in I$. Again, a constraint can be added to limit the capacity at facilities $j \in J$. When facilities are treated as warehouses, facility capacity can be treated as warehouse capacity. Daskin and Jones (1993) note that warehouse capacities, which are commonly measured in terms of annual throughput, are rarely known with great precision, as they depend on many factors, including the number of inventory turns at the warehouse. This corresponds with the situation at Euroma, where only estimations can be made about the time that raw materials and finished goods spend in external warehouses, as discussed in Section 2.5. Geoffrion and Graves (1974) extend the traditional fixed charge facility location problem by including shipments from plants to distribution centers and by including multiple commodities. Demand for a variety of commodities is considered and constraints are imposed on the minimum and maximum annual throughput at distribution centers. More detailed capacity constraints can also be added to their mathematical model, for example if different commodities use different amounts of resources at the distribution centers.

The traditional fixed charge facility location problem can be integrated with other mathematical models. Section 3.1.2 discusses the integration of location and routing models, and Section 3.1.3 discusses the integration of location and inventory models. Section 3.1.4 discusses the integration of uncertainty aspects in location models and Section 3.1.5 discusses the integration of location and facility failure models.

3.1.2. Integrating location and routing models

The assumption in traditional fixed charge facility location problems is that full truckload quantities are transported from distribution centers to customers, i.e., transportation costs are calculated by a linear function of the load that is transported. In practice, however, multiple customers are visited in a multi-stop route in which customers receive less-than-truckload (LTL) quantities from the distribution centers (Langevin & Riopel, 2005). The order in which customers are visited then determines the route and with that, the transportation costs. The error of approximating LTL shipments by full-truckload (FTL) shipments was first highlighted by Eilon et al. (1971). To overcome this error, location and routing problems should be integrated. The integration of location and routing problems contains the following three components: facility location, customer allocation to facilities, and vehicle routing. Different types of formulations of these models, solution algorithms, and computational results published prior to 1988 are reviewed and summarized by Laporte (1988). Several types of location routing models are formulated; one possibility of classifying these models concerns the number of layers of facilities. While three-layer problems include flows from plants to distribution centers to customers, two-layer problems include flows from distribution centers to customers. One example of a three-layer problem is the formulation of Perl and Daskin (1985), which is an extended version of the model of Geoffrion and Graves (1974) to include multi-stop routes to serve the customers; this model is however limited to one commodity. Berger (1997) formulates a two-layer problem that closely resembles the traditional fixed charge facility location problem, where routes are formulated in terms of paths.

3.1.3. Integrating location and inventory models

In the traditional fixed charge facility location problem, inventory aspects such as economic order quantities, safety stock levels, and inventory costs are ignored. Ignoring these inventory aspects can result in radically different location decisions in comparison to the situation where inventory is taken into account. When inventory aspects are taken into account, typically fewer facilities are used since inventory costs increase approximately with the square root of the number of facilities used (Langevin & Riopel, 2005). Besides that, safety stock costs also increase approximately with the square root of the number of facilities used (Eppen, 1979). A model that incorporates these (safety stock) inventory costs is the model of Shen et al. (2003). In this model, the objective function of the traditional fixed charge facility location problem is extended; however, it has the same constraints as the traditional fixed charge facility location problem. Compared to the traditional fixed charge facility location problem, the number of used facilities in the model of Shen et al. (2003) is significantly smaller as risk pooling effects of inventory management are taken into account. In this model, however, capacity aspects at facilities are not taken into account. Typically, capacity is measured in terms of throughput per unit time; however, this value can change as the number of inventory turns per unit time changes (Langevin & Riopel, 2005).

3.1.4. Integrating uncertainty aspects in location models

Decisions involving facility locations are often long-term strategic decisions and are often made in an uncertain environment. After these decisions have been made, costs and demands may change drastically. This is not taken into account in the traditional fixed charge facility location problem, as the problem data is treated as known and deterministic. Ignoring data uncertainty can therefore result in highly sub-optimal solutions (Langevin & Riopel, 2005). Two examples of approaches that are used for decision-making under uncertainty are stochastic programming and robust optimization. In stochastic programming, uncertain parameters are described by discrete scenarios with a given probability of occurrence. The objective here is to minimize the expected cost (Birge & Louveaux, 2011). Robust optimization is a more recent approach to optimization under uncertainty, in which the uncertainty model is not stochastic but deterministic and set-based. In robust optimization, the decision-maker constructs a solution that is feasible for any realization of the uncertainty in a given set, instead of seeking to immunize the solution in some probabilistic sense to stochastic uncertainty (Bertsimas et al., 2011). Both approaches seek solutions that perform well, though not necessarily optimally, under any realization of the data. Extensive literature reviews have been performed on facility location under uncertainty by Owen and Daskin (1998) and Berman and Krass (2002).

3.1.5. Integrating location and facility failure models

Facilities, once built, may become unavailable from time to time. Examples of causes are labor actions, natural disasters, or changes in ownership and are referred to as "failures". When these failures occur, customers that were previously served by these facilities must now be served by other facilities against higher costs (Langevin & Riopel, 2005). Similar to the models discussed in Section 3.1.4, uncertainty is again taken into account when integrating location and facility failure models. In Section 3.1.4, "demand-side" uncertainty was taken into account, which consists of uncertainty in demand and costs, and in this section, "supply-side" uncertainty is taken into account, which consists of uncertainty in the availability of plants or distribution centers (Langevin & Riopel, 2005).

Integrated location and facility failure models address the tradeoff between (i) location costs and transportation costs and (ii) failure costs. The latter comprises the resulting transportation costs for serving a customer of which the allocated facility has failed. In these models, primary and (multiple) backup facilities are assigned to customers (Langevin & Riopel, 2005).

3.2. Comparing our problem to facility location problems

This section discusses similarities and differences between our problem and the problems described in Section 3.1. The core of our problem is similar to the traditional fixed charge facility problem since decisions should be made on which full-truckload shipments should be made between production locations and external warehouses. The integrated location and routing models as discussed in Section 3.1.2 are not suitable for our problem, as only one external warehouse or production location is visited within a route. Section 3.1.1 discussed using decision variables that indicate which quantities are shipped between facilities and customer locations. When treating facilities as production locations and customer locations as external warehouses, these decision variables resemble part of the decisions that should be made in our problem. These models also include constraints for meeting demand at customer locations, which is closely related to meeting demand at production locations and for indicating that all finished products have to be shipped to external warehouses. Regarding the latter, constraints on warehouses capacity, which are also considered in our problem, were also discussed.

There are several differences between our problem and the problems discussed in Section 3.1. In most facility location problems, facilities are currently non-existent and should be built for a given fixed price. In our problem, the external warehouses are already built and therefore, no fixed price should be paid if Euroma decides to use those external warehouses. Our problem also includes two types of products, i.e., raw materials and finished goods, which have different shipment directions. Raw materials are sent from external warehouses to production locations and finished goods are sent from production locations to external warehouses. Section 3.1.1 discussed the idea of modeling multiple commodities, which can be used to model raw materials and finished goods. Sahyouni et al. (2007) extend the traditional fixed charge facility location problem by taking into account bidirectional flows of products. Forward logistic flows are considered, which can be compared to the flows of finished goods from production locations to external warehouses. Reverse logistic flows are considered as well, which can be compared to the flows of raw materials from external warehouses to production locations. Constraints are included for meeting the demand of both forward and reverse product flows. Qiu et al. (2018c) proposed a production routing model that takes into account forward and reverse product flows. Constraints are included for meeting the demand of both forward and reverse product flows and inventory balance constraints are added for measuring inventory levels of both types of products at external warehouses during several time periods.

The model of Qiu et al (2018c) also corresponds with our problem in the sense that our problem includes multi-period demand for both raw materials and finished goods. An additional set is introduced for these time periods. As discussed, this model also introduces inventory balance constraints to measure inventory levels at time periods by taking into account inventory levels at the previous time period and ingoing and outgoing product flows. This model also distinguishes between inventory levels of both types of products. Our problem includes flows of raw materials at external warehouses where raw materials are sent from external production locations to these external warehouses (i.e., ingoing flows) and where raw materials are sent from these external warehouses to production locations of Euroma (i.e., outgoing flows). For the flows of finished goods at external warehouses, there are flows of finished goods from production locations of Euroma to these external warehouses (i.e., ingoing flows) and flows of finished goods from these external warehouses to external customers (i.e., outgoing flows). Warehouse capacity constraints for each time period are also included in this model. There are also other possibilities to model these inventory balance constraints (Absi et al., 2014; Adulyasak et al., 2015; Bard & Nananukul, 2009; Brunaud et al., 2018; Chandra & Fisher, 1994; Coelho et al., 2013; Hinojosa et al., 2008; Qiu et al., 2018a, 2018b; Russell, 2017; Solyali & Süral, 2017).

The ingoing and outgoing flows at external warehouses do not only contribute to transportation costs, but these also contribute to warehousing costs in terms of inbound and outbound handling costs. For raw materials that are transported from external warehouses to production locations, outbound handling costs are charged by the external warehouses. For finished goods that are transported from production locations to external warehouses, inbound handling costs are charged by the external warehouses. Inbound and outbound handling costs are not taken into account in the papers discussed in this literature review but should be included in our model.

Section 3.1.3 also discussed integrating location and inventory models. In these models, decisions are made on optimal inventory levels including safety stocks. Although inventory aspects are considered in our problem, optimal inventory levels including safety stocks are not considered, as discussed in Section 1.3. The inventory levels determined by Euroma are, however, followed and the time that raw materials and finished goods spend in the external warehouses are also considered. Furthermore, the capacity constraints of vehicles are considered in our model. This can, for example, be modeled by the vehicle capacity constraint in the model of Perl and Daskin (1985). Finally, a multi-objective objective function should be considered. In the models discussed in this literature review, the objective functions concern minimizing the total costs. As discussed in Section 2.4, the objectives “sustainability” and “supply chain complexity” should also be added.

3.3. Problem-solving approaches

As the problems discussed in this literature review are NP-hard, typically heuristics are used to solve them (Langevin & Riopel, 2005). Several heuristics are used to solve these problems, such as branch-and-cut, branch-and-price, Lagrangian relaxation, and variable neighborhood search.

Table 3.1 provides an overview of heuristics that are used to solve facility location problems and production routing problems as discussed earlier in this chapter.

Author(s)	Problem type	Solution approach
Geoffrion and Graves (1974)	Facility location problem	Benders decomposition
Berger (1997)	Facility location problem	Branch-and-price
Shen et al. (2003)	Facility location problem	Column generation
Erlenkotter (1978)	Facility location problem	DUALOC procedure
Galvão (1993)	Facility location problem	Lagrangian relaxation
Daskin (1995)	Facility location problem	Lagrangian relaxation
Geoffrion (1974)	Facility location problem	Lagrangian relaxation
Daskin et al. (2002)	Facility location problem	Lagrangian relaxation
Sahyouni et al. (2007)	Facility location problem	Lagrangian relaxation
Hinojosa et al. (2008)	Facility location problem	Lagrangian relaxation
Teitz and Bart (1968)	Facility location problem	Swap algorithm
Al-Sultan and Al-Fawzan (1999)	Facility location problem	Tabu search
Wu et al. (2002)	Facility location problem	Two-phase heuristic
Hansen and Mladenovic (1997)	Facility location problem	Variable neighborhood search
Qiu et al. (2018c)	Production routing problem	Branch-and-cut
Qiu et al. (2018b)	Production routing problem	Branch-and-cut
Fumero and Vercellis (1999)	Production routing problem	Lagrangian relaxation
Solyali and Süral (2017)	Production routing problem	Multi-phase heuristic
Russell (2017)	Production routing problem	Multi-phase heuristic
Absi et al. (2014)	Production routing problem	Two-phase heuristic
Qiu et al. (2018a)	Production routing problem	Variable neighborhood search

Table 3.1 | Heuristics for solving facility location and production routing problems

From Table 3.1, we observe that the most common solution approach to solve facility location problems and production routing problems is Lagrangian relaxation (Fisher, 2004). In Lagrangian relaxation, constraints are dualized to obtain lower bounds or upper bounds for minimization or maximization problems, respectively. Lagrangian relaxation can thus be used in branch-and-bound algorithms. By dualizing constraints, the problem is easier to solve. An example of Lagrangian relaxation is provided below (Fisher, 2004).

Consider the following integer program (P):

Objective function

Minimize cx (3b.1)

Constraints

$Ax = b$ (3b.2)

$Dx \leq e$ (3b.3)

$x \geq 0$ (3b.4).

Applying Lagrangian relaxation to (P) results in the following integer program (LR_u):

Objective function

Minimize $cx + u(Ax - b)$	(3c.1)

Constraints

$Dx \leq e$	(3c.2)
$x \geq 0$	(3c.3).

The integer program (LR_u) is easier to solve than (P) (Fisher, 2004) and can be used to obtain bounds of the original problem. Fumero and Vercellis (1999) used Lagrangian relaxation to solve a variant of the production routing problem and obtained lower bounds with an average gap of 5.5% compared to an upper bound obtained by a heuristic.

3.4. Summary and research contribution

This chapter analyzed facility location problems related to our problem and compared these with our problem. The core of our problem is similar to the traditional fixed charge facility location problem, especially when using decision variables that indicate quantities shipped between facilities and customer locations. The assumption that FTL shipments are made between facilities and customer locations is included, which corresponds to our problem. Vehicle capacity constraints in the model of Perl and Daskin (1985) are related to our problem as well. However, gaps between our problem and the facility location problems were also identified. In facility location problems, facilities are currently non-existent, which is not the case in our problem. Furthermore, bidirectional flows with two types of products, i.e., raw materials and finished goods, are not considered in facility location problems; however, this is included in the model of Qiu et al. (2018c). This model also includes inventory balance and facility capacity constraints that are included in our problem. Inbound and outbound handling costs are not included in the models discussed in the literature review and the ideas of integrated location and inventory models cannot be used, as optimal inventory levels and safety stocks are not considered in our problem. Finally, the objectives “sustainability” and “supply chain complexity” are not considered in the models discussed in this literature review. With respect to problem-solving approaches of facility location problems and production routing problems, Lagrangian relaxation turned out to be the most common problem-solving approach.

Our research contributes to the scientific body of knowledge in several ways. First, we extend a problem similar to the fixed charge facility location problem with bidirectional flows that are not in the context of reverse logistics. Second, we take into account the time that raw materials and finished goods spend in external warehouses. Third, we integrate transportation and warehousing decisions, i.e., determining the routes of the vehicles, the number of vehicles to be reserved in each time period, and the number of pallet locations to be reserved at external warehouses. Fourth, we create an objective function with the KPIs “total costs”, “sustainability”, and “supply chain complexity”, which is not common in the field of fixed charge facility location problems. Finally, we perform a realistic case study in the field of fixed charge facility location problems.

4. Mathematical model

Please note that pallet volumes and financial data are indexed. This chapter presents the mathematical model that is based on the literature review in Chapter 3. Section 4.1 introduces the mathematical model and lists several assumptions. Section 4.2 presents the mathematical model and its notation. Section 4.3 discusses the implementation of the mathematical model. Section 4.4 summarizes this chapter.

4.1. Introduction to the mathematical model

As discussed in Section 3.4, the core of our problem is similar to the traditional fixed charge facility location problem, especially when using decision variables that indicate quantities shipped between facilities and customer locations. In our model, we, therefore, use decision variables that indicate quantities shipped between production locations and external warehouses. These decision variables also indicate at which time period the transportation movement takes place and which transportation company is used. Furthermore, we add decision variables that indicate how many raw materials are supplied from external suppliers to external warehouses in each time period and how many finished goods are sent from external warehouses to external customers in each time period. We do not determine the production planning of the production locations; we use the production planning of the production locations as input data for our model, as discussed in Section 1.3.

As discussed in Section 2.5, raw materials and finished goods are stored in the external warehouses for 6 weeks because of safety stock considerations. Therefore, we create constraints that indicate that raw materials and finished goods can only be sent to production locations or external customers after these have been stored in the external warehouses for 6 weeks. Furthermore, we have to keep track of ingoing and outgoing flows of raw materials and finished products in the external warehouses. For the flows of raw materials in external warehouses, we take into account the ingoing flows from external suppliers and the outgoing flows to production locations. For the flows of finished goods in external warehouses, we take into account the ingoing flows from production locations and the outgoing flows to external customers. To model the inventory positions of raw materials and finished goods in external warehouses and these ingoing and outgoing flows of raw materials and finished products in the external warehouses, we use the idea of inventory balance constraints from the model of Qiu et al. (2018c). We link these constraints to warehouse capacity constraints, which are based on the facility capacity constraints from the model of Qiu et al. (2018c).

Finally, we propose a multi-objective objective function taking into account the KPIs “total costs”, “sustainability”, and “supply chain complexity”. For the KPI “total costs”, we take into account transportation costs and external warehousing costs, of which the latter consists of inbound handling, storage, and outbound handling costs. For the KPI “sustainability”, we take into account the approximate number of kilometers traveled by transportation companies. For the KPI “supply chain complexity”, we take into account the number of contracts with external warehouses and transportation companies that are used to supply production locations with raw materials and external warehouses with finished goods.

In our mathematical model, we use several assumptions. These assumptions are listed below.

Deterministic demand (Assumption 1)

We assume that demand for finished goods is deterministic. This means that no online changes occur, e.g., no emergency orders are placed at production locations of Euroma or orders are canceled by external customers. The impact of this decision is low since emergency orders are not transported with traditional transportation companies, such as the transportation companies mentioned in our research, but with transportation companies that are specialized in emergency deliveries. Therefore, emergency orders do not influence the decisions made by our model. Furthermore, the frequency of cancellations is very low compared to the demand volume; therefore, the impact of this assumption on our model is negligible.

Deterministic production quantities (Assumption 2)

As discussed in Section 1.3, we do not determine the production planning, i.e., we use the production planning as input data for our model. We assume that these input data, i.e., the production quantities of finished goods, are deterministic. No online changes occur, such as machine failures, labor strikes, or producing finished goods that do not meet quality standards, resulting in a lower production quantity than expected. The impact of this assumption is low since these are already corrected for not meeting the quality standards. Furthermore, the frequency and duration of machine failures and labor strikes are negligible compared to the number of time periods considered in our model; therefore, the impact of this assumption on our model is negligible.

No distinction between different goods (Assumption 3)

We assume that all raw materials and finished goods are equal, i.e., we consider raw materials and finished goods on pallet level. However, we distinguish between "normal" goods and refrigerated and frozen goods. For the latter, we assume that all raw materials and finished goods that are requested by and produced at the production location in Schijndel are refrigerated and frozen goods. We assume that the raw materials and finished goods at the other production locations are "normal" goods. Finally, we assume that each good spends the same time in an external warehouse. The impact of this assumption is very high. In practice, effective warehouse capacities, i.e., the number of pallet locations that can be used instead of the number of pallet locations being available, are smaller because of restrictions that some products might not be stored near each other, which is very common in the food sector. Section 5.5.4 discusses the impact of these storage restrictions in terms of costs. Furthermore, some contracts with customers contain the condition that their products should be stored in specific warehouses; these agreements are ignored in our model. These agreements can only be adjusted after the contract is expired. In practice, the total costs are, therefore, very likely to be higher than our model suggests.

Deterministic transportation costs (Assumption 4)

We assume that transportation costs are deterministic. No truck failures or traffic jams occur, the driver takes the shortest route from origin to destination, travel times and travel distances are deterministic, symmetric, and independent of the driver, and trucks are always available. Therefore, transportation times are deterministic and result in deterministic transportation costs in case transportation companies charge costs per hour of transportation. We also ignore volume discounts and calculate the weighted average transportation costs per pallet, as discussed in Section 2.2. The impact of this assumption is low. The volume-rated prices have roughly the same ratio for each transportation company, and therefore the weighted average transportation costs per pallet give an accurate indication of average price differences between transportation companies. Furthermore, the travel times are estimated as an average situation and corrected for traffic jams and small differences in travel direction between origin and destination. Therefore, the impact of this assumption on our model is negligible.

Fixed contracts (Assumption 5)

We assume that the contracts with transportation companies and external warehouses are fixed, i.e., the price agreements are not dependent on the number of transportation movements related to these transportation companies and external warehouses. The impact of this assumption is low. The price agreements can be adjusted only once per year, often on January 1. Furthermore, the prices can only be raised for a small percentage. However, prices can be raised for a higher percentage depending on the market situation to adapt to, amongst others, increase in fuel prices and minimum wages, which is the same, legally determined, percentage for all transportation companies or external warehouses. Therefore, the changes in prices are either small or proportional for each transportation company or external warehouse, and these small or proportional price adjustments are thus not likely to influence the decisions made by our model.

Warehouses are always operational (Assumption 6)

We assume that warehouses are operational all the time, i.e., warehousing equipment is always operational for inbound handling, storage, and outbound handling. Furthermore, warehousing personnel is always available, i.e., no labor strikes occur. The impact of this assumption is low, as, in practice, it hardly occurs that warehouses are not operational. The frequency of warehouses becoming not operational for a short amount of time is negligible compared to the number of time periods considered in our model; therefore, the impact of this assumption on our model is negligible.

Inventory levels (Assumption 7)

We assume that the inventory level at the end of the time period represents the highest inventory level during that time period. Our model uses the inventory level at the end of the time period to calculate inventory costs, while the highest inventory level is used in practice, as discussed in Section 2.3. The impact of this assumption is low since this holds for all external warehouses. This assumption does not make a specific warehouse more preferable than another warehouse; therefore, this assumption does not influence the decision which warehouses are used. The total storage costs, however, are calculated in a less accurate manner; only in a situation where the daily inflow of products is equal to the daily outflow of products in an external warehouse, i.e., the inventory level in this warehouse is always the same, including or excluding this assumption yields the same total storage costs.

4.2. Mathematical model and its notation

This section presents the mathematical model and its notation. We propose a Mixed Integer Linear Programming (MILP) model with the objective of minimizing a weighted average of the total costs, sustainability, and supply chain complexity. Below, the sets, parameters, variables, objective function, and constraints in our model are explained and after that, a textual explanation of the objective function and the constraints is provided.

Set	**Definition**
$I = \{0, \dots, \lvert I \rvert - 1\}$	Set of production locations
$J = \{0, \dots, \lvert J \rvert - 1\}$	Set of external warehouses
$K = \{0, \dots, \lvert K \rvert - 1\}$	Set of transportation companies
$T = \{0, \dots, \lvert T \rvert - 1\}$	Set of time periods

Parameter	**Definition**
α	Weight of total costs objective
β	Weight of sustainability objective
γ	Weight of supply chain complexity objective
q	Capacity of a truck in pallets
w	Number of time periods that a raw material or finished product is stored in an external warehouse
m	Number of days in each time period
$d_{i,t}$	Demand for raw materials at production location $i \in I$ in time period $t \in T \cup \{-w, -w+1, \dots, -1\}$ in pallets
$p_{i,t}$	Production quantity of finished goods at production location $i \in I$ in time period $t \in T \cup \{-w, -w+1, \dots, -1\}$ in pallets
$c_{i,j,k}^{TR}$	Transportation costs for transporting one pallet between production location $i \in I$ and external warehouse $j \in J$ with transportation company $k \in K$
$v_{i,j}$	Distance between production location $i \in I$ and external warehouse $j \in J$ in kilometers
s_j^{RM}	Initial inventory level of raw materials in pallets at external warehouse $j \in J$
s_j^{FG}	Initial inventory level of finished goods in pallets at external warehouse $j \in J$
c_j^{IB}	Inbound handling costs per pallet at external warehouse $j \in J$
c_j^{ST}	Storage costs per pallet per time period at external warehouse $j \in J$
c_j^{OB}	Outbound handling costs per pallet at external warehouse $j \in J$
a_j	Maximum number of pallet locations to be used at external warehouse $j \in J$
b_k	Maximum number of trips per day with transportation company $k \in K$

Variable	Definition
$X_{i,j,k,t}$	The number of pallets of finished goods transported from production location $i \in I$ to external warehouse $j \in J$ with transportation company $k \in K$ in time period $t \in T$
$Y_{j,i,k,t}$	The number of pallets of raw materials transported from external warehouse $j \in J$ to production location $i \in I$ with transportation company $k \in K$ in time period $t \in T$
$E_{j,t}^{RM}$	The number of pallets of raw materials transported from external suppliers to external warehouse $j \in J$ in time period $t \in T$
$E_{j,t}^{FG}$	The number of pallets of finished goods transported from external warehouse $j \in J$ to external customers in time period $t \in T$
$Z_{k,t}$	The number of trips of transportation company $k \in K$ per day in time period $t \in T$
$I_{j,t}^{RM}$	Inventory level of raw materials in pallets at external warehouse $j \in J$ at the end of time period $t \in T$
$I_{j,t}^{FG}$	Inventory level of finished goods in pallets at external warehouse $j \in J$ at the end of time period $t \in T$
L_j	The number of pallet locations to be reserved in external warehouse $j \in J$
U_j^{EW}	1, if external warehouse $j \in J$ is used to supply production locations with raw materials and external warehouses with finished goods; 0, otherwise
U_k^{TC}	1, if transportation company $k \in K$ is used to supply production locations with raw materials and external warehouses with finished goods; 0, otherwise

Using these sets, parameters, and variables, we propose the following MILP-model:

Objective function

$$\text{Minimize } \alpha\left(\sum_{i\in I,j\in J,k\in K,t\in T}\left((c_{i,j,k}^{TR} + c_j^{IB})X_{i,j,k,t} + (c_{i,j,k}^{TR} + c_j^{OB})Y_{j,i,k,t}\right) + \sum_{j\in J,t\in T} c_j^{ST}(I_{j,t}^{RM} + I_{j,t}^{FG})\right) + \beta \sum_{i\in I,j\in J,k\in K,t\in T}\left(\frac{v_{i,j}}{q}(X_{i,j,k,t} + Y_{j,i,k,t})\right) + \gamma\left(\sum_{j\in J} U_j^{EW} + \sum_{k\in K} U_k^{TC}\right) \quad (4.1)$$

Constraints

$$\sum_{j\in J,k\in K} Y_{j,i,k,t} = d_{i,t} \qquad \forall i \in I, \forall t \in T \qquad (4.2)$$

$$\sum_{j\in J,k\in K} X_{i,j,k,t} = p_{i,t} \qquad \forall i \in I, \forall t \in T \qquad (4.3)$$

$$\sum_{i\in I,j\in J}\left(X_{i,j,k,t} + Y_{j,i,k,t}\right) \leq mqZ_{k,t} \qquad \forall k \in K, \forall t \in T \qquad (4.4)$$

$$Z_{k,t} \leq b_k \qquad \forall k \in K, \forall t \in T \qquad (4.5)$$

$$I_{j,0}^{RM} = s_j^{RM} \qquad \forall j \in J \qquad (4.6)$$

$$I_{j,t}^{RM} = I_{j,t-1}^{RM} + E_{j,t}^{RM} - \sum_{i\in I,k\in K} Y_{j,i,k,t} \qquad \forall j \in J, \forall t \in T\backslash\{0\} \qquad (4.7)$$

$$\sum_{j\in J} E_{j,t}^{RM} = \sum_{i\in I} d_{i,t-w} \qquad \forall t \in T \qquad (4.8)$$

$$\sum_{i\in I,k\in K} Y_{j,i,k,t} \leq I_{j,t-w}^{RM} \qquad \forall j \in J, \forall t \in T\backslash\{0,\dots,w-1\} \qquad (4.9)$$

$$I_{j,0}^{FG} = s_j^{FG} \qquad \forall j \in J \qquad (4.10)$$
$$I_{j,t}^{FG} = I_{j,t-1}^{FG} - E_{j,t}^{FG} + \sum_{i \in I, k \in K} X_{i,j,k,t} \qquad \forall j \in J, \forall t \in T \backslash \{0\} \qquad (4.11)$$
$$E_{j,t}^{FG} \leq I_{j,t-w}^{FG} \qquad \forall j \in J, \forall t \in T \backslash \{0, \dots, w-1\} \qquad (4.12)$$
$$\sum_{j \in J} E_{j,t}^{FG} = \sum_{i \in I} p_{i,t-w} \qquad \forall t \in T \qquad (4.13)$$
$$I_{j,t}^{RM} + I_{j,t}^{FG} \leq L_j \qquad \forall j \in J, \forall t \in T \qquad (4.14)$$
$$L_j \leq a_j \qquad \forall j \in J \qquad (4.15)$$
$$X_{i,j,k,t} + Y_{j,i,k,t} \leq (p_{i,t} + d_{i,t}) U_j^{EW} \qquad \forall i \in I, \forall j \in J, \forall k \in K, \forall t \in T \qquad (4.16)$$
$$Z_{k,t} \leq b_k U_k^{TC} \qquad \forall k \in K, t \in T \qquad (4.17)$$
$$X_{i,j,k,t} \geq 0 \qquad \forall i \in I, \forall j \in J, \forall k \in K, \forall t \in T \qquad (4.18)$$
$$Y_{j,i,k,t} \geq 0 \qquad \forall i \in I, \forall j \in J, \forall k \in K, \forall t \in T \qquad (4.19)$$
$$E_{j,t}^{RM} \geq 0 \qquad \forall j \in J, \forall t \in T \qquad (4.20)$$
$$E_{j,t}^{FG} \geq 0 \qquad \forall j \in J, \forall t \in T \qquad (4.21)$$
$$Z_{k,t} \geq 0 \qquad \forall k \in K, \forall t \in T \qquad (4.22)$$
$$I_{j,t}^{RM} \geq 0 \qquad \forall j \in J, \forall t \in T \qquad (4.23)$$
$$I_{j,t}^{FG} \geq 0 \qquad \forall j \in J, \forall t \in T \qquad (4.24)$$
$$U_j^{EW} \in \{0,1\} \qquad \forall j \in J \qquad (4.25)$$
$$U_k^{TC} \in \{0,1\} \qquad \forall k \in K \qquad (4.26).$$

The objective function (4.1) minimizes the weighted average of the total costs, sustainability, and supply chain complexity. The total costs include transportation and external warehousing costs, of which the latter consists of inbound handling, storage, and outbound handling costs. Constraint (4.2) ensures that demand for raw materials is met in each time period and Constraint (4.3) stipulates that all finished goods that are produced at production locations are sent to external warehouses in each time period. Constraint (4.4) ensures that the transportation capacity of the transportation companies is taken into account and Constraint (4.5) ensures that no more trips can be made than available. Constraint (4.6) sets the initial inventory of raw materials at the external warehouses and Constraint (4.7) calculates the inventory level of raw materials at external warehouses in each time period. Constraint (4.8) and Constraint (4.9) ensure that raw materials that are (i) sent from external warehouses to production locations and (ii) supplied from external suppliers to external warehouses spend the required number of time periods in the external warehouses. Constraint (4.10) sets the initial inventory of finished goods at the external warehouses and Constraint (4.11) calculates the inventory level of finished goods at external warehouses in each time period. Constraint (4.12) and Constraint (4.13) ensure that finished goods that are (i) sent from external warehouses to external customers and (ii) supplied from production locations to external warehouses spend the required number of time periods in the external warehouses. Constraint (4.14) ensures that only reserved pallet locations are used to store raw materials and finished goods and Constraint (4.15) ensures that no more pallet locations can be reserved than are available for Euroma. Constraint (4.16) activates the binary variable indicating whether external warehouses are used and Constraint (4.17) activates the binary variable indicating whether transportation companies are used. Constraint (4.18) until Constraint (4.26) are the domain restrictions.

4.3. Implementation of the mathematical model

Our MILP-model is implemented in Python. The data of the problem instance is imported into Python, our model is then solved with the Gurobi package in Python, and finally, the solution is exported to Excel, in which a dashboard with a graphical overview of the solution is automatically generated.

Our dashboard consists of six components. Component 1 of the dashboard comprises the graph "Transportation volumes per transportation company". This graph depicts the transportation volumes (in pallets) of each transportation company, in which raw materials and finished goods are also distinguished. Figure 4.1 depicts this graph.

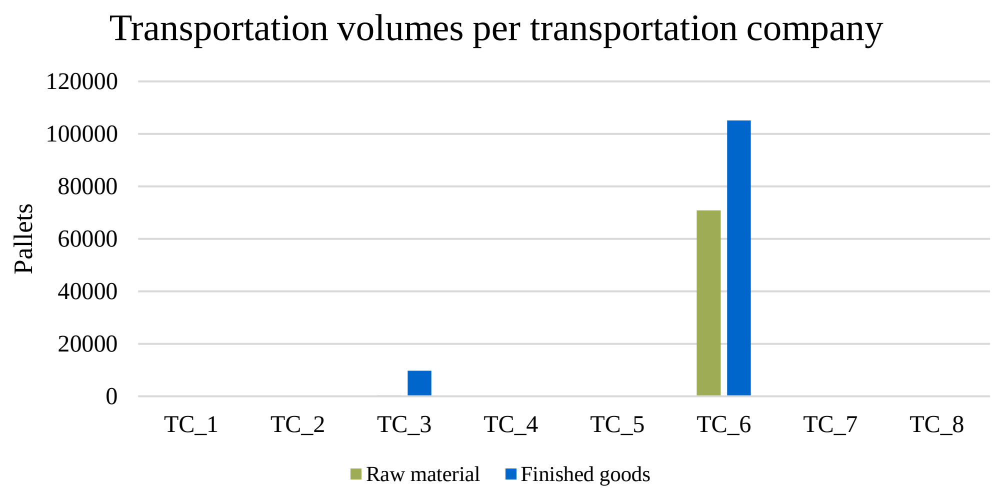

Figure 4.1 | Transportation volumes per transportation company

Component 2 of the dashboard comprises the graph "Transportation volumes per external warehouse". This graph depicts the transportation volumes (in pallets) to and from each external warehouse, in which raw materials and finished goods are also distinguished. Figure 4.2 depicts this graph.

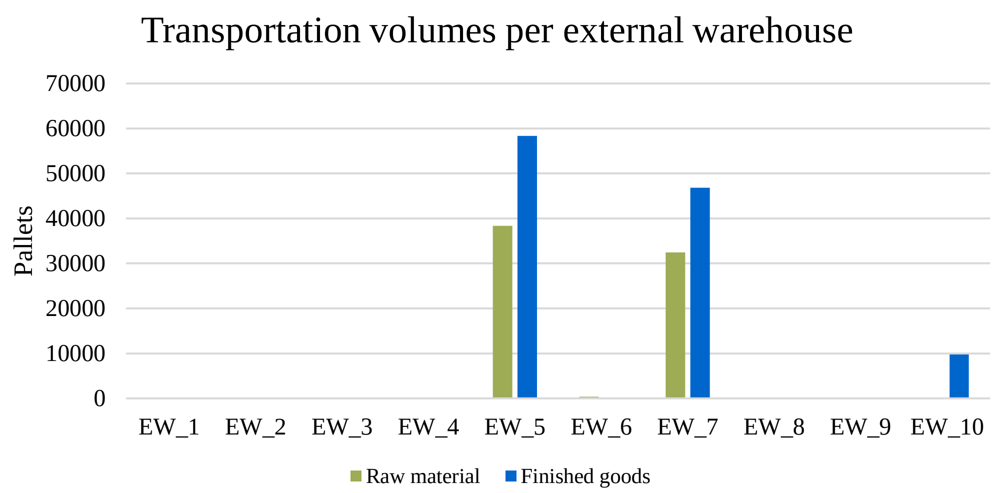

Figure 4.2 | Transportation volumes per external warehouse

Component 3 of the dashboard comprises the table “Global information”. This table depicts (i) the total costs, consisting of transportation and external warehousing costs, (ii) the number of transportation companies that are used to supply production locations with raw materials and external warehouses with finished goods, (iii) the number of external warehouses that are used to supply production locations with raw materials and external warehouses with finished goods, (iv) the supply chain complexity, i.e., the number of contracts with transportation companies and external warehouses that are used to supply production locations with raw materials and external warehouses with finished goods, and (v) the total number of kilometers traveled by transportation companies. Figure 4.3 depicts this table.

Global information

Total costs	**€ 5,303,098**
Transportation companies used	**2**
External warehouses used	**4**
Number of contracts	**6**
Kilometers travelled	**67,912**

Figure 4.3 | Global information

Component 4 of the dashboard comprises the graph “Inventory level raw materials external warehouses”. This graph depicts the inventory level (in pallets) of raw materials of the external warehouses over time. Figure 4.4 depicts this graph.

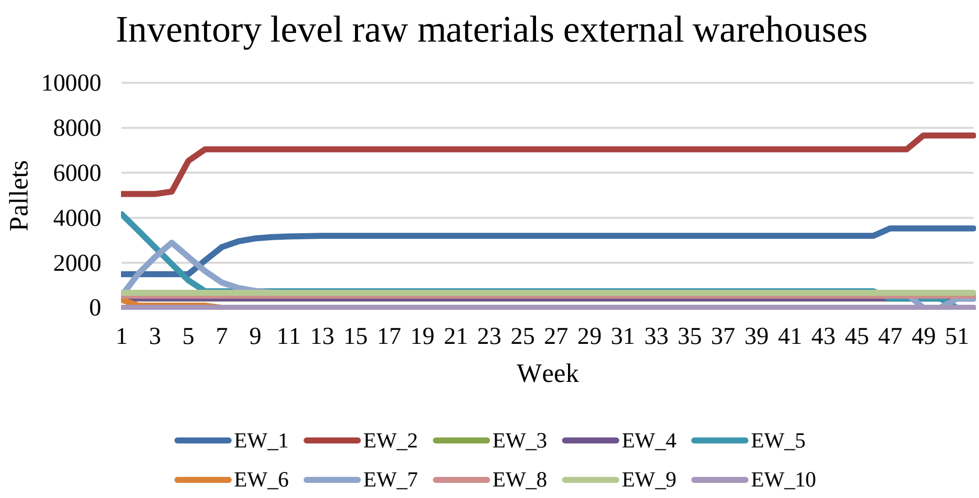

Figure 4.4. | Inventory level of raw materials at external warehouses

Component 5 of the dashboard comprises the graph "Inventory level finished goods external warehouses". This graph depicts the inventory level (in pallets) of finished goods of the external warehouses over time. Figure 4.5 depicts this graph.

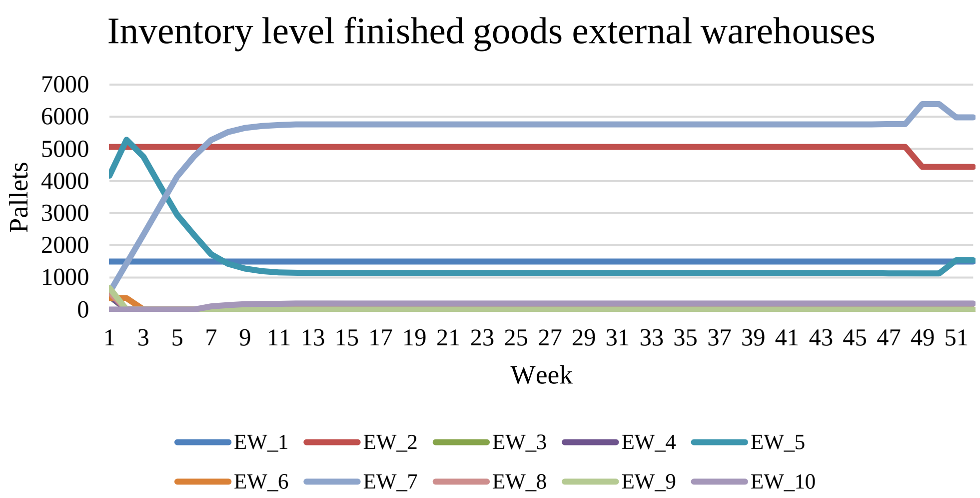

Figure 4.5 | Inventory level of finished goods at external warehouses

Component 6 of the dashboard comprises the graph "Number of trips per day per transportation company". This graph depicts the number of daily trips per transportation company over time. Figure 4.6 depicts this graph.

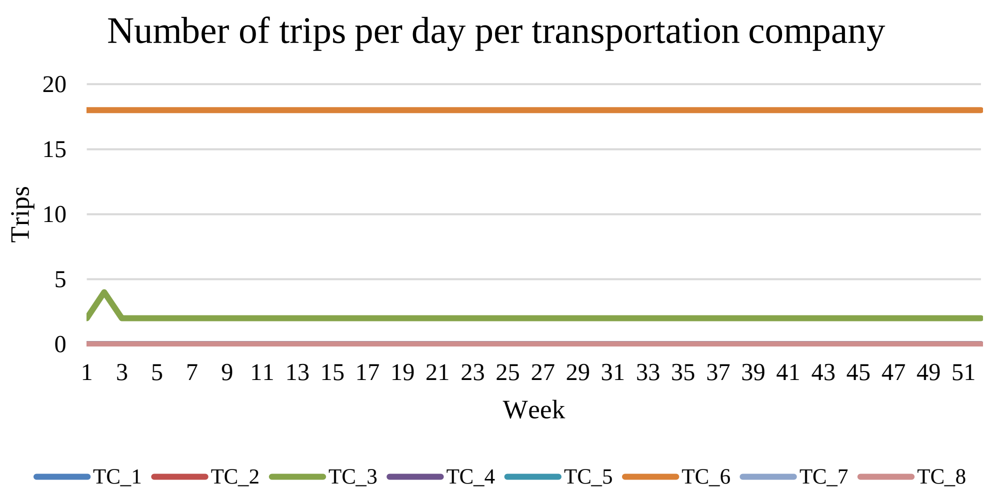

Figure 4.6 | Number of trips per day per transportation company

4.4. Summary

This chapter presented our mathematical model. Assumptions were first explained and reflections were made on the impact of these assumptions. Then, our mathematical model was introduced by presenting its sets, parameters, variables, objective function, and constraints. After that, the objective function and constraints were explained. Finally, the dashboard that visualizes the solution that is found by our model was presented and explained.

5. Experiments

Please note that pallet volumes and financial data are indexed. This chapter presents the experiments with the mathematical model. Section 5.1 describes the problem instances. Section 5.2 describes the performance of the current transportation and external warehousing process on the main problem instance. Section 5.3 gives a brief introduction to the experiments. Section 5.4 and Section 5.5 present the outcomes of these experiments. Section 5.6 summarizes this chapter.

5.1. Description of problem instances

This section describes the problem instances. The larger part of the data for these problem instances is extracted from (i) LN, (ii) contracts between, on the one hand, Euroma, and on the other hand, transportation companies and external warehouses, and (iii) reports and overviews of transportation companies and external warehouses, as already discussed in Chapter 2. Furthermore, quotations from transportation companies and external warehouses that are not yet contracted by Euroma were requested. Data regarding the demand for raw materials and finished goods are estimated based on our data analysis in Chapter 2 and expert opinions of, amongst others, the logistics manager.

Our problem instance considers the 4 production locations: (i) Zwolle, (ii) Wapenveld, (iii) Schijndel, and (iv) Nijkerk. It also considers 10 external warehouses: (i) EW_1, (ii) EW_2, (iii) EW_3, (iv) EW_4, (v) EW_5, (vi) EW_6, (vii) EW_7, (viii) EW_8, (ix) EW_9, and (x) EW_10. In EW_4 and EW_5, frozen and refrigerated goods coming from Schijndel can be stored. Furthermore, it considers 8 transportation companies: (i) TC_1, (ii) TC_2, (iii) TC_3, (iv) TC_4, (v) TC_5, (vi) TC_6, (vii) TC_7, and (viii) TC_8. The number of time periods is 52, with 7 days per time period, i.e., a time period equals one week. Finally, the (used) truck capacity is set at 28 pallets, as discussed in Section 2.2.

The smaller part of the data is varied throughout the experiments. These concern (i) the weights in the objective function, α, β, and γ, (ii) the number of time periods that a raw material or finished product is stored in an external warehouse, w, (iii) the additional parameters $DemandMultiplier$, $InventoryMultiplier$, and $CapacityMultiplier$, which are further elaborated upon in Sections 5.5.2 and 5.5.4, (iv) the maximum number of trips per day with transportation company $k \in K$, b_k, and (v) the upper bounds for the KPIs "total costs", "sustainability", and "supply chain complexity", which are further elaborated upon in Sections 5.4.3, 5.4.4, and 5.4.5, respectively. These data are provided in the subsections for the corresponding experiments. In the main problem instance, the number of time periods that a raw material or finished product is stored in an external warehouse, w, is set to 6 time periods, and the maximum number of trips per day with transportation company $k \in K$, b_k, is set to 20.

The larger part of the data is constant for all experiments; Table 5.1 presents an overview of these data. This overview provides the parameter, the notation in the mathematical model, the mean value, and the standard deviation, referred to as "StDev". The value "NA" is used to indicate that the data is not applicable or available.

Parameter	Notation	Mean	StDev
Number of production locations	$\|I\|$	4	NA
Number of external warehouses	$\|J\|$	10	NA
Number of transportation companies	$\|K\|$	8	NA
Number of time periods	$\|T\|$	52	NA
Capacity of a truck in pallets	q	28	NA
Number of days in each time period	m	7	NA
Demand for raw materials at production location $i \in I$ in time period $t \in T \cup \{-w, -w+1, \dots, -1\}$ in pallets	$d_{i,t}$	342.1	232.6
Production quantity of finished goods at production location $i \in I$ in time period $t \in T \cup \{-w, -w+1, \dots, -1\}$ in pallets	$p_{i,t}$	552.2	255.4
Transportation costs for transporting one pallet between production location $i \in I$ and external warehouse $j \in J$ with transportation company $k \in K$	$c_{i,j,k}^{TR}$	34.7	12.0
Distance between production location $i \in I$ and external warehouse $j \in J$ in kilometers	$v_{i,j}$	92.8	41.0
Initial inventory level of raw materials in pallets at external warehouse $j \in J$	s_j^{RM}	1,363.8	1,190.2
Initial inventory level of finished goods in pallets at external warehouse $j \in J$	s_j^{FG}	1,363.8	1,190.2
Inbound handling costs per pallet at external warehouse $j \in J$	c_j^{IB}	11.2	1.5
Storage costs per pallet per time period at external warehouse $j \in J$	c_j^{ST}	6.9	1.5
Outbound handling costs per pallet at external warehouse $j \in J$	c_j^{OB}	11.2	1.5
Maximum number of pallet locations to be used at external warehouse $j \in J$	a_j	6,755.8	2,127.6

Table 5.1 | The data that is constant for all experiments

5.2. Performance of the current configuration

This section describes the performance of the current transportation and external warehousing process on the main problem instance, by extrapolating the analysis from Figure 2.6. The KPI "total costs" consists of transportation costs and external warehousing costs, of which the latter also contains the costs for holding safety stock. The total safety stock is assumed to be equal to the sum of initial inventory levels of raw materials and finished goods in the external warehouses. It is currently unknown from which external warehouses Euroma sends the finished goods to the external customers and where the safety stock is kept; therefore, we make a conservative estimation for the storage costs of the initial inventory of raw materials and finished goods. Storing the sum of the initial inventory levels in external warehouses with the lowest storage costs per pallet per time period is possible for €3.80 (at EW_7). So, in the cheapest option, all safety stock is stored for all 52 time periods at EW_7 at total costs of €2,357,520.

Figure 5.1 shows an overview of the transportation volumes between production locations and external warehouses for the main problem instance.

Figure 5.1 | Overview of the transportation movements

In total, these transportation volumes include around 141,000 pallets, of which 70,000 are pallets containing raw materials and 71,000 are pallets containing finished goods. The transportation movements can also be translated into kilometers that are traveled by transportation companies. Table 5.2 shows the number of driven kilometers by each transportation company based on the transportation volumes between production locations and external warehouses for the main problem instance.

Transportation company	Kilometers driven
TC_3	86,339
TC_2	18,866
TC_1	40,133
TC_4	12,775
TC_5	4,697
TC_6	162
Total	**162,971**

Table 5.2 | Kilometers driven by transportation companies

The largest number of kilometers are traveled by TC_3 since the transportation movements of TC_3 have long travel distances and a large part of the transportation movements arises from TC_3. The number of kilometers traveled by TC_1 are also high since the transportation movements of TC_1 have long travel distances and a large part of the transportation movements arises from TC_1. The total number of kilometers driven is 162,971, which comprises the KPI "sustainability" that Euroma uses to measure the performance of the transportation and external warehousing process. This results in a total emission of 146,674 kg of $CO2$ (Ambel, 2021).

Table 5.3 presents the resulting transportation costs arising from these transportation movements.

Transportation company	Transportation movement	Number of pallets	Costs
TC_3	Zwolle → EW_2	3,133	€ 54,215
	Schijndel → EW_2	341	€ 10,110
	Nijkerk → EW_2	43,595	€ 596,191
	EW_6 → Nijkerk	12,976	€ 200,162
	Total	**60,045**	**€ 860,678**
TC_2	Zwolle → EW_5	990	€ 9,279
	Wapenveld → EW_5	5,469	€ 42,804
	EW_5 → Zwolle	8,241	€ 72,118
	EW_6 → Zwolle	5,394	€ 123,197
	Total	**20,095**	**€ 247,399**
TC_1	Zwolle → EW_1	37	€ 618
	Wapenveld → EW_1	1,591	€ 16,069
	EW_1 → Zwolle	22,939	€ 230,535
	Total	**24,567**	**€ 247,223**
TC_4	Zwolle → EW_2	607	€ 17,955
	Zwolle → EW_3	1,474	€ 16,176
	Nijkerk → EW_2	3,194	€ 94,366
	EW_3 → Zwolle	1,749	€ 19,232
	Total	**7,025**	**€ 147,728**
TC_5	Schijndel → EW_4	9,383	€ 351,018
	Total	**9,383**	**€ 351,018**
TC_6	EW_7 → Nijkerk	19,857	€ 148,929
	Total	**19,857**	**€ 148,929**
		Total	**€ 2,002,975**

Table 5.3 | Transportation costs

The total transportation costs comprise €2,002,975 A large part of the transportation costs arises from the transportation movements of TC_3 since TC_3 transports the most pallets. When investigating the transportation costs of the other transportation companies, we observe that TC_5 has the highest transportation costs while the number of pallets transported is relatively low. This is caused by the high transportation price in comparison to other transportation companies, as depicted in Table 2.2. The value for the KPI “supply chain complexity” is 13, since there are 6 contracts with transportation companies and 7 contracts with external warehouses, resulting in 13 contracts in total.

The transportation movements can also be translated into external warehousing costs. Table 5.4 presents the resulting external warehousing from these transportation movements.

External warehouse	Activity	Number of pallets	Costs
EW_1	Inbound handling	1,628	€ 6,178
	Storage	24567	€ 296,283
	Outbound handling	22939	€ 87,055
		Total	**€ 389,516**
EW_2	Inbound handling	52279	€ 235,254
	Storage	52279	€ 625,775
	Outbound handling	0	€ 0
		Total	**€ 861,029**
EW_3	Inbound handling	5276	€ 31,654
	Storage	7025	€ 104,128
	Outbound handling	5551	€ 33,304
		Total	**€ 169,085**
EW_4	Inbound handling	9383	€ 35,608
	Storage	9383	€ 200,984
	Outbound handling	0	€ 0
		Total	**€ 236,592**
EW_5	Inbound handling	6459	€ 24,222
	Storage	14700	€ 312,180
	Outbound handling	8241	€ 30,905
		Total	**€ 367,307**
EW_6	Inbound handling	0	€ 0
	Storage	12976	€ 204,366
	Outbound handling	12976	€ 97,317
		Total	**€ 301,683**
EW_7	Inbound handling	0	€ 0
	Storage	19857	€ 205,522
	Outbound handling	19857	€ 89,357
		Total	**€ 294,879**
		Total	**€ 2,620,091**

Table 5.4 | External warehousing costs

The total external warehousing costs comprise €2,620,091. A large part of these external warehousing costs arises from the external warehouses EW_2, EW_1, and EW_5 since a large number of pallets are stored there.

So, the total costs of transportation are €2,002,975, the total external warehousing costs arising from the transportation movements are €2,620,091, and the costs for holding safety stock are €2,357,520 (based on a conservative estimation). Therefore, the value for the KPI "total costs" comprises €6,980,586. Besides that, the value for the KPI "sustainability" comprises 162,971 kilometers and the value for the KPI "supply chain complexity" comprises 13 contracts.

5.3. Introduction to experiments

This section introduces two types of experiments with the mathematical model: experiments with different objective functions and sensitivity analyses. Section 5.3.1 and 5.3.2 introduce these experiments, respectively.

5.3.1. Experiments with different objective functions

This section introduces the experiments with different objective functions. As discussed in Chapter 4, we propose a multi-objective objective function taking into account the KPIs "total costs", "sustainability", and "supply chain complexity", with weights α, β, and γ, respectively. These experiments vary the values for α, β, and γ to create different objective functions, which are described below.

Experiment 1 | Determine the values of α, β, and γ

This experiment determines the values for α, β, and γ. Experiments with different values for α, β, and γ are performed and the solutions of these experiments are investigated on the KPIs "total costs", "sustainability", and "supply chain complexity". Based on the best overall solution, which decision is made based on the expert opinion of the logistics manager of Euroma, the values for α, β, and γ are chosen that are used in the experiments in which the multi-objective objective function is used. This experiment is presented in Section 5.4.1.

Experiment 2 | The main experiment

This is the main experiment of this research, which is the experiment with the values for α, β, and γ that yield the best overall solution. This experiment is already performed in experiment 1 but is repeated in experiment 2 for readability purposes in order to give a detailed overview of the solution. This experiment is presented in Section 5.4.2.

Experiment 3 | Optimizing the KPI "total costs"

The goal of this experiment is to find the minimum value for the KPI "total costs" with acceptable values for the KPIs "sustainability" and "supply chain complexity". For this experiment, the KPI "total costs" is optimized given certain upper bounds for the KPIs "sustainability" and "supply chain complexity", which are not included in the objective function of this experiment. These solutions can then be compared to the solution of the main experiment to determine whether the solution of the main experiment has the optimal value for the KPI "total costs" and which tradeoffs have to be made regarding the KPIs "sustainability" and "supply chain complexity" in order to attain the optimal value for the KPI "total costs". This experiment is presented in Section 5.4.3.

Experiment 4 | Optimizing the KPI "sustainability"

The goal of this experiment is to find the minimum value for the KPI "sustainability" with acceptable values for the KPIs "total costs" and "supply chain complexity". For this experiment, the KPI "sustainability" is optimized given certain upper bounds for the KPIs "total costs" and "supply chain complexity", which are not included in the objective function of this experiment. These solutions can then be compared to the solution of the main experiment to determine whether the solution of the main experiment has the optimal value for the KPI "sustainability" and which tradeoffs have to be made regarding the KPIs "total costs" and "supply chain complexity" in order to attain the optimal value for the KPI "sustainability". This experiment is presented in Section 5.4.4.

Experiment 5 | Optimizing the KPI "supply chain complexity"

The goal of this experiment is to find the minimum value for the KPI "supply chain complexity" with acceptable values for the KPIs "total costs" and "sustainability". For this experiment, the KPI "supply chain complexity" is optimized given certain upper bounds for the KPIs "total costs" and "sustainability", which are not included in the objective function of this experiment. These solutions can then be compared to the solution of the main experiment to determine whether the solution of the main experiment has the optimal value for the KPI "supply chain complexity" and which tradeoffs have to be made regarding the KPIs "total costs" and "sustainability" in order to attain the optimal value for the KPI "supply chain complexity". This experiment is presented in Section 5.4.5.

5.3.2. Sensitivity analyses

This section introduces the sensitivity analyses. Four types of sensitivity analyses are performed: (i) using different values for the number of time periods that a raw material or finished product is stored in an external warehouse, (ii) using different values for the current number of pallets stored in external warehouses, the demand for raw materials and finished goods, and the maximum number of trips per day with transportation companies, (iii) investigating the robustness of the solution of the main experiment from Section 5.4.2, and (iv) investigating the impact of product-related storage restrictions. These sensitivity analyses are described below.

Experiment 6 | The length of stay in external warehouses

This experiment investigates the impact of varying the length of stay of raw materials and finished goods on the KPIs "total costs", "sustainability", and "supply chain complexity". This experiment is presented in Section 5.5.1.

Experiment 7 | Varying occupied pallet locations, demand, and trips

This experiment investigates the impact when using different values for (i) the current number of pallets stored in external warehouses, (ii) the demand for raw materials and finished goods, and (iii) the maximum number of trips per day with transportation companies, on the impact on the KPIs "total costs", "sustainability", and "supply chain complexity". This experiment is presented in Section 5.5.2.

Experiment 8 | The robustness of the main solution

This experiment evaluates the robustness of the main solution by investigating when the configuration of the main solution (i.e., which transportation companies and external warehouses are used) changes when manipulating the input data. To achieve this, transportation costs of the transportation companies and warehousing costs of external warehouses that are currently used (see Section 2.5 or Section 5.2) but not included in the solution of the main experiment (see Section 5.4.2) are lowered. Subsequently, the robustness of the main solution is investigated by analyzing the sensitivity to price changes of these transportation companies and external warehouses.

Experiment 9 | The impact of product-related storage restrictions

This experiment quantifies the effect of Assumption 3 of our model regarding product-related storage restrictions, i.e., restrictions that some products might not be stored near each other. The effective warehouse capacities, i.e., the number of pallet locations that can be used are, therefore, lower than the number of pallet locations being available.

5.4. Experiments with different objective functions

This section describes the experiments with different objective functions. Section 5.4.1 describes experiment 1, in which the weights in the objective function are determined and Section 5.4.2 describes experiment 2, in which the main experiment is conducted. Section 5.4.3 describes experiment 3, in which the total costs objective is optimized, Section 5.4.4 describes experiment 4, in which the sustainability objective is optimized, and Section 5.4.5 describes experiment 5, in which the supply chain complexity objective is optimized. Finally, Section 5.4.6 analyzes the differences in solutions for all these experiments.

5.4.1. Experiment 1 | Determine the weights in the objective function

This experiment determines the weights in the objective function. Experiments are performed with different values for α, β, and γ and the solutions of these experiments are evaluated on the KPIs "total costs", "sustainability", and "supply chain complexity".

As discussed in Section 4.2, the proposed objective function (4.1) is:

$$\text{Minimize } \alpha\Big(\sum_{i\in I, j\in J, k\in K, t\in T}\big((c_{i,j,k}^{TR} + c_j^{IB})X_{i,j,k,t} + (c_{i,j,k}^{TR} + c_j^{OB})Y_{j,i,k,t}\big) + \sum_{j\in J, t\in T} c_j^{ST}(I_{j,t}^{RM} + I_{j,t}^{FG})\Big) + \beta \sum_{i\in I, j\in J, k\in K, t\in T}\Big(\frac{v_{i,j}}{q}(X_{i,j,k,t} + Y_{j,i,k,t})\Big) + \gamma\Big(\sum_{j\in J} U_j^{EW} + \sum_{k\in K} U_k^{TC}\Big) \quad (4.1).$$

In textual form, this objective function is given as:

Minimize $\alpha \times \textit{total costs} + \beta \times \textit{sustainability} + \gamma \times \textit{supply chain complexity}$.

For this experiment, the data for the main problem instance is used, as discussed in Section 5.1. Furthermore, the input data from Table 5.5 is used, which presents (i) the experiment number, referred to as "ExperimentNr" which serves as a key to describe the input data and output data of each unique experiment and (ii) the values for α, β, and γ that are used in the multi-objective objective function. These values for α, β, and γ are set in cooperation with the logistics manager of Euroma.

ExperimentNr	α	β	γ
1	1	1	10,000
2	1	5	10,000
3	1	10	10,000
4	1	1	20,000
5	1	5	20,000
6	1	10	20,000
7	1	1	30,000
8	1	5	30,000
9	1	10	30,000

Table 5.5 | Input data for experiment 1

Table 5.6 presents the outcomes of experiment 1 in terms of the KPIs "total costs", "sustainability", and "supply chain complexity", and the solving time of the experiment in seconds. The details of which transportation companies and external warehouses are used for each experiment are presented in Appendix 1, Section A1.1.

ExperimentNr	Total costs	Sustainability	Supply chain complexity	Solving time (s)
1	5,303,098	67,912	6	1.59
2	5,308,375	67,510	6	1.48
3	5,607,903	56,463	7	1.44
4	5,303,098	67,912	6	1.50
5	5,308,375	67,510	6	1.45
6	5,308,375	67,510	6	1.53
7	5,303,098	67,912	6	1.44
8	5,308,375	67,510	6	1.58
9	5,747,946	56,479	5	1.50

Table 5.6 | Results of experiment 1

From Table 5.6, we observe that the solving time ranges between 1.44 and 1.59 seconds, which means that no heuristics, such as Lagrangian relaxation, are required to solve these experiments. This holds for the remainder of our experiments. Furthermore, we observe that the solutions of ExperimentNr 1, 4, and 7 are equal. The same holds for the solutions of ExperimentNr 2, 5, 6, and 8. The solutions for ExperimentNr 3 and 9 are unique and have much higher total costs compared to the other solutions. The values of the KPIs from ExperimentNr 1 and 2 are similar, in the sense that the total costs are slightly lower in ExperimentNr 1 and the value for sustainability is slightly lower in ExperimentNr 2. The best overall solution according to the logistics manager of Euroma is the solution of ExperimentNr 1, as he prioritizes the KPI "total costs" over the KPIs "sustainability" and "supply chain complexity". Therefore, we use the values $\alpha = 1$, $\beta = 1$, and $\gamma = 10{,}000$ in experiments 2, 6, 7, 8, and 9. Section 5.4.2 presents a detailed analysis of the corresponding solution.

5.4.2. Experiment 2 | The main experiment

Experiment 2 is the main experiment of this research. As discussed in Section 5.4.1, the values for α, β, and γ are set at 1, 1, and 10,000, respectively. This experiment corresponds with ExperimentNr 1 from experiment 1. Table 5.7 presents the results of this experiment for readability purposes.

ExperimentNr	Total costs	Sustainability	Supply chain complexity	Solving time (s)
10	5,303,098	67,912	6	1.59

Table 5.7 | Results of experiment 2

From Table 5.7, we conclude that the best overall solution comprises total costs of €5,303,098, a value for sustainability of 67,912 kilometers, and a value for supply chain complexity of 6 contracts. In comparison to the performance of the current configuration of the transportation and external warehousing process on the main problem instance, our model yields an improvement of at least €1,677,488 (31.6%) on the KPI "total costs", based on the conservative estimation of the storage costs of the initial inventory of raw materials and finished goods, as discussed in Section 5.2. Furthermore, our model yields an improvement of 95,059 kilometers (58.3%) on the KPI "sustainability" and an improvement of 7 contracts (53.8%) on the KPI "supply chain complexity".

Figure 5.2 depicts the transportation volumes per transportation company. We conclude that in the optimal solution, only 2 transportation companies are used; TC_3 and TC_6. TC_6 is responsible for 94.6% of the total transportation volume and TC_3 for the remaining 5.4%. TC_6 transports (i) raw materials and finished goods between the external warehouse EW_7 and Nijkerk, (ii) raw materials and finished goods between the external warehouse EW_5 and Zwolle, and (iii) finished goods from Wapenveld to the external warehouse EW_5. TC_3 transports (i) raw materials from the external warehouse EW_6 to Nijkerk and (ii) finished goods from Schijndel to the external warehouse EW_10.

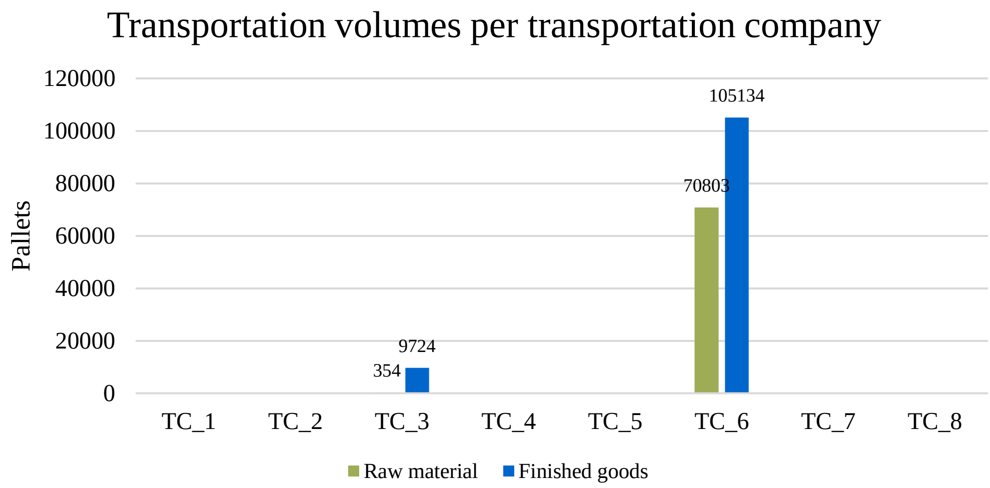

Figure 5.2 | Transportation volumes per transportation company in experiment 2

Figure 5.3 depicts the transportation volumes per external warehouse. We conclude that in the optimal solution, 4 external warehouses are used. Of the total transportation volume, 52.0% is stored at the external warehouse EW_5, 0.2% at the external warehouse EW_6, 42.6% at the external warehouse EW_7, and 5.2% at the external warehouse EW_10.

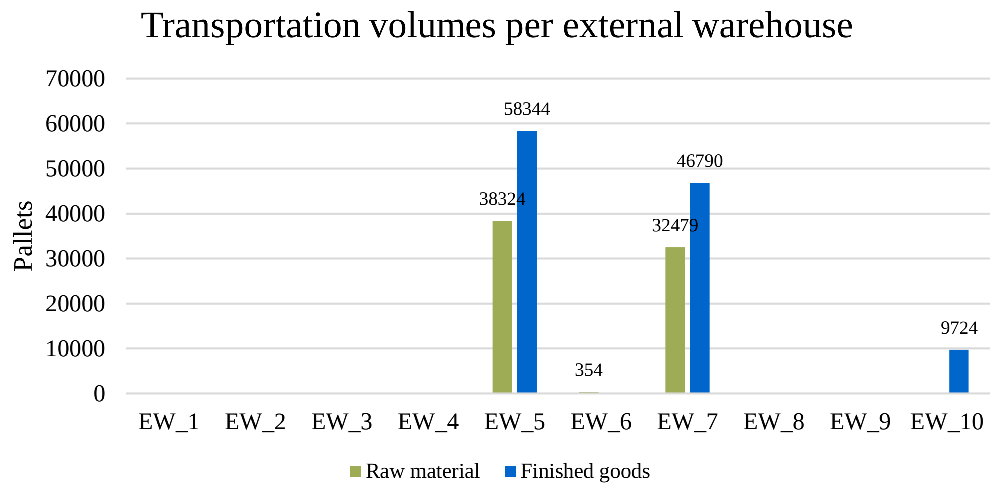

Figure 5.3 | Transportation volumes per external warehouse in experiment 2

Figure 5.4 depicts the inventory level of raw materials in external warehouses. We conclude that in the optimal solution, inventory levels of raw materials are high in the external warehouses EW_2 and EW_1, while inventory levels of raw materials are relatively low in other external warehouses, in which the warehouse EW_1 is purely used to store the safety stock of raw materials, as discussed in Section 5.2.

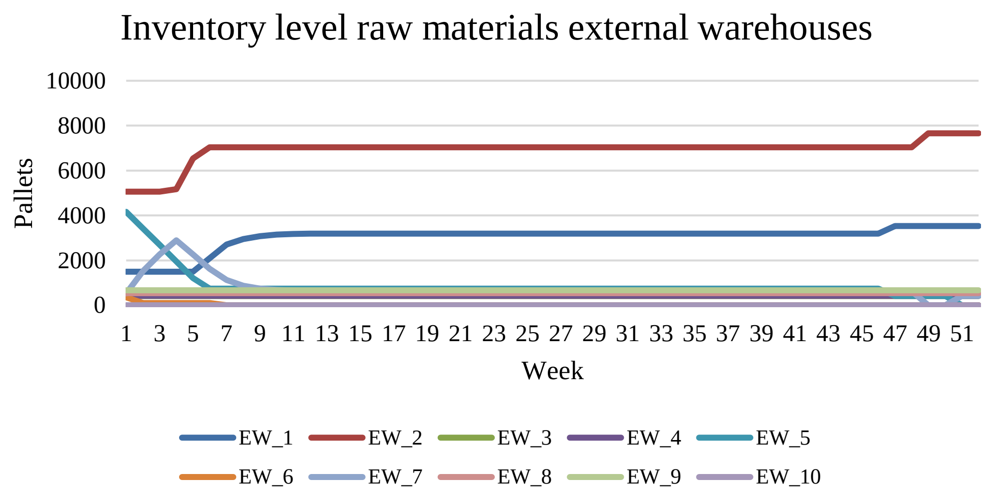

Figure 5.4 | Inventory level of raw materials in external warehouses in experiment 2

Figure 5.5 depicts the inventory level of finished goods in external warehouses. We conclude that in the optimal solution, the inventory levels of finished goods are high in the external warehouses of EW_2 and EW_7, while the inventory levels of raw materials are relatively low in other external warehouses. When analyzing the combination of Figure 5.4 and Figure 5.5, we conclude that, in the optimal solution, the external warehouses of EW_2 and EW_7 reach their capacity limit relatively early, while capacity limits are not reached at other external warehouses. The external warehouses EW_5, EW_7, and EW_10 are used to transport raw materials to the production locations and to receive finished goods from the production locations; the external warehouse EW_6 transports raw materials to Nijkerk. The other external warehouses are used to store the safety stock of raw materials and finished goods.

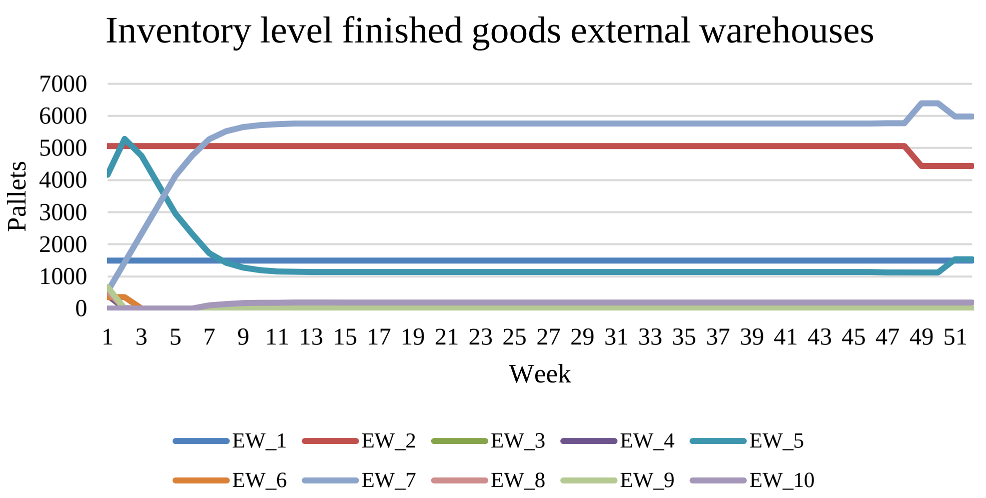

Figure 5.5 | Inventory level of finished goodss in external warehouses in experiment 2

Figure 5.6 depicts the number of trips per day per transportation company. We conclude that in the optimal solution, TC_6 always performs 18 trips per day. TC_3 always performs 2 trip per day, except in week 2; then, 4 trips are performed per day. The latter comes from the extra transportation movements to deliver raw materials from EW_6 to Nijkerk, of which there is a peak in week 2.

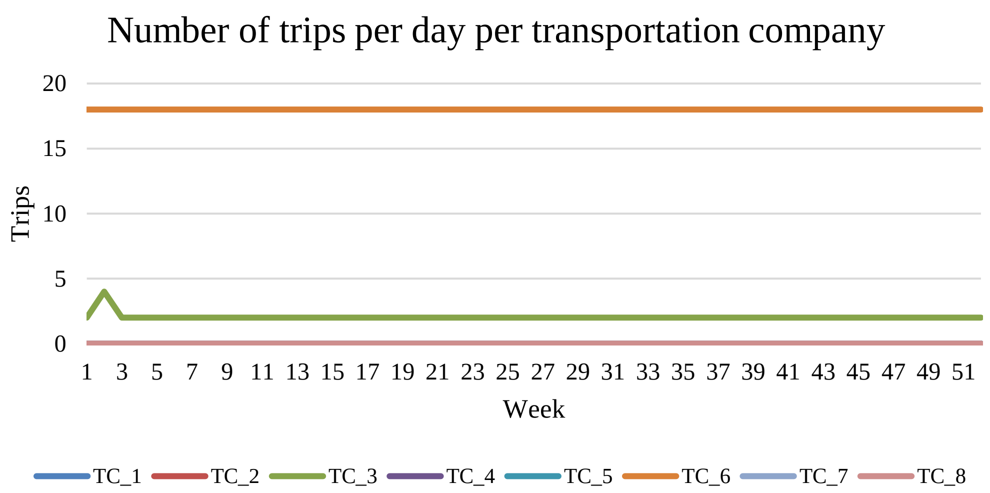

Figure 5.6 | Number of trips per day per transportation company in experiment 2

Sections 5.4.3, 5.4.4, and 5.4.5 present experiments with a single objective, i.e., optimizing only one KPI, while constraining the other two KPIs with upper bounds. Section 5.4.6 analyzes the differences in solutions for all the experiments 1-5.

5.4.3. Experiment 3 | Optimizing the KPI "total costs"

This experiment optimizes the KPI "total costs", i.e., the values for α, β, and γ, are 1, 0, and 0, respectively, resulting in the following objective function:

$$\text{Minimize} \sum_{i\in I, j\in J, k\in K, t\in T}\left((c^{TR}_{i,j,k} + c^{IB}_j)X_{i,j,k,t} + (c^{TR}_{i,j,k} + c^{OB}_j)Y_{j,i,k,t}\right) + \sum_{j\in J, t\in T} c^{ST}_j\,(I^{RM}_{j,t} + I^{FG}_{j,t}) \quad (4.1a).$$

We replace the original objective function (4.1) with this objective function (4.1a) for this experiment. Furthermore, we add the following constraints to the original model from Section 4.2:

$$\sum_{i\in I,j\in J,k\in K,t\in T}\left(\frac{v_{i,j}}{q}(X_{i,j,k,t}+Y_{j,i,k,t})\right)\leq UB^{sustainability} \quad (4.27)$$

$$\sum_{j\in J}U_j^{EW}+\sum_{k\in K}U_k^{TC}\leq UB^{supply\ chain\ complexity} \quad (4.28).$$

Constraint (4.27) ensures that the KPI "sustainability" is bounded from above by the upper bound $UB^{sustainability}$, i.e., the maximum number of kilometers traveled by transportation companies. Constraint (4.28) ensures that the KPI "supply chain complexity" is bounded from above by the upper bound $UB^{supply\ chain\ complexity}$, i.e., the maximum number of contracted transportation companies and external warehouses.

The goal of this experiment is to find the minimum value for the KPI "total costs" with reasonable values for the other KPIs "sustainability" and "supply chain complexity". From Table 5.6, we observe that the values for the KPI "sustainability" range between 56,463 kilometers and 67,912 kilometers; therefore, we set upper bounds of 60,000, 65,000, and 70,000 kilometers; these values are also classified as reasonable by the logistics manager of Euroma. We also observe that the values for the KPI "supply chain complexity" range between 5 and 7 contracts with transportation companies and external warehouses; therefore, we set upper bounds of 6, 7, and 8 contracts with transportation companies and external warehouses; these values are also classified as reasonable by the logistics manager of Euroma.

For this experiment, the data for the main problem instance is used, as discussed in Section 5.1. Furthermore, the input data from Table 5.8 is used, which presents (i) the experiment number, referred to as "ExperimentNr" which serves as a key to describe the input data and output data of each unique experiment and (ii) the upper bounds for the KPIs "sustainability" and "supply chain complexity".

ExperimentNr	$UB^{sustainability}$	$UB^{supply\ chain\ complexity}$
11	60,000	6
12	65,000	6
13	70,000	6
14	60,000	7
15	65,000	7
16	70,000	7
17	60,000	8
18	65,000	8
19	70,000	8

Table 5.8 | Input data for experiment 3

Table 5.9 presents the outcomes of experiment 3 in terms of the KPIs "total costs", "sustainability", and "supply chain complexity", and the solving time of the experiment in seconds. The details of which transportation companies and external warehouses are used for each experiment are presented in Appendix 1, Section A1.3.

ExperimentNr	Total costs	Sustainability	Supply chain complexity	Solving time (s)
11	5,743,929	57,941	6	3.73
12	5,743,929	57,941	6	4.09
13	5,303,098	67,912	6	1.28
14	5,600,512	56,910	7	2.95
15	5,517,475	65,000	7	2.69
16	5,303,098	67,912	6	1.16
17	5,510,987	60,000	8	1.09
18	5,376,099	65,000	8	1.05
19	5,303,098	67,912	6	1.18

Table 5.9 | Results of experiment 3

From Table 5.9, we conclude that the minimum total costs that can be attained are €5,303,098, in combination with a value for sustainability of 67,912 kilometers traveled by transportation companies and 6 contracts with transportation companies and external warehouses. This solution is equal to the solution of the main experiment, as discussed in Section 5.4.2. A solution that is quite similar to this solution in terms of the KPIs "total costs" and "sustainability" is the solution of ExperimentNr 18. Here, the total costs are €5,375,099 and the value for sustainability is 65,000, i.e., the transportation companies traveled 65,000 kilometers; so, there is a relatively small increase in total costs of €72,001 and a relatively small decrease in the value for sustainability of 2,912 kilometers compared to the solution of the main experiment. There is, however, a relatively large increase in the value for supply chain complexity of 2 contracts compared to the solution of the main experiment. Finally, when lowering the upper bounds of the KPIs "sustainability" and "supply chain complexity", we conclude that the total costs increase significantly, for example to €5,743,929 in ExperimentNr 11 and 12.

5.4.4. Experiment 4 | Optimizing the KPI "sustainability"

This experiment optimizes the KPI "sustainability", i.e., the values for α, β, and γ, are 0, 1, and 0, respectively, resulting in the following objective function:

$$\text{Minimize } \sum_{i\in I, j\in J, k\in K, t\in T}\left(\frac{v_{i,j}}{q}\left(X_{i,j,k,t} + Y_{j,i,k,t}\right)\right) \quad (4.1b).$$

We replace the original objective function (4.1) with this objective function (4.1b) for this experiment. Furthermore, we add the following constraints to the original model from Section 4.2:

$$\sum_{i\in I, j\in J, k\in K, t\in T}\left(\left(c^{TR}_{i,j,k} + c^{IB}_j\right)X_{i,j,k,t} + \left(c^{TR}_{i,j,k} + c^{OB}_j\right)Y_{j,i,k,t}\right) + \sum_{j\in J, t\in T} c^{ST}_j\left(I^{RM}_{j,t} + I^{FG}_{j,t}\right) \leq UB^{total\ costs} \quad (4.27)$$

$$\sum_{j\in J} U^{EW}_j + \sum_{k\in K} U^{TC}_k \leq UB^{supply\ chain\ complexity} \quad (4.28).$$

Constraint (4.27) ensures that the KPI "total costs" is bounded from above by the upper bound $UB^{total\ costs}$, i.e., the maximum total costs. Constraint (4.28) ensures that the KPI "supply chain complexity" is bounded from above by the upper bound $UB^{supply\ chain\ complexity}$, i.e., the maximum number of contracted transportation companies and external warehouses.

The goal of this experiment is to find the minimum value for the KPI "sustainability" with reasonable values for the other KPIs "total costs" and "supply chain complexity". From Table 5.6, we observe that the values for the KPI "total costs" range between €5,303,098 and €5,747,946; therefore, we set upper bounds of €5,400,000, €5,600,000, and €5,800,000 these values are also classified as reasonable by the logistics manager of Euroma. For the KPI "supply chain complexity", we set upper bounds of 6, 7, and 8 contracts with transportation companies and external warehouses, as discussed in Section 5.4.3.

For this experiment, the data for the main problem instance is used, as discussed in Section 5.1. Furthermore, the input data from Table 5.10 is used, which presents (i) the experiment number, referred to as "ExperimentNr" which serves as a key to describe the input data and output data of each unique experiment and (ii) the upper bounds for the KPIs "total costs" and "supply chain complexity".

ExperimentNr	$UB^{total\ costs}$	$UB^{supply\ chain\ complexity}$
20	5,400,000	6
21	5,600,000	6
22	5,800,000	6
23	5,400,000	7
24	5,600,000	7
25	5,800,000	7
26	5,400,000	8
27	5,600,000	8
28	5,800,000	8

Table 5.10 | Input data for experiment 4

Table 5.11 presents the outcomes of experiment 4 in terms of the KPIs "total costs", "sustainability", and "supply chain complexity", and the solving time of the experiment in seconds. The details of which transportation companies and external warehouses are used for each experiment are presented in Appendix 1, Section A1.4.

ExperimentNr	Total costs	Sustainability	Supply chain complexity	Solving time (s)
20	5,400,000	67,431	6	7.74
21	5,600,000	67,308	6	10.27
22	5,800,000	56,401	6	2.11
23	5,400,000	67,363	7	3.45
24	5,600,000	56,462	7	2.92
25	5,800,000	56,401	6	1.66
26	5,400,000	62,446	8	2.60
27	5,600,000	56,462	7	2.25
28	5,800,000	56,401	6	1.71

Table 5.11 | Results of experiment 4

From Table 5.11, we conclude that the minimum value for "sustainability" that can be attained is 56,401 kilometers in ExperimentNr 22, 25, and 28 with equal solutions. This is 11,511 kilometers lower than the value for the KPI "sustainability" in the main solution. Furthermore, we can conclude that to attain this solution, the value for the KPI "total costs" should be between €5,600,000 and €5,800,000, and the value for the KPI "supply chain complexity" should be between 6 and 7. So, to attain the optimal solution in terms of the KPI "sustainability" from the main solution, we should (i) increase the value for the KPI "total costs" by at least €296,902 and (ii) retain the value for the KPI "supply chain complexity" or increase this value with at most 1. We also conclude that lowering the upper bounds for the KPIs "total costs" and "supply chain complexity" results in a large increase in the number of kilometers traveled by transportation companies, especially for the solutions of ExperimentNr 20, 21, and 23.

5.4.5. Experiment 5 | Optimizing the KPI "supply chain complexity"

This experiment optimizes the KPI "supply chain complexity", i.e., the values for α, β, and γ, are 0, 0, and 1, respectively, resulting in the following objective function:

$$\text{Minimize } \sum_{j\in J} U_j^{EW} + \sum_{k\in K} U_k^{TC} \quad (4.1c).$$

We replace the original objective function (4.1) with this objective function (4.1c) for this experiment. Furthermore, we add the following constraints to the original model from Section 4.2:

$$\sum_{i\in I,j\in J,k\in K,t\in T}\left((c_{i,j,k}^{TR} + c_j^{IB})X_{i,j,k,t} + (c_{i,j,k}^{TR} + c_j^{OB})Y_{j,i,k,t}\right) + \sum_{j\in J,t\in T} c_j^{ST}(I_{j,t}^{RM} + I_{j,t}^{FG}) \leq UB^{total\ costs} \quad (4.27)$$

$$\sum_{i\in I,j\in J,k\in K,t\in T}\left(\frac{v_{i,j}}{q}(X_{i,j,k,t} + Y_{j,i,k,t})\right) \leq UB^{sustainability} \quad (4.28).$$

Constraint (4.27) ensures that the KPI "total costs" is bounded from above by the upper bound $UB^{total\ costs}$, i.e., the maximum total costs. Constraint (4.28) ensures that the KPI "sustainability" is bounded from above by the upper bound $UB^{sustainability}$, i.e., the maximum number of kilometers traveled by transportation companies.

The goal of this experiment is to find the minimum value for the KPI "supply chain complexity" with reasonable values for the other KPIs "total costs" and "sustainability". For the KPI "total costs", we set upper bounds of €5,400,000, €5,600,000, and €5,800,000, as discussed in Section 5.4.4. For the KPI "sustainability", we set upper bounds of 60,000, 65,000, and 70,000 kilometers, as discussed in Section 5.4.3.

For this experiment, the data for the main problem instance is used, as discussed in Section 5.1. Furthermore, the input data from Table 5.12 is used, which presents (i) the experiment number, referred to as "ExperimentNr" which serves as a key to describe the input data and output data of each unique experiment and (ii) the upper bounds for the KPIs "total costs" and "sustainability".

ExperimentNr	$UB^{total\ costs}$	$UB^{sustainability}$
29	5,400,000	60,000
30	5,600,000	60,000
31	5,800,000	60,000
32	5,400,000	65,000
33	5,600,000	65,000
34	5,800,000	65,000
35	5,400,000	70,000
36	5,600,000	70,000
37	5,800,000	70,000

Table 5.12 | Input data for experiment 5

Table 5.13 presents the outcomes of experiment 5 in terms of the KPIs "total costs", "sustainability", and "supply chain complexity", and the solving time of the experiment in seconds. The details of which transportation companies and external warehouses are used for each experiment are presented in Appendix 1, Section A1.5.

ExperimentNr	Total costs	Sustainability	Supply chain complexity	Solving time (s)
29	Infeasible	Infeasible	Infeasible	Infeasible
30	5,600,000	56,910	7	10.63
31	5,800,000	56,479	5	5.82
32	5,400,000	65,000	8	11.81
33	5,600,000	64,999	7	21.01
34	5,800,000	56,479	5	10.24
35	5,400,000	67,530	6	15.42
36	5,600,000	67,424	5	17.43
37	5,800,000	67,437	5	16.79

Table 5.13 | Results of experiment 5

From Table 5.10, we conclude that ExperimentNr 29 is infeasible, i.e., there is no feasible solution with maximum values of €5,400,000 and 60,000 kilometers for the KPIs "total costs" and "sustainability", respectively. We conclude that the minimum value for the KPI "supply chain complexity", i.e., the minimum number of contracts with transportation companies and external warehouses, that can be attained is 5. These values are attained in ExperimentNr 31, 34, 36, and 37. These solutions have values for the KPI "total costs" between €5,600,000 and €5,800,000 and values for the KPI "sustainability" between 56,479 kilometers and 67,437 kilometers. So, to attain the optimal solution in terms of the KPI "supply chain complexity" from the main solution, we should (i) increase the value for the KPI "total costs" by at least €296,902 and (ii) we should decrease the value for the KPI "sustainability" with at least 475 kilometers. Finally, we conclude that lowering the upper bounds for the KPIs "total costs" and "sustainability" results in a large increase in the number of contracts with transportation companies and external warehouses, especially for the solution of ExperimentNr 32.

5.4.6. Comparing all the solutions of experiments 1-5

This section compares all the solutions of experiments 1-5. Figure 5.7 presents all these solutions. From Figure 5.7, we observe efficient solutions in terms of the KPIs "total costs" and "sustainability", when one of these KPIs is held constant. For example, we observe that the KPI "total costs" for a value of the KPI "sustainability" of around 56,500 ranges between €5,600,000 and €5,800,000. This means that the solution with a value of €5,600,000 for the KPI "total costs" and a value of 56,500 for the KPI "sustainability" is more efficient than the solution with a value of €5,800,000 for the KPI "total costs" and a value of 56,500 for the KPI "sustainability", when neglecting the value for the KPI "supply chain complexity". Figure 5.7 encircles all the efficient solutions in terms of the KPIs "total costs" and "sustainability".

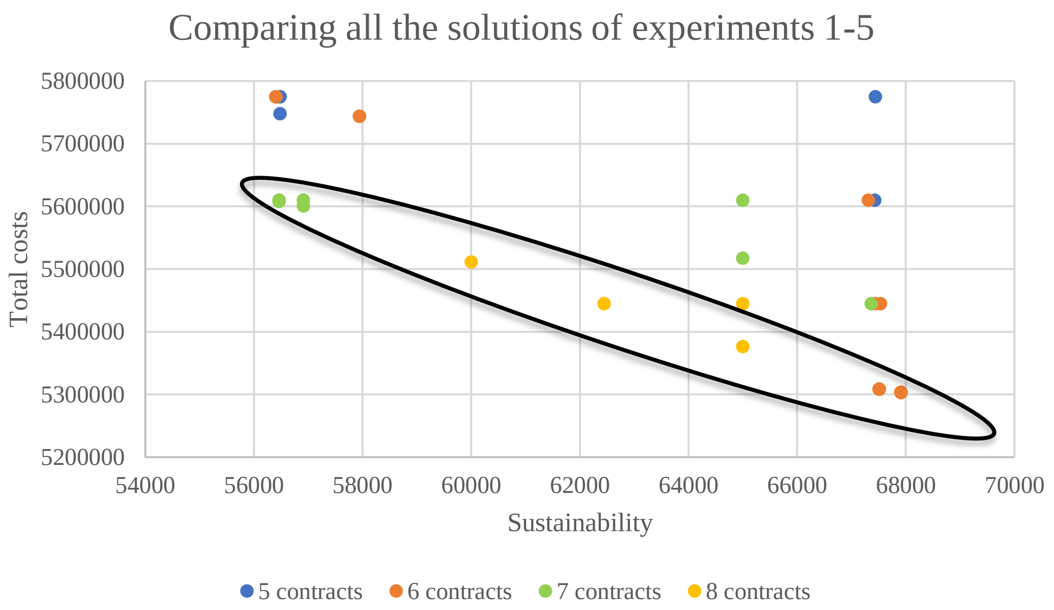

Figure 5.7 | The solutions of experiments 1-5

From Figure 5.7, we conclude that, regarding the efficient solutions, the value for the KPI "sustainability" increases when the value for the KPI "total costs" decreases. For the efficient solutions in terms of the KPI "total costs", we find 2 solutions in the range of €5,300,000. The next efficient solution is in the range of €5,370,000, which is €70,000 higher; however, the value for the KPI "sustainability" is approximately 2,500 kilometers lower. For the efficient solutions in terms of the KPI "sustainability", we find 3 solutions in the range of 57,000 kilometers. The next efficient solution is in the range of 60,000 kilometers, which is 3,000 kilometers higher; however, the value for the KPI "total costs" is approximately €100,000 lower. The efficient solution with a value for the KPI "total costs" of approximately €5,450,000 and a value for the KPI "sustainability" of approximately 62,500 resembles a solution of mid-range values for both the KPIs "total costs" and "sustainability".

5.5. Sensitivity analyses

This section describes the sensitivity analyses. Section 5.5.1 describes experiment 6, which investigates the impact of varying the number of time periods that a raw material or finished product is stored in an external warehouse on the KPIs "total costs", "sustainability", and "supply chain complexity". Section 5.5.2 describes experiment 7, in which a sensitivity analysis is performed on (i) the demand for raw materials and finished goods, (ii) the number of occupied pallet locations, and (iii) the maximum number of trips per day with each transportation company. Section 5.5.3 investigates the robustness of the main solution by investigating whether lowering transportation costs of unused transportation companies or warehousing costs of unused external warehouses changes the configuration of the main solution. Section 5.5.4 describes experiment 8, which quantifies the effect of product-related storage restrictions, i.e., restrictions that some products might not be stored near each other.

5.5.1. Experiment 6 | The length of stay in external warehouses

This experiment investigates the impact of varying the number of time periods that a raw material or finished product is stored in an external warehouse, w, on the KPIs "total costs", "sustainability", and "supply chain complexity".

For this experiment, the data for the main problem instance is used, as discussed in Section 5.1. Furthermore, the input data from Table 5.14 is used, which presents (i) the experiment number, referred to as "ExperimentNr" which serves as a key to describe the input data and output data of each unique experiment and (ii) the number of time periods that a raw material or finished product is stored in an external warehouse, w.

ExperimentNr	w
38	1
39	2
40	3
41	4
42	5
43	6
44	7
45	8

Table 5.14 | Input data for experiment 6

Table 5.15 presents the outcomes of experiment 6 in terms of the KPIs "total costs", "sustainability", and "supply chain complexity", and the solving time of the experiment in seconds. The details of which transportation companies and external warehouses are used for each experiment are presented in Appendix 1, Section A1.6.

From Table 5.15, we conclude that the value for the KPI "total costs" remains fairly constant when w is varied. The configuration of the solution remains constant; therefore, the values for the KPIs "sustainability" and "supply chain complexity" remain constant. The maximum difference in the KPI "total costs" is €6,764, which is approximately 0.1% of the value for the KPI "total costs". The decrease in the value for the KPI "total costs" when incrementing the number of time periods that a raw material or finished product is stored in an external warehouse is a limitation of our model, which is further discussed in Section 6.3.

ExperimentNr	Total costs	Sustainability	Supply chain complexity	Solving time (s)
38	5,309,156	67,912	6	1.68
39	5,304,585	67,912	6	1.53
40	5,304,080	67,912	6	1.76
41	5,303,780	67,912	6	1.55
42	5,303,444	67,912	6	1.49
43	5,303,098	67,912	6	1.59
44	5,302,748	67,912	6	1.49
45	5,302,392	67,912	6	1.67

Table 5.15 | Results of experiment 6

5.5.2. Experiment 7 | Varying occupied pallet locations, demand, and trips

This experiment investigates the impact of varying (i) the demand for raw materials and finished goods, (ii) the number of occupied pallet locations, and (iii) the maximum number of trips per day with each transportation company on the KPIs “total costs”, “sustainability”, and “supply chain complexity”.

The demand for raw materials, $d_{i,t}$, and the demand for finished goods, $p_{i,t}$ is varied to investigate how the transportation and external warehousing process is optimized when demand increases, for example as the consequence of future mergers or increased demand from customers, or decreases, for example as the consequence of losing market share to competitors. The demand parameters are varied as follows:

$$d_{i,t} \coloneqq d_{i,t} \times DemandMultiplier \qquad \forall i \in I, \forall t \in T$$
$$p_{i,t} \coloneqq p_{i,t} \times DemandMultiplier \qquad \forall i \in I, \forall t \in T.$$

The parameter $DemandMultiplier$ has a value of 75%, 100%, 125%, or 150%.

Furthermore, the initial inventory levels of both raw materials and finished goods in external warehouses are varied to investigate how the transportation and external warehousing process is optimized when different safety stock agreements are used.

The initial inventory levels are varied as follows:

$$s_j^{RM} \coloneqq s_j^{RM} \times InventoryMultiplier \qquad \forall j \in J$$
$$s_j^{FG} \coloneqq s_j^{FG} \times InventoryMultiplier \qquad \forall j \in J.$$

The parameter $InventoryMultiplier$ has a value of 90%, 100%, or 110%.

Finally, the maximum number of trips per day with transportation company $k \in K$, b_k is varied to investigate how the transportation and external warehousing process is optimized when transportation companies have fewer or more trucks available. The parameter b_k has the value 15, 20, or 25.

For this experiment, the data for the main problem instance is used, as discussed in Section 5.1. Furthermore, the input data from Table 5.16 is used, which presents (i) the experiment number, referred to as "ExperimentNr" which serves as a key to describe the input data and output data of each unique experiment and (ii) the parameters $DemandMultiplier$, $InventoryMultiplier$, and b_k.

ExperimentNr	$\boldsymbol{DemandMultiplier}$ **(%)**	$\boldsymbol{InventoryMultiplier}$ **(%)**	$\boldsymbol{b_k}$
46	75	90	15
47	75	90	20
48	75	90	25
49	75	100	15
50	75	100	20
51	75	100	25
52	75	110	15
53	75	110	20
54	75	110	25
55	100	90	15
56	100	90	20
57	100	90	25
58	100	100	15
59	100	100	20
60	100	100	25
61	100	110	15
62	100	110	20
63	100	110	25
64	125	90	15
65	125	90	20
66	125	90	25
67	125	100	15
68	125	100	20
69	125	100	25
70	125	110	15
71	125	110	20
72	125	110	25
73	150	90	15
74	150	90	20
75	150	90	25
76	150	100	15
77	150	100	20
78	150	100	25
79	150	110	15
80	150	110	20
81	150	110	25

Table 5.16 | Input data for experiment 7

Table 5.17 presents the outcomes of experiment 7 in terms of the KPIs “total costs”, “sustainability”, and “supply chain complexity”, and the solving time of the experiment in seconds. The details of which transportation companies and external warehouses are used for each experiment are presented in Appendix 1, Section A1.7.

ExperimentNr	Total costs	Sustainability	Supply chain complexity	Solving time (s)
46	4,426,381	50,516	5	1.65
47	4,426,381	50,516	5	1.39
48	4,426,381	50,516	5	1.37
49	4,739,044	50,516	5	1.34
50	4,739,044	50,516	5	1.39
51	4,739,044	50,516	5	1.36
52	5,059,641	50,516	5	1.41
53	5,059,641	50,516	5	1.39
54	5,059,641	50,516	5	1.43
55	5,073,043	67,856	7	1.72
56	4,992,241	67,856	6	1.48
57	4,992,241	67,856	6	1.41
58	5,383,832	67,912	7	1.47
59	5,303,098	67,912	6	1.59
60	5,303,098	67,912	6	1.44
61	5,703,692	67,968	7	1.50
62	5,623,028	67,968	6	1.55
63	5,623,028	67,968	6	1.49
64	5,732,875	84,695	7	1.93
65	5,601,704	84,695	7	2.17
66	5,566,131	84,695	6	1.80
67	6,043,215	84,751	7	1.57
68	5,912,044	84,751	7	1.45
69	5,876,540	84,751	6	1.69
70	6,361,165	84,807	7	1.48
71	6,229,994	84,807	7	1.60
72	6,194,559	84,807	6	1.78
73	6,400,186	101,557	7	1.49
74	6,269,015	101,557	7	1.47
75	6,147,791	101,557	6	1.49
76	6,710,927	101,498	7	1.44
77	6,579,756	101498	7	1.45
78	6,458,428	101,498	6	2.03
79	7,019,197	101,645	7	1.40
80	6,888,026	101,645	7	1.44
81	6,766,650	101,645	6	1.59

Table 5.17 | Results of experiment 7

From Table 5.17, we conclude that the value for the KPI “total costs” is nonincreasing in case the maximum number of trips per day with transportation company $k \in K$, b_k, increases while having constant values for the parameters $DemandMultiplier$ and $InventoryMultiplier$. When observing the transportation companies and external warehouses that are used in each experiment, as presented in Appendix 1, Section A1.7, we conclude that the largest part of the configuration is constant. In case the parameter $DemandMultiplier$ has a value of 75%, however, the external warehouse EW_6 is not necessary anymore to supply raw materials to Nijkerk, and therefore, the KPI “supply chain complexity” has the value 5 instead of 6 in the main solution. In case the external warehouse EW_7 is unable to supply the raw materials to Nijkerk, the external warehouse EW_6 is used. When the external warehouse EW_6 is also unable to supply the raw materials to Nijkerk, the external warehouse EW_2 is used. Finally, we conclude that if capacity issues arise at the trucks of TC_6, the transportation volume is first taken over by TC_2 for Wapenveld and Zwolle, and then by TC_3 in the case of Nijkerk.

5.5.3. Experiment 8 | The robustness of the solution of the main experiment

This experiment evaluates the robustness of the main solution by investigating when the configuration of the main solution (i.e., which transportation companies and external warehouses are used) changes when changing the input data. To achieve this, transportation costs of the transportation companies and warehousing costs of external warehouses that are currently used (see Section 2.5 or Section 5.2) but not included in the solution of the main experiment (see Section 5.4.2) are lowered. Subsequently, the robustness of the main solution is investigated by analyzing the sensitivity to price changes of other transportation companies and external warehouses

When comparing the used transportation companies in the main solution (see Section 5.4.2) and the transportation companies that are currently used by Euroma (see Section 2.5 or Section 5.2), we observe that the transportation companies (i) TC_1, (ii) TC_2, (iii) TC_4, and (vi) TC_5 are currently used by Euroma but are not included in the main solution. Experiment 8a investigates which percentual decrease in transportation costs is needed in order to change the configuration of the main solution. For this experiment, the data for the main problem instance is used, as discussed in Section 5.1.

Table 5.18 presents the outcomes of experiment 8a in terms of the KPIs “total costs”, “sustainability”, and “supply chain complexity”, the solving time of the experiment in seconds, and the percentual cost decrease that is needed for the corresponding transportation company to change the configuration of the main solution. The details of which transportation companies and external warehouses are used for each experiment are presented in Appendix 1, Section A1.8.

ExperimentNr	Total costs	Sustainability	Supply chain complexity	Solving time (s)	Decrease (%)
82	4,872,094	188,265	7	1.77	TC_1 (79%)
83	5,265,671	67,912	7	1.98	TC_2 (24%)
84	5,218,607	73,367	8	1.73	TC_4 (81%)
85	5,304,856	56,910	7	1.69	TC_5 (65%)

Table 5.18 | Results of experiment 8a

From Table 5.18, we conclude that the minimal decrease in transportation costs required for a change of the configuration of the main solution is 24%, in the case of TC_2. Therefore, the main solution is fairly robust to changes in transportation costs of these transportation companies. In comparison to the main solution, the value for the KPI "total costs" then decreases with €37,427, the value for the KPI "sustainability" remains constant, and the value for the KPI "supply chain complexity" increases with 1 contract. In this case, TC_2 takes over the transportation movements from and to EW_5 from TC_6. For the other transportation companies, a transportation costs decrease of at least 65% is required for a change of the configuration of the main solution. In the solution of ExperimentNr 82, TC_1 takes over the transportation movements from and to EW_5 from TC_6 and transports them to their own warehouse instead. In comparison to the main solution, the value for the KPI "total costs" then decreases with €431,004, the value for the KPI "sustainability" increases by 120,353 kilometers, and the value for the KPI "supply chain complexity" increases with 1 contract.

When comparing the used external warehouses in the main solution (see Section 5.4.2) and the external warehouses that are currently used by Euroma (see Section 2.5 or Section 5.2), we observe that the external warehouses of (i) EW_1, (ii) EW_3, (iii) EW_4, and (vi) EW_2 are currently used by Euroma but are not included in the main solution. Experiment 8b investigates which percentual decrease in warehousing costs, i.e., inbound handling costs, storage costs, and outbound handling costs, is needed in order to change the configuration of the main solution. For this experiment, the data for the main problem instance is used, as discussed in Section 5.1.

From experiment 8b, we can conclude that the configuration of the main solution remains unaltered after a percentual decrease of 100% of the warehousing costs of the corresponding warehouses. Therefore, the main solution is completely robust to changes in warehousing costs of these external warehouses. The value for the KPI "total costs", however, decreases since the storage costs of the initial inventory of raw materials and finished goods, as discussed in Section 5.2, decrease.

5.5.4. Experiment 9 | The impact of product-related storage restrictions

This experiment quantifies the effect of Assumption 3 of our model regarding product-related storage restrictions, i.e., restrictions that some products might not be stored near each other. The effective warehouse capacities, i.e., the number of pallet locations that can be used, are, therefore, lower than the number of pallet locations being available.

The maximum number of pallet locations to be used at external warehouse $j \in J$, a_j, is varied to investigate how the transportation and external warehousing process is optimized when product-related storage restrictions are taken into account. Based on expert opinions of warehousing personnel, the effective warehouse capacity is set to at least 85% of the number of pallet locations being available. The demand parameters are varied as follows:

$$a_j \coloneqq a_j \times CapacityMultiplier \qquad \forall j \in J.$$

The parameter $CapacityMultiplier$ has a value of 85%, 90%, 95%, or 100%.

For this experiment, the data for the main problem instance is used, as discussed in Section 5.1. Furthermore, the input data from Table 5.19 is used, which presents (i) the experiment number, referred to as "ExperimentNr" which serves as a key to describe the input data and output data of each unique experiment and (ii) the values for the parameter $CapacityMultiplier$.

ExperimentNr	$CapacityMultiplier$ (%)
86	85
87	90
88	95
89	100

Table 5.19 | Input data for experiment 9

Table 5.20 presents the outcomes of experiment 9 in terms of the KPIs "total costs", "sustainability", and "supply chain complexity", and the solving time of the experiment in seconds. The details of which transportation companies and external warehouses are used for each experiment are presented in Appendix 1, Section A1.9.

ExperimentNr	Total costs	Sustainability	Supply chain complexity	Solving time (s)
86	5,331,315	67,912	6	1.43
87	5,321,385	67,912	6	1.56
88	5,311,578	67,912	6	1.49
89	5,303,098	67,912	6	1.59

Table 5.20 | Results of experiment 9

From Table 5.20, we conclude that the impact of product-related storage restrictions is relatively small with regard to the KPI "total costs" and there is no impact on the KPIs "sustainability" and "supply chain complexity", i.e., the configuration of the solution remains unaltered. In the scenario where the effective warehouse capacity is set to 85% of the number of pallet locations being available, the value for the KPI "total costs" increases by only €28,217 (0.53%) compared to the main problem instance where product-related storage restrictions are not taken into account.

5.6. Summary

This chapter presented our experiments. First, the problem instances of our experiments were described. Second, the performance of the current configuration of the transportation and external warehousing process on the main problem instance was investigated. We concluded that this performance has the values €6,980,586, 162,971 kilometers, and 13 contracts on the KPIs "total costs", "sustainability", and "supply chain complexity", respectively. Third, the experiments were introduced: experiments with different objective functions and sensitivity analyses.

For the experiments with different functions, we first determined the weights of the KPIs "total costs", "sustainability", and "supply chain complexity", resulting in values for α, β, and γ of 1, 1, and 10,000, respectively. From the main experiment, we concluded that the performance of our model has the values €5,303,098, 67,912 kilometers, and 6 contracts on the KPIs "total costs", "sustainability", and "supply chain complexity", respectively. This is an improvement of (i) at least €1,677,488 (31.6%) on the KPI "total costs", based on the conservative estimation of the storage costs of the initial inventory of raw materials and finished goods, as discussed in Section 5.2, (ii) 95,059 kilometers (58.3%) on the KPI "sustainability" and, (iii) 7 contracts (53.8%) on the KPI "supply chain complexity". For the single-objective experiments, we concluded that the main solution (i) is optimal from a total cost perspective, (ii) has a value of 11,511 kilometers higher than the optimal solution from a sustainability perspective, and (iii) has a value of 1 contract higher than the optimal solution from a supply chain complexity perspective. Figure 5.7 visualized the (efficient) solutions of these experiments.

The first sensitivity analysis comprised investigating the impact of the number of time periods that a raw material or finished product is stored in an external warehouse on the KPIs "total costs", "sustainability", and "supply chain complexity". We concluded that this impact is minimal. The second sensitivity analysis comprised investigating the impact of varying (i) the demand for raw materials and finished goods, (ii) the number of occupied pallet locations, and (iii) the maximum number of trips per day with each transportation company. The largest part of the solution configuration remained constant; in case of capacity issues at transportation companies or external warehouses, additional transportation companies and external warehouses were used. The third sensitivity analysis comprised investigating the robustness of the main solution. We concluded that the main solution is fairly robust to changes in transportation costs of the corresponding transportation companies and completely robust to changes in warehousing costs of the corresponding external warehouses. The final sensitivity analysis comprised investigating the impact of product-related storage restrictions. We concluded that the impact of product-related storage restrictions is relatively small with regard to the KPI "total costs" and there is no impact on the KPIs "sustainability" and "supply chain complexity".

6. Conclusion

Please note that pallet volumes and financial data are indexed. This chapter concludes this research. Section 6.1 presents the conclusions and answers the main research question. Section 6.2 presents the contributions of this research to the theory. Section 6.3 discusses the limitations of this research and provides opportunities for further research. Section 6.4 presents the recommendations to Euroma.

6.1. Conclusion

Currently, the decisions regarding (i) which external warehouses are used to store raw materials and finished goods and (ii) the corresponding transportation process configuration are not based on a structured analysis of the transportation and external warehousing process, taking into account the KPIs total costs, sustainability, and supply chain complexity. Currently, Euroma uses the following transportation companies: (i) TC_1, (ii) TC_2, (iii) TC_3, (iv) TC_4, (v) TC_5, and (vi) TC_6. Furthermore, Euroma uses the following external warehouses: (i) EW_1, (ii) EW_2, (iii) EW_3, (iv) EW_4, (v) EW_5, (vi) EW_6, and (vii) EW_7. This results in 13 contracts in total, which leads to a high supply chain complexity.

Because the production volumes are expected to increase in the near future, i.e., in the coming three to five years, especially because of potential takeovers and the growth opportunities of Euroma, the transportation and external warehouses should be reconfigured to accommodate these increasing volumes. Therefore, the main research question of this research is:

"What is the optimal configuration of the transportation and external warehousing process for the near future?"

To answer the main research question, we created a mathematical model that optimizes the transportation and external warehousing process. Our mathematical model optimizes a multi-objective objective function including the KPIs "total costs", "sustainability", and "supply chain complexity". It decides on which transportation companies and external warehouses should be used and how the transportation movements between production locations and external warehouses are configured. Furthermore, it decides on inventory levels of raw materials and finished goods in external warehouses, the delivery of raw materials to external warehouses, and the delivery of finished goods to external customers.

We performed several experiments with our mathematical model to determine the optimal configuration of the transportation and external warehousing process on different problem instances. First, the performance of the current configuration of the transportation and external warehousing process on the main problem instance was investigated. We conclude that this performance has the values €6,980,586, 162,971 kilometers, and 13 contracts on the KPIs "total costs", "sustainability", and "supply chain complexity", respectively.

The optimal configuration of the transportation and external warehousing process found from our mathematical model comprises the values €5,303,098, 67,912 kilometers, and 6 contracts on the KPIs “total costs”, “sustainability”, and “supply chain complexity”, respectively. This is an improvement of (i) at least €1,677,488 (31.6%) on the KPI “total costs”, based on the conservative estimation of the storage costs of the initial inventory of raw materials and finished goods, as discussed in Section 5.2, (ii) 95,059 kilometers (58.3%) on the KPI “sustainability” and, (iii) 7 contracts (53.8%) on the KPI “supply chain complexity”. Only 2 transportation companies are used; TC_3 and TC_6. TC_6 is responsible for 94.6% of the total transportation volume and TC_3 for the remaining 5.4%. TC_6 transports (i) raw materials and finished goods between the external warehouse EW_7 and Nijkerk, (ii) raw materials and finished goods between the external warehouse EW_5 and Zwolle, and (iii) finished goods from Wapenveld to the external warehouse EW_5. TC_3 transports (i) raw materials from the external warehouse EW_6 to Nijkerk and (ii) finished goods from Schijndel to the external warehouse EW_10. Besides that, only 4 external warehouses are used. Of the total transportation volume, 52.0% is stored at the external warehouse EW_5, 0.2% at the external warehouse EW_6, 42.6% at the external warehouse EW_7, and 5.2% at the external warehouse of EW_10. Finally, we conclude that the main solution (i) is optimal from a total cost perspective, (ii) has a value of 11,511 kilometers higher than the optimal solution from a sustainability perspective, and (iii) has a value of 1 contract higher than the optimal solution from a supply chain complexity perspective.

We also performed several sensitivity analyses. First, we conclude that the impact of varying the number of time periods that a raw material or finished product is stored in an external warehouse on the KPIs “total costs”, “sustainability”, and “supply chain complexity” is minimal. Second, we conclude that the largest part of the solution configuration remains constant when varying (i) the demand for raw materials and finished goods, (ii) the number of occupied pallet locations, and (iii) the maximum number of trips per day with each transportation company. In case of capacity issues at transportation companies or external warehouses, additional transportation companies and external warehouses were used; TC_2 and the external warehouse EW_2. Third, we conclude that the main solution is fairly robust to changes in transportation costs of the corresponding transportation companies since a transportation costs decrease of at least 24% (in the case of TC_2) is required to change the solution configuration. The main solution is completely robust to changes in warehousing costs of these external warehouses, as a decrease of 100% in warehousing costs does not change the solution configuration. Finally, we conclude that the impact of product-related storage restrictions is relatively small with regard to the KPI “total costs” and there is no impact on the KPIs “sustainability” and “supply chain complexity” and that the solution configuration remains unaltered.

6.2. Contributions to theory

Our research contributes to the scientific body of knowledge in several ways. The main contribution comprises the extension of the fixed charge facility location problem. First, we incorporated bidirectional flows of goods, in this case raw materials and finished goods, that are not included in the context of reverse logistics. In the models of Sahyouni et al. (2007) and Qiu et al. (2018c), for example, only bidirectional flows in the context of reverse logistics are considered. To the best of our knowledge, bidirectional flows of raw materials and finished goods are not yet included in the scientific body of knowledge of facility location problems. Second, we integrated several transportation and warehousing decisions in a single model, i.e., determining (i) how raw materials are transported to external warehouses and production locations, (ii) how finished goods are transported to external warehouses and external customers, (iii) how many raw materials and finished goods are stored in external warehouses, and (iv) how many pallet locations should be reserved at external warehouses. This integration is a useful extension to the scientific body of knowledge of facility location problems and production routing problems. Third, we take into account the time raw materials and finished goods spend in an external warehouse. To the best of our knowledge, this is ignored in the currently known facility location problems and production routing problems. The assumption is then made that products can be sent from a production location to an external warehouse and then from the external warehouse to an external customer in the same time period; this is not realistic in practical cases where safety stock should be created for external customers. Finally, we introduced an objective function with multiple KPIs: total costs, sustainability, and supply chain complexity. Especially the KPI “supply chain complexity” is often ignored in these types of problems, while an easier to manage supply chain, i.e., with fewer transportation companies and external warehouses, provides significant advantages that cannot directly be translated to cost savings.

6.3. Limitations and further research

Some limitations impede the direct implementation of the solution of our model. The first practical constraint comprises the storage possibilities for some type of raw materials or finished goods. In our model, we assume that all raw materials and finished goods are equal. In practice, however, there are several types of raw materials and finished goods, which cannot be stored next to each other, for example. Therefore, a suggestion for further research comprises distinguishing between different types of raw materials and finished goods and integrating these types of storage constraints in our model. One example comprises introducing product groups and to add constraints that indicate the maximum number of pallets of certain product groups that can be stored in each external warehouse. This can, for example, be implemented if the number of product groups and product-related storage constraints is not too large, such that our model can still be solved to optimality. Another example, particularly useful if the number of product groups and product-related storage constraints is large, comprises transforming our model into a math-heuristic. After our model is solved, a heuristic could determine whether all product-related storage restrictions are met at each point in time. If not, the heuristic could provide feedback to our model, i.e., lowering the number of available pallet locations at the warehouses where the product-related storage constraints are violated, after which our model is solved again. This process could be iterated till all product-related storage restrictions are met at each point in time.

Another limitation comprises the scope of our research. In our research, we neglect the costs made for (i) the production of raw materials at external suppliers and the transportation costs of raw materials from these external suppliers to the external warehouses and (ii) the transportation of finished goods from external warehouses to external customers. Hence, a suggestion for further research is to extend our model accordingly, i.e., including the costs for (i) the production of raw materials at external suppliers and the transportation costs of raw materials from these external suppliers to the external warehouses and (ii) the transportation of finished goods from external warehouses to external customers. Regarding the transportation of finished goods to external customers, one could also extend the model by including the possibility to directly distribute the finished goods from the production location to the external customer, without using an external warehouse, for some goods. Another extension to the transportation of finished goods from external warehouses or production locations to external customers comprises optimizing the transportation schedule of transportation companies. In production routing problems, e.g., see Qiu et al. (2018c), one part of the objective comprises the optimization of transportation routes. An interesting opportunity for further research comprises the collaboration of multiple production locations, transportation companies, and external warehouses to optimize the entire supply chain, which may provide costs benefits for all parties and environmental benefits, i.e., fewer CO2 emissions.

Another limitation concerns including the number of time periods that a raw material or finished product is stored in an external warehouse, w, in our model. We concluded that the value for the KPI "total costs" remains fairly constant when the number of time periods that a raw material or finished product is stored in an external warehouse is varied. However, the value for the KPI "total costs" slightly decreases when the parameter w increases. This is caused by Constraint (4.9) and Constraint (4.12); these impede transporting raw materials and finished goods, respectively, that are stored for fewer time periods than required. However, these constraints are de-activated for the time period $t \in \{0, \dots, w-1\}$, which makes it possible to transport raw materials and finished goods that are stored fewer time periods than required in these time periods. The higher the value for w, the more constraints are de-activated; hence, the lower the value for the KPI "total costs". In practice, the value for the KPI "total costs" should decrease when raw materials and finished goods are required to be stored for fewer time periods. One can investigate solving this problem by including a warm-up period in our model that is at least equal to the value w. When distinguishing between different types of raw materials and finished goods, one can also include different values for w per type of raw material and finished good and investigate how to adjust the warm-up period accordingly.

The final opportunity for further research comprises the short-term use of our model. One can investigate transforming our model to, for example, a Reinforcement Learning or Approximate Dynamic Programming model to find a policy that optimizes decisions in the longer term, i.e., one can use a combined cost function with direct costs and an estimate of the future, long-term costs of a decision policy (Powell, 2007). This is particularly useful in case there is a high fluctuation in demand, which may cause that more than one transportation company and external warehouse is needed to transport and store the finished goods of one production location.

Based on the current state, i.e., incoming orders, order forecasts, available trucks, inventory levels at external warehouses, transportation and external warehousing costs, et cetera, one can derive how many pallets with finished goods from that production location should be transported to each external warehouse and by which transportation company. This policy should then minimize direct costs and future costs. Future costs could be learned by an iteratively learned value function approximation that estimates the future value of different decision policies. These models might be especially useful in the market situation nowadays, in which the availability of transportation companies is limited as a result of the growth in at-home deliveries during the Covid-19 Pandemic.

6.4. Recommendations

We first recommend investigating the possibilities of only using the transportation companies TC_3 and TC_6, while using the external warehouses EW_5, EW_7, EW_6, and EW_10. We advise Euroma to make customer-specific analyses to determine whether it is beneficial to make these proposed logistics switches, e.g., storing the products of this customer in the external warehouse EW_5 instead of in the external warehouse EW_1. Of course, the KPIs “total costs”, “sustainability”, and “supply chain complexity” should be examined, but practical KPIs such as customer preferences, product-related storage and transportation constraints, and IT configuration constraints should also be taken into account. After a switch between transportation companies or external warehouses has been made, we advise Euroma to organize periodical meetings, e.g., twice per week, with their new partners for the first couple of weeks to ensure that operational issues, that logically arise after these logistical switches, are tackled directly to optimally benefit from the logistical switch. Finally, Euroma should run our model at least once a year, preferably at a fixed date after (i) the yearly demand and production forecasts are made and (ii) transportation companies and external warehouses updated their cost and capacity information, to determine whether the configuration of the transportation and external warehousing process is still optimal. In case a change in (i) production quantities, (ii) demand, or (iii) cost and capacity information of transportation companies and external warehouses is detected, Euroma should directly run the model again to determine whether a direct change in the configuration of the transportation and external warehousing process is necessary.

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Appendix 1. Details of experiments

This appendix presents the details of the experiments in terms of which transportation companies and external warehouses are used in each experiment. A separate subsection is used for each experiment, following the structure of Sections 5.3 and 5.4. These subsections include tables that present these details; in case a transportation company or external warehouse is never used in an experiment, these are from the corresponding tables for readability purposes.

A1.1. Details of experiment 1

This section presents the details of experiment 1. Table A1.1 presents the transportation companies that are used in experiment 1.

ExperimentNr	TC_3	TC_5	TC_6
1	1		1
2	1		1
3	1	1	1
4	1		1
5	1		1
6	1		1
7	1		1
8	1		1
9		1	1

Table A1.1 | Transportation companies used in experiment 1

Table A1.2 presents the external warehouses that are used in experiment 1.

ExperimentNr	EW_2	EW_4	EW_5	EW_6	EW_7	EW_10
1			1	1	1	1
2			1	1	1	1
3	1	1	1		1	
4			1	1	1	1
5			1	1	1	1
6			1	1	1	1
7			1	1	1	1
8			1	1	1	1
9		1	1		1	

Table A1.2 | External warehouses used in experiment 1

A1.2. Details of experiment 2

This section presents the details of experiment 2. Table A1.3 presents the transportation companies that are used in experiment 2.

ExperimentNr	TC_3	TC_6
10	1	1

Table A1.3 | Transportation companies used in experiment 2

Table A1.4 presents the external warehouses that are used in experiment 2.

ExperimentNr	EW_5	EW_6	EW_7	EW_10
10	1	1	1	1

Table A1.4 | External warehouses used in experiment 2

A1.3. Details of experiment 3

This section presents the details of experiment 3. Table A1.5 presents the transportation companies that are used in experiment 3.

ExperimentNr	TC_3	TC_5	TC_6
11		1	1
12		1	1
13	1		1
14	1	1	1
15	1	1	1
16	1		1
17	1	1	1
18	1	1	1
19	1		1

Table A1.5 | Transportation companies used in experiment 3

Table A1.6 presents the external warehouses that are used in experiment 3.

ExperimentNr	EW_4	EW_5	EW_6	EW_7	EW_8	EW_10
11	1	1		1	1	
12	1	1		1	1	
13		1	1	1		1
14	1	1	1	1		
15	1	1		1		1
16		1	1	1		1
17	1	1	1	1		1
18	1	1	1	1		1
19		1	1	1		1

Table A1.6 | External warehouses used in experiment 3

A1.4. Details of experiment 4

This section presents the details of experiment 4. Table A1.7 presents the transportation companies that are used in experiment 4.

ExperimentNr	TC_3	TC_5	TC_6
20	1		1
21	1		1
22		1	1
23	1		1
24	1	1	1
25		1	1
26	1	1	1
27	1	1	1
28		1	1

Table A1.7 | Transportation companies used in experiment 4

Table A1.8 presents the external warehouses that are used in experiment 4.

ExperimentNr	EW_2	EW_3	EW_4	EW_5	EW_6	EW_7	EW_10
20				1	1	1	1
21			1	1		1	1
22		1	1	1		1	
23	1		1	1		1	1
24	1		1	1		1	
25		1	1	1		1	
26			1	1	1	1	1
27	1		1	1		1	
28		1	1	1		1	

Table A1.8 | External warehouses used in experiment 4

A1.5. Details of experiment 5

This section presents the details of experiment 5. Table A1.9 presents the transportation companies that are used in experiment 5.

ExperimentNr	TC_3	TC_5	TC_6
29			
30	1	1	1
31		1	1
32	1	1	1
33	1	1	1
34		1	1
35	1		1
36	1		1
37	1		1

Table A1.9 | Transportation companies used in experiment 5

Table A1.10 presents the external warehouses that are used in experiment 5.

ExperimentNr	EW_2	EW_4	EW_5	EW_6	EW_7	EW_10
29						
30		1	1	1	1	
31		1	1		1	
32		1	1	1	1	1
33		1	1		1	1
34		1	1		1	
35	1		1		1	1
36			1		1	1
37			1		1	1

Table A1.10 | External warehouses used in experiment 5

A1.6. Details of experiment 6

This section presents the details of experiment 6. Table A1.11 presents the transportation companies that are used in experiment 6.

ExperimentNr	TC_3	TC_6
38	1	1
39	1	1
40	1	1
41	1	1
42	1	1
43	1	1
44	1	1
45	1	1

Table A1.11 | Transportation companies used in experiment 6

Table A1.12 presents the external warehouses that are used in experiment 6.

ExperimentNr	EW_5	EW_6	EW_7	EW_10
38	1	1	1	1
39	1	1	1	1
40	1	1	1	1
41	1	1	1	1
42	1	1	1	1
43	1	1	1	1
44	1	1	1	1
45	1	1	1	1

Table A1.12 | External warehouses used in experiment 6

A1.7. Details of experiment 7

This section presents the details of experiment 7. Table A1.13 presents the transportation companies that are used in experiment 7.

ExperimentNr	TC_2	TC_3	TC_6
46		1	1
47		1	1
48		1	1
49		1	1
50		1	1
51		1	1
52		1	1
53		1	1
54		1	1
55	1	1	1
56		1	1
57		1	1
58	1	1	1
59		1	1
60		1	1
61	1	1	1
62		1	1
63		1	1
64	1	1	1
65	1	1	1
66		1	1
67	1	1	1
68	1	1	1
69		1	1
70	1	1	1
71	1	1	1
72		1	1
73	1	1	1
74	1	1	1
75		1	1
76	1	1	1
77	1	1	1
78		1	1
79	1	1	1
80	1	1	1
81		1	1

Table A1.13 | Transportation companies used in experiment 7

Table A1.14 presents the external warehouses that are used in experiment 7.

ExperimentNr	EW_2	EW_5	EW_6	EW_7	EW_10
46		1		1	1
47		1		1	1
48		1		1	1
49		1		1	1
50		1		1	1
51		1		1	1
52		1		1	1
53		1		1	1
54		1		1	1
55		1	1	1	1
56		1	1	1	1
57		1	1	1	1
58		1	1	1	1
59		1	1	1	1
60		1	1	1	1
61		1	1	1	1
62		1	1	1	1
63		1	1	1	1
64		1	1	1	1
65		1	1	1	1
66		1	1	1	1
67		1	1	1	1
68		1	1	1	1
69		1	1	1	1
70		1	1	1	1
71		1	1	1	1
72		1	1	1	1
73	1	1		1	1
74	1	1		1	1
75	1	1		1	1
76	1	1		1	1
77	1	1		1	1
78	1	1		1	1
79		1	1	1	1
80		1	1	1	1
81		1	1	1	1

Table A1.14 | External warehouses used in experiment 7

A1.8. Details of experiment 8

This section presents the details of experiment 8. Table A1.15 presents the transportation companies that are used in experiment 8a.

ExperimentNr	Used transportation companies
82	TC_1, TC_3, TC_6
83	TC_2, TC_3, TC_6
84	TC_3, TC_4, TC_6
85	TC_3, TC_5, TC_6

Table A1.15 | Transportation companies used in experiment 8a

Table A1.16 presents the external warehouses that are used in experiment 8a.

ExperimentNr	Used external warehouses
82	EW_1, EW_6, EW_7, EW_10
83	EW_5, EW_6, EW_7, EW_10
84	EW_3, EW_5, EW_6, EW_7, EW_10
85	EW_4, EW_5, EW_6, EW_7

Table A1.16 | External warehouses used in experiment 8a

A1.9. Details of experiment 9

This section presents the details of experiment 9. Table A1.17 presents the transportation companies that are used in experiment 9.

ExperimentNr	TC_3	TC_6
86	1	1
87	1	1
88	1	1
89	1	1

Table A1.17 | Transportation companies used in experiment 9

Table A1.18 presents the external warehouses that are used in experiment 9.

ExperimentNr	EW_5	EW_6	EW_7	EW_10
86	1	1	1	1
87	1	1	1	1
88	1	1	1	1
89	1	1	1	1

Table A1.18 | External warehouses used in experiment 9