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Master Thesis

Network Integration with Forward and Returning Product Flows

A case study at Quooker

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Preface

This report is written for the completion of the Master of Science degree in Transport, Infrastructure and Logistics at the Delft University of Technology. The research was conducted at Quooker, a company where I started my internship in September 2022. This thesis focused on improving a distribution network, and this was done whilst taking both the products into account that are sent to customers as well as the products that customers send back towards a production facility. Performing this research has been both interesting and challenging. Ensuring that this thesis had practical and academic relevance was an educational experience. This thesis has given me a better view of logistical problems' complexity and has given me experience in analysing these problems through mathematical modelling and programming. Applying the methods I learned during my studies to a real-life problem was interesting. Although applying these methods during this thesis was very challenging, I can now say that it was an insightful experience.

First of all, I would like to thank Bilge Atasoy and Stefano Fazi for always making time to give feedback and support me throughout the thesis process. Moreover, I would like to thank Pieter Jonkman for his time, for his feedback and for his answers to sometimes impossible questions. Furthermore, I would like to thank everyone at Quooker that has provided me with information for this project. I would also like to thank my friends for their support during the last couple of years at the TU Delft. I had fun during our many group projects, and your support during the last months was essential for finishing this project. Lastly, I would like to thank my family for their optimism and confidence in me.

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Summary

Transport networks are becoming increasingly complex. With customers and suppliers expected to be connected globally, the pressure on designing efficient transport networks increases. This research analyses the network of Quooker, a Dutch company that sells boiling water taps throughout Europe. The goal is to develop an efficient service network design for this company. This company has different flows in its network. On the one hand, products are sent to customers; on the other hand, there is a returning flow of products that must be refilled and replaced. While analysing and optimising the service network, the forward and return flow integration and its effects are examined.

The main question that this research answers is how to best design a transport network for these forward and returning flows. To analyse this, a service network design is optimised with three different techniques throughout several scenarios:

1. Current practice: a network in which there are no depots available, so no consolidation opportunities
2. Sequential optimisation: depot is available, return and forward flow are optimised sequentially
3. Simultaneous optimisation: depot is available, return and forward flow are optimised simultaneously

When optimising the flows sequentially, first only the forward flows are taken into account, after which the return flow is added to the existing infrastructure. The optimisation of forward and returning flows happens at the same time when performing simultaneous optimisation. This research first formulates a mathematical model that can optimise the service network design and its characteristics, after which different scenarios are analysed regarding network costs, truck usage and network design. Decision variables of the model are the amount of flow on an arc, the services that are used on such an arc, if a depot is opened at a location and its capacity. The objective of this model is to minimise the total network costs, which are service costs, inventory costs and depot-specific costs (if one is opened).

The scenarios that are analysed either have a country-based or distance-based cost structure. For the country-based structure, service prices are based on which country it was sent to, and the distance-based structure is based on the amount of kilometres driven. The three country-based scenarios analysed are the current state of the case study, a scenario where the return flow is increased and a scenario where it is possible to send products by train. The distance-based scenarios are the distance-based model with the same volumes as the current state of the case study, the scenario where transport is done internally and a generic scenario with two production facilities. The main finding is that performing simultaneous optimisation is better than sequential optimisation for all scenarios except the current state, since it is not beneficial to open a depot in this scenario. Only when the volume is increased for this scenario, the benefits between simultaneous and sequential optimisation are around 1%. For the other scenarios, simultaneous optimisation ensures that the depot is built with the right capacity to handle all flows. Moreover, the depot's location can also differ between these optimisation techniques. Simultaneous optimisation for these scenarios is around 2-5% better than using sequential optimisation. Cost reduction of opening a depot ranges between 4-13%. Using the train for transportation was not efficient for realistic input parameters.

Next to the results on the network costs, another finding is that using a simultaneous optimisation technique increases the number of used services but decreases the total amount of driven kilometres by these services.

Lastly, results show that external logistics providers are already very efficient in consolidating products, which is why they can offer their services at a very competitive price. This means that optimising the flows generally does not result in substantial network cost reductions.

All in all, in the current situation scenario, it is not effective to open a depot and use simultaneous optimisation. However, when parameters like the volume or the service costs are increased, or a distance-based pricing system is implemented, it is beneficial in terms of costs. Simultaneous optimisation ensures that, contrary to sequential optimisation, depots are built in the right location and at the right capacity. Choosing a different pricing system will have more effect than staying with the current country-based system. These results can be generalised to other cases with a network that consists of forward and returning flows. Before doing so, it is recommended that all costs are re-estimated and that a new focus should lie on increasing the number of nodes in the network. Increasing the number of nodes gives a more detailed, realistic model.

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1. Introduction

In recent years, several manufacturing companies have established increasingly complex supply chains due to the variety of customers' requirements. Many different transport flows exist in these supply chains. Typically, global suppliers forward their products to a local production facility. Afterwards, from the production facility, finished goods are transported to consumers located all over the world. These companies often have many different suppliers in different places, since companies want to find the cheapest suppliers of all the raw materials needed (Shibasaki et al., 2021). This results in a complex network with many different, small individual flows. Decisions involving handling these flows, like which flows to consolidate to a depot and what depots to open, are important for a long-lasting, efficient supply chain (Ramezani et al., 2013a).

This paper analyses the flows of a production location that receives goods from suppliers, which they turn into usable end-products, and send to consumers. Next to these flows, there are returning flows that go towards the production location, one is from the suppliers of raw materials, and the other is from consumers. This last flow exists because products must be repaired, replaced or refilled. A problem for production locations with this many flows is that the individual streams of products are small, and because of this, economies of scale cannot be achieved even though the total volume of flows can be quite large. A solution for this is to consolidate the shipments into larger flows that are sent to a depot. Consolidating shipments has proven to be economically beneficial (Van Belle et al., 2012). However, it is still a challenge to implement this.

To reduce transportation costs, companies can integrate small flows into larger flows. For example, products can be shipped together to an intermediate facility, from where the products can individually be transported towards their final destination. Such a problem can be optimised with a service network design. In a service network design problem, the volume of products towards or from depots is optimised by looking at available services (Crainic and Hewitt, 2021). Currently, companies do not consider that the returning flow can be taken into account in their decision-making simultaneously with the outbound flow, making their solution even more sub-optimal (Pishvaee et al., 2010). By considering all these flows simultaneously, a more efficient network can be designed where both flows make use of the built infrastructure.

Previous literature on service network design focuses on multiple aspects. Most research on the integration of forward and returning flows focuses on a supply chain network design (like papers by Zhang et al., 2014, Sadjady and Davoudpour, 2012 and Amin and Baki, 2017). The difference between a service network design and a supply chain network design is that the latter mainly focuses on the facility locations and allocation of goods, whereas the former has a bigger focus on how to distribute these goods in terms of available services. For a service network design, the effect of considering forward and returning flows has not been researched before. In addition to investigating the integration of all flows in a network, this paper focuses on a combination of strategic decisions like which depots to open, and on tactical decisions like which modes should transport the goods and what the capacity of the depot should be. As done in previous papers, this paper also considers a multi-commodity network (like Xiang et al., 2022 and Pedersen et al., 2009). Moreover, this research allows that some shipments can go directly to a consumer, and others go indirectly through a depot. Lastly, a multi-modal network is investigated, where it is possible to transport goods by both rail and road. To our knowledge, a study considering all these aspects together does not yet exist in the literature.

This research aims to design a network with possible depot locations and goods that must be transported to their destination, which can either be the production facility or the final customer. This network is designed by considering both the forward (to the customer) and reverse (to the production facility) flow in a network. The goal is reached by using a network design model and by including multiple commodities and modalities. This research investigates different possible future scenarios which can include the growth of the flows in the network and the usage of different modes of transportation. To support this research, the data of Quooker, a company that sells boiling water taps, is used for the case study.
This research paper focuses on answering the following question:

How can a combined forward and returning transport network for a production facility be designed effectively and efficiently?

Throughout this research, a forward flow is a flow that originates from the production facility, whereas a return flow ends at the production facility. This main question can be answered with the help of the following sub-questions:

1. What is the state-of-the-art in designing transport networks with combined flows?

To make sure that this paper focuses on a new research direction, the state of the art in literature has to be found. By answering this question, it is known what has already been researched and where the literature gaps lie.

2. What is the right methodology to optimise the network?

There are different ways to optimise problems, and this question helps find the suitable method to solve the state-of-the-art problem.

3. What network characteristics should be taken into account when composing the model?

This question addresses which characteristics are integrated into the model, and equally important, which characters are left out.

4. What are the network results when optimising the model for a case study?

By answering this question, the model's results are known, three sub-questions support this question:

4.1. When is it useful to open new depots in this case study?
4.2. When is it useful to implement multi-modal transport in this case study?
4.3 What is the effect of taking both the forward and return flow into account, compared to only the forward flow when designing a network?

Sub-question 1 investigates the threshold of opening new depots. Opening this can be expensive and may only be helpful for a particular minimal volume of goods or for a certain price of opening a depot. Sub-question 3.2 is similar to sub-question 3.1, but instead of investigating the depots, it examine the threshold for using multi-modal transport. Wanting to use both trains and trucks in a network results in a different infrastructure of the network (locations of depots can for example only be near railway hubs). These extra costs may be too much when a network has a small flow of products but can be more beneficial when the volume is high. The last sub-question addresses the effect of considering both flow types instead of only forward flows.

5. To what extent can the results of the case study be generalized to other cases?

This question is answered so that it is known what aspects of the case study are case-specific and what aspects and benefits can be generalized towards other cases.

This paper is structured as follows: chapter 2 presents the literature review that is performed to find the knowledge gap. Afterwards, chapter 3 discusses the research methods. Chapter 4 describes the system that is investigated. In chapter 5, the mathematical model for this system is given. This mathematical model is applied to a case study. The explanation of the case study and its results are shown in chapter 6. Lastly, the discussion, conclusion and recommendations are presented in chapter 7.

2. Literature review

Network design for logistics consists of multiple aspects. There are four decision layers in network design problems: location, topology, allocation, and routing decisions (Maknoon, 2021). In each of these layers, different problems may occur. As is stated in chapter 1, the focus of this paper will be on an integrated service network design, where different flows can share the same infrastructures, and on the consolidation of the flows in this network. The following section will analyse literature that has already been written on the network design problem in general and will later go more in depth on the integration of flows.

2.1 Network design

Network design is a strategic decision that deals with the design of infrastructures (Maknoon, 2021). When designing a network in logistics, multiple characteristics can be taken into account. One of these characteristics is a multi-commodity network. One of the first research papers on a multi-commodity network design is by Ford and Fulkerson written in 1957. They looked at a mathematical model to determine the maximum multi-commodity flow in a network. Many adaptations to this model were made later in time. Another extension of the network design problem is the implementation of multiple modalities.

Multi-modality network design is when multiple modes of transportation can transport products. The product can for example first go by ship and do the last-mile transportation by truck. Multi-modality can also be combined with other extensions of the service network design problem, like multi-commodity. Multi-modality is very useful to take into account for long-haul transportation, since it can be cheaper and more sustainable. For short-haul transportation, it can be helpful since the network will be more flexible (SteadieSeifi et al., 2014). One paper discusses a multi-commodity supply chain network design with mode selection. This model decides on aspects like the distribution centres' location, the manufacturing plants' size and the customers' allocation to these centres. Moreover, since it is a multi-modal problem, they decide on what transport mode should be used for the links (Sadjady and Davoudpour, 2012).

A more recent network study on multi-modality aimed to design a sustainable maritime distribution network in which multiple types of ships could be used to carry goods (Dong et al., 2020). Next to that, trucks were also available for transportation. Their case study proved that multi-modal transport is both environmentally friendly and economically beneficial. The authors state that future research could focus on changes in the fuel prices of ships. Next to that, they did not include the fact that a ship's fuel consumption is non-linear when the ship's speed is adapted. Future research should focus on this non-linearity. In addition to these studies, many studies about network design problems focus on how to solve the mathematical model best instead of only making a design. Many algorithms have been developed to ensure that a (near-)optimal solution can be found in a relatively short running time. For example, a study by Barahimi et al. used a particle-swarm-optimisation (PSO) algorithm to solve a network design in an urban area. Different public transport modes are considered while designing this network in this urban area. One important extension to this study could be the integration of air pollution and fuel consumption, since this is important when researching urban areas where many people live (2021).

2.2 Service network design problem

Where network design planning involves strategic, long-term decisions, a service network design focuses on tactical decisions. Network design decides how a network should be connected and by which type of mode. Service network design goes more into detail, and involves decisions on the planning, routing and scheduling of services. A service network design is useful in consolidation-based transportation, since it can consider service schedules and capacities (Crainic and Hewitt, 2021). The planning horizon for tactical problems is around 3-5 years. If a new network is designed, a strategic decision could for example be which depots to build and which nodes should be connected to this depot, whereas a service network design decides when these modes should transport the goods and which goods should be consolidated. Products can be consolidated until they reach a depot, after which they will be separated for individual last-mile delivery.

A scheduled service network design (SSND) is similar to the service network design. However, the nodes are modelled on a time-space network. Demand nodes also have some different characteristics. Next to a commodity's origin and destination nodes, it also has an availability time and a due time. The node set in a SSND consists of both the node and the time at which this node is available for activities, so node i is in the form of: (i, t). The arc set consists of an arc leaving from one node at a particular time and arriving at another node at a specific time, thus $a = ((i, t_d), (j, t_a))$, thus a node with its departure time and a node with its arrival time. A holding arc comes in play when a commodity stays at a node, either to wait for consolidation or to be processed. A holding arc is an arc that stays at the same physical node for a time step. Holding arcs can be modelled as the following: $a = ((i, t_d), (i, t_d + 1))$. With these node and arc definitions, the 'basic' mathematical model of a SSND can be made. The mathematical model below is adapted from the model by Crainic and Hewitt (2021). The basic version of a SSND consists of two decision variables:

- y_{ij}: a variable indicating whether a service is used on an arc or not
- x_{ij}^k: a variable indicating the flow on an arc

These decision variables will change when changing the service network design. These changes can for example be adapting the model to a multi-modal network. Next to the decision variables, there are some important parameters for a service network design.

- w^k:the demand for commodity k
- u_{ij}: the capacity on arc (i,j)
- f_{ij}: the fixed costs associated with the use of arc (i,j)
- c_{ij}^k: the variable costs associated with moving commodity k on arc (i,j)

$$Minimize \sum_{((i,t_d),(j,t_a))\in A} (f_{ij} \times y_{ij}) + \sum_{((i,t_d),(j,t_a))\in A} \sum_{k\in K} (c_{ij}^k \times x_{ij}^k) \tag{2.1}$$

s.t.

$$\sum_{j\in N^+(i,t)} x_{ij}^k - \sum_{j\in N^-(i,t)} x_{ji}^k = \begin{cases} W^k, & \text{if } i = o_k \\ -W^k, & \text{if } i = d_k \\ 0, & \text{otherwise} \end{cases} \quad \forall \quad (i,t) \in N, k \in K \tag{2.2}$$

$$\sum_{k\in K} x_{ij}^k \leq u_{ij} \times y_{ij} \quad \forall \quad ((i,t_d),(j,t_a)) \in A \tag{2.3}$$

$$y_{ij} \in \{0,1\} \quad \forall \quad ((i,t_d),(j,t_a)) \in A \tag{2.4}$$

$$x_{ij}^k \geq 0 \quad \forall \quad ((i,t_d),(j,t_a)) \in A, k \in K \tag{2.5}$$

The objective (Equation 2.1) of the model is to minimize all costs. These costs include the fixed costs of opening a service (i.e. paying a truck driver) and the costs per commodity transported. Constraint 2.2 is the flow conservation constraint. If the node is an origin of a specific commodity, then all outgoing flow minus all incoming flow should equal the demand. If the node is the destination of that commodity, then it should equal the negative of the demand. If a node is neither the origin nor the destination, but for example a depot, then the incoming flow should equal the outgoing flow. Constraint 2.3 makes sure that the capacity of a certain service cannot be smaller than the flow on that service arc. The last two constraints (Equation 2.4 and Equation 2.5) are variable-type constraints that state that the service used on an arc is a binary variable, and that the flow cannot be a negative number.

Early works on the service network design date (SND) from 1986, which looked at a multi-modal, multi-commodity freight transportation problem on the tactical planning level (Crainic and Rousseau, 1986). Many adaptations on this topic were made later on. An example of an extension is a paper by Sung and Song, where they introduce cross-docks as a decision variable of the SND (2003). Instead of modelling on a time-space network, these authors have set time limits to the routes of products. Moreover, they only use forward flows in their cross-docking system, no returning flows. Another aspect that is often researched in a SND is fleet management. This can be in terms of design-balanced constraints, where the number of services that enter a terminal and leave one should be balanced (Pedersen et al., 2009), or in terms of a limited set of vehicles that have to be re-positioned, for example, a paper where empty containers had to be re-positioned in a service network design (Meng and Wang, 2011). An example of one of the more recent papers about this topic is the one written by Xiang et al. in 2022. In this paper, a robust service network design problem is examined. A robust network is a network that also performs well when different, more unexpected scenarios occur. The network performance variation is minimized by making a robust network design (Ghayoori and Leon-Garcia, 2013). When for example worst-case scenarios occur, the network is designed in such a way that it still performs relatively well. This paper makes it robust by implementing penalty-limiting constraints. If the model provides an infeasible scenario, it will be penalized. Decision makers can set their penalty limit. When this limit is set high, the model takes more risks than when it is low.

2.3 Integrated reverse logistics

Taking this literature review to a more detailed level, the integration of different flows in a network will be looked at. This topic has been studied increasingly over the last few years. What is meant by the integration of different flows is that the forward and return flow of products is optimised simultaneously in the network instead of sequentially. Fleischmann et al. showed that optimising these two flows simultaneously could result in a significant cost reduction compared to the sequential approach (2009).

In literature, the return flow is defined as reverse logistics (RL), which is “the role of logistics in product returns, source reduction, recycling, materials substitution, reuse of materials, waste disposal and refurbishing, repair, and remanufacturing” (Stock and Council of Logistics Management, 1998). Over the last few years, research has focused increasingly on the area of RL. A measurement from 2019 shows that since 2008, the increase in the number of publications about reverse logistics is 300% (Prajapati et al., 2019). This increase is due to multiple aspects like environmental, economic and social factors (Alshamsi and Diabat, 2015). Reverse logistics in most papers is seen as a separate flow. A limited number of papers discuss an integrated forward/reverse logistics flow for their network design. An integrated forward/reverse logistics network design means that the infrastructure of the forward flow can also be used for the returning flow. Activities of the reverse flow can strongly influence the activities of forward flow and network when these flows are integrated, like the capacity of storage spaces and transport capacity (Lee and Dong, 2008).

Integrated reverse logistics is mostly researched in a supply chain network design (SCND). SCND mostly deals with decisions like the number, size and location of facilities throughout a full supply chain, and sometimes also expands to some tactical and operational decisions (Farahani et al., 2014). The difference between a SND and a SCND is that the SCND mainly focuses on the facility locations and allocation of goods, whereas the SND focuses more on how to distribute these goods in terms of available services. One way to integrate reverse logistics into a supply chain is to make the supply chain a closed-loop process. By doing this, products that are broken and need to be fixed are sent back to the production facility and then added to the forward logistics process again (Shekarian, 2020). A study on closed-loop supply chains was performed in 2020 by Govindan et al. This paper studied the effectiveness of a closed-loop supply chain with uncertain factors. This study used separate distribution and collection centres, and from collection centres, products could either be disposed of or repaired and put back into the forward logistics process. Another study on closed-loop supply chains used a different network design. In this network, there was an extra option for returning products. Products from a customer could either go back to the suppliers of raw materials, go back to the production plants or go towards the distribution centre to be reused (Soleimani et al., 2017). A different study on closed-loop supply chain network design integrated global factors for the facility location model (Amin and Baki, 2017). These global factors were for example exchange rates and customs duties. Investigating a global supply chain is important since suppliers, producers and customers are often located in different countries. They conclude that global factors play an important role in the closed-loop network, and that the optimal network may change when not considering these factors. However, Amin and Baki have only taken into account that just suppliers are located all over the world, and they advise future research to also look at international plants and collection centres in addition. An interesting aspect is that this research, unlike the other research described above, considers multi-commodity networks. When looking at the integration of reverse flows in a service network design specifically, no literature is found.

As described before, an expansion in terms of flow integration compared to the closed-loop supply chain papers is the usage of a facility that can integrate both forward and returning flows, instead of making two separate facilities for this. A paper on this topic was written by Pishvaee et al. They integrate the flows by designing a network with cross-docks for RL and distribution centres for the forward logistics (FL). The location of these centres is a decision variable in the mathematical model (2010). This paper mainly focuses on the effectiveness of their algorithm and states that future research could address robust models to integrate the changing parameters over a long period of time. Furthermore, they state that papers can focus more on stochastic parameters in the model, which were not implemented in their research. This is what was done in a paper by Ramezani et al. in 2013a. They considered stochasticity in variables like production costs, demands and return rates, which is an interesting and valuable enlargement of the integrated FL/RL research. Another paper that took uncertainty into account while designing an integrated network was by De Rosa et al. (2013). They used facilities to collect and deliver products and looked at a long-term time horizon. To take this long-term horizon into account, extreme uncertainty was taken into account to be able to design a robust model.

2.4 Fully integrated network design

The previous section only described papers where forward and reverse logistics were integrated into a supply chain network design. However, they did not consider that suppliers could also be integrated into a network. When looking at a network design where the supply flow of 'raw materials', the demand flow towards the consumer and the returns flow are integrated, only one paper is found. This paper is written by Zhang et al. They investigated an integrated supply chain network design problem (2014). In this network, hybrid collection/distribution centres handle incoming products from suppliers and outgoing products towards customers. There could also be separate distribution and collection centres. The model used in this paper decided the location of these new centres, the type (distribution, collection or hybrid) and allocated customers and suppliers to these locations to save costs for this network. This paper describes a single-commodity deterministic network design and uses bi-directional flows between the distribution/collection centres and the manufacturer of products. They state that future research should focus on both practical considerations of the model and the model's stochasticity. For practical considerations, they state that future research can expand the model with hybrid direct/indirect shipping (now only indirect shipping is taken into account) as well as time window constraints. Furthermore, this paper does not take multi-commodities into account.

2.5 Network design with direct and indirect shipments

Sometimes, a distribution or collection centre is not always necessary. In such networks, direct shipments from origin A to destination B occur. Reasons for direct shipments could for example be that there is a high demand for a product to a particular location or that the distance from manufacturer to the customer is short (Mokhtarinejad et al., 2015). A distribution centre can be skipped in this case, and a direct flow can occur. A paper considering this within a closed-loop supply chain is by Behmanesh and Pannek in 2016. Within this network, direct shipments and indirect shipments could occur. Next to that, since it is a closed-loop network, the returns stream of products is collected and then integrated into the forward stream. They looked at a seven-stage closed-loop supply chain network whose goal was to minimize the transportation and operation cost of the network. The authors state that an expansion of this study could be that multi-commodity, multi-capacity, and multi-period networks could be taken into account. This study also did not consider multi-modality. Next, they advise also considering a more robust network design. Another study, later on, was also done on the possibility of a network with direct and indirect shipments. This model's objective was also to minimize the costs. This model did not look at a closed-loop supply chain, but they added solid transportation to the model. Solid transportation is a method to bring flexibility into the supply chain by letting the model choose between different modes of transportation (Shoja et al., 2020). This research mainly focused on comparing thirteen algorithms for solving this problem. Next to directions for future research on the algorithms, they also advise that more echelons can be added to the network and that perishable products are an interesting expansion.

2.6 Conclusion

This chapter has presented a literature review on different forms of the network design problem. Many papers are already written on this topic, together with its adaptations. Adaptations to the original network design are for example a supply chain network design or a service network design, both with different expansions like multi-commodity or multi-modal networks. Next to these early network extensions, a more recent focus has been on integrating flows in a network, which could also be combined with the network adaptations mentioned above. Especially the integration of reverse logistics in a network has lately gotten more attention, also because sustainability is an important driver for companies today. Other recently studied adaptations to the network design problem are the possibility of having direct and indirect shipments. This is relevant when a depot is built in the network. The model can then decide if a flow should be allocated to a depot or directly moved to the main production location. Each model has different, more general aspects that they consider, like multi-commodity, stochasticity, multi-modality and global factors. The more recent studies mainly state that future research should focus on improving the algorithms, especially for studies with time-space networks. This improvement can be focused on the calculation time for a problem, which is essential since problems in network design get more complex every day. Goods can come from all over the world with many modes of transport. If all options are considered, the time it takes to calculate a (near-)optimal solution is an important aspect. Next to the calculation time, the improvement can also be focused on the solution. Some algorithms find better solutions for the problem objective than others. Next to the algorithm improvements, other new expansions to network design problems can be done for future studies. These expansions are shown in the columns of Table 2.1. Some critical papers from this literature study can be found in the rows of the table. Each paper has an 'x' if the corresponding network characteristic is used in their research. What can quickly be noticed is that an important aspect of what is missing in these papers is the integration of supplier returns together with the customer returns. Suppliers of raw materials are often not combined with the returns flow, while in some cases, that could be efficient since they are both backward flows. The main difference between a returning flow from a customer and a supplier is that they are most likely different in size. It is also possible that these flows are transported in a different mode since they are different types of goods (in bulk or separate products). Next to that, a returns flow from a customer is not planned in either the location or in terms of time. Contrary to this flow, the flow from a supplier is usually known in size and rough planning. Research on integrating all these flows can still be expanded in many forms. Moreover, specifically for a service network design, no research has been conducted on the effect of the integration of forward and reverse flows. Only research that focuses on the forward flow of products has been found within a service network design. This paper will focus on this gap, being the effect of integrating flows in a service network design. More specifically, it will look at the facility's location, capacity for a given demand, and the services necessary to fulfil this demand. It will be a multi-commodity, multi-modal network where suppliers' and customers' forward and returning flows will be considered simultaneously

Paper	**Network design**	**Supply chain network design**	**Service network design**	**Facility location**	**Multi-commodity**	**Multi-modality**	**Integrated suppliers returns**	**Integrated customer returns**	**Uncertain/ stochastic**	**Direct and indirect flows**
Ford and Fulkerson (1957)	x				x					
Xiang et al. (2022)	x		x		x				x	
Sadjady and Davoudpour (2012)	x	x		x	x	x				
Govindan et al. (2020)	x	x			x			x	x	
Soleimani et al. (2017)	x	x		x	x			x	x	
Amin and Baki (2017)	x	x		x	x				x	
Pishvaee et al. (2010)	x	x						x		
Ramezani et al. (2013b)	x	x		x	x			x	x	
De Rosa et al. (2013)	x	x		x				x	x	
Crainic and Rousseau (1986)	x		x		x	x				x
Sung and Song (2003)	x		x	x		x				
Zhang et al. (2014)	x	x		x			x	x		
Behmanesh and Pannek (2016)	x	x		x				x		x
Pedersen et al. (2009)	x		x		x					
Meng and Wang (2011)	x		x			x				
This paper	x		x	x	x	x	x	x		x

Table 2.1: *Overview of papers from literature review*

3. Research methods

In this chapter, the problem statement is presented together with the research methods that are applied to solve the problem at hand.

3.1 Problem statement

As described in chapter 1, some companies transport their goods through small, 'direct' flows. They do not consolidate any goods. However, the external shipping carriers that transport these goods may do that later in their own process. The problem is that companies still pay for the transportation of one single product (or one transport unit, like a parcel or a pallet), which can be expensive. This research examines the benefits of a service network design where all flows in the network (i.e. forward and backward) are considered. Implementing a network that considers all flows can reduce costs for the production company because these flows can use the same infrastructures. An example of a possible network design is presented in Figure 3.1. In this network, three depots are opened. Some are depots where both the backwards flow of products and the forward flow are collected and consolidated or separated; for others, only the return flow is consolidated. Furthermore, the consolidated flow can be transported by train instead of a truck. What the exact (near-)optimal network design will be is what is investigated throughout this paper. Using only direct, individual flows for transporting products may be cheaper in one case. However, a network design with depots can be more economically beneficial for another case with a larger volume. The following section explains how the model can get to a design like the one presented below.

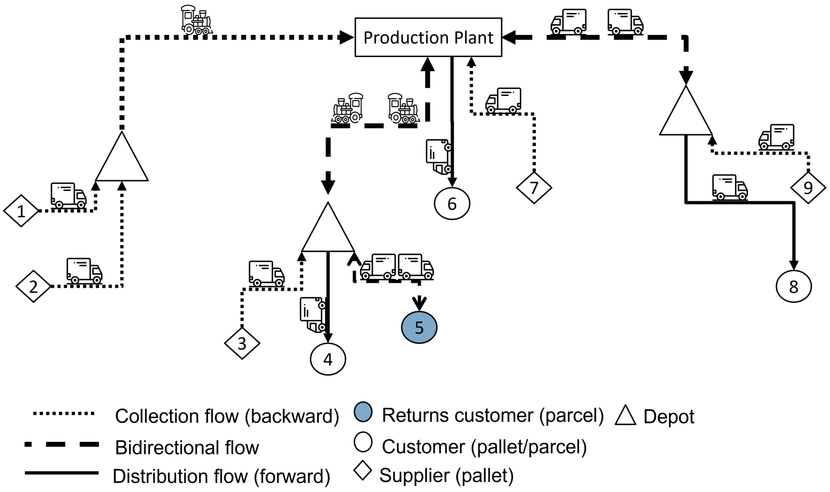


Figure 3.1: *Possible network design (nodes 6,7 are directly connected to the production facility, while others consolidate through a depot)*

3.2 Research methods

The table below shows which methods are used to answer the sub-questions. The methods are further explained in subsection 3.2.2, subsection 3.2.3 and subsection 3.2.4.

Sub-question	**Method**
1. What is the state-of-the-art in designing transport networks with combined flows?	Literature study
2. What is the right methodology to optimise the network?	Literature study
3. What network characteristics should be taken into account when composing the model?	Expert consulting & desk research
4. What are the network results when optimising the model for a case study? 4.1. When is it useful to open new depots in this case study? 4.2. When is it useful to implement multi-modal transport in this case study? 4.3 What is the effect of taking both the forward and return flow into account, compared to only the forward flow when designing a network?	Mathematical modelling & case study
5. To what extent can the results of the case study be generalized to other cases?	Conclusion

Table 3.1: *Sub-questions and methods used*

These methods are used to answer the sub-questions, which subsequently answers the main research question:

How can a combined forward and returning transport network for a production facility be designed effectively and efficiently?

3.2.1 Literature study

A literature review is conducted to determine the state-of-the-art on transport networks. Moreover, literature research is performed to find the correct methodology for optimising a transport network. The literature review has already been performed in chapter 2. What methodology is chosen and why is explained in subsection 3.2.3 of this chapter.

3.2.2 Desk research & expert consulting

The third question is answered by consulting experts and performing desk research. For expert consulting, important actors, possibly from the case study, are consulted to answer the questions. These experts have a better view of the current network of production facilities and future possibilities due to their experience with the problem. Desk research is also performed to answer the first two questions. For desk research, information is collected and analysed, and with this information, research questions can be answered.

3.2.3 Mathematical modelling

To optimise the service network design, mathematical modelling can be used as a tool. As Bender stated: “A model is something that mimics relevant features of the situation being studied” (2000). Bender subsequently calls a mathematical model “an abstract, simplified, mathematical construct related to a part of reality and created for a particular purpose”. Based on the model’s goal, decision variables and constraints, a mathematical optimisation model is able to decide what the (near-)optimal network design is. There are many different types of mathematical models. They can be linear or nonlinear, static or dynamic, explicit or implicit, discrete or continuous, deterministic or stochastic, deductive or inductive, strategic or non-strategic. Different aspects are implemented in a mathematical model depending on the problem that has to be solved. A mathematical model is chosen over a simulation model as mathematical models can generate (near)-optimal solutions. This is something that simulation models cannot do (Caggiano et al., 2015).

Mathematical models have some limitations, which should be considered when choosing a research method. The limitations of mathematical models, specifically models in transportation policy analysis, were already described in 1979 by Richardson. One of the limitations described is that models are incomplete. They are not the same as real-world situations but are abstractions of reality. It is important to ensure that key aspects of the real-world situation are included in a model. Furthermore, limitations often occur in the data. A model is dependent on its input data, and a wrong number in the input data could have a big impact on the outcome of a model. Furthermore, input data may be uncertain and some models do not take this uncertainty into account. Another limitation of a model is that its usefulness is limited to its original purpose. Models are adaptable to situations other than the original ones. However, changing it is a task that requires expertise. Lastly, the limitation that Richardson describes is that the apparent precision of model forecasts may be misleading. Model outputs are exact; however, one should consider that this precision is not always accurate. Mathematical models also have many advantages. Advantages described by Hillier and Liebermann are presented below. A big advantage to a mathematical model is that it describes a problem without biases (contrary to a verbal description of a problem). Moreover, it can describe important causal relationships and, in that way, indicate additional relevant data for the analysis. It can also consider a large problem with all interrelationships at the same time, which a human cannot always do due to the size of a problem. Finally, a mathematical model can be put in a software program to solve the problem. If the limitations to mathematical modelling are considered whilst creating one, a mathematical model can be a handy optimisation tool for a wide selection of problems.

The majority of papers that use mathematical modelling in supply chain production and transport planning are (mixed) integer linear programming models (Mula et al., 2010). These models are becoming more popular due to the emergence of linear-programming solvers and the flexibility of these models (Vielma, 2015). This paper uses an integer programming model since there are only binary and integer variables. Next to that, a linear model is used for this service network design. This means that the objective function and its constraints are linear formulations. A literature study is performed to learn more about how similar models are designed. Then, these models can be adapted to develop the mathematical model for this specific case.

3.2.4 Case study

Since a mathematical model is a description of a real-world phenomenon, it is interesting to see how this model performs in real-life situations. This mathematical model is put into practice by performing a case study. The parameter values, network possibilities and demand in the network represents the case studied. Data is needed from the case to perform the study, because before one can solve a problem, data about this problem needs to be collected. Hillier and Liebermann state that researchers typically spend much time gathering data about the problem. According to them, this is necessary to better understand and provide the input needed for the eventual mathematical model (2015). Next to data collection, data also needs to be processed, which can be time-consuming. It cannot be expected that all the collected data can immediately be put into the model. Multiple types of data are to be collected to solve this case study. First of all, the network's demand must be known for all flows per commodity. Furthermore, the parameter values for the network costs have to be collected. Moreover, the possibilities for modes throughout this network has to be researched before formulating the model. The mathematical model can be formulated and solved with all information collected from the case. Solving the model can be done multiple times for different scenarios. This is important since companies change over time, so flows may also change over time. It is important to consider future changes when making a network design.

Figure 3.2 shows the process of performing a case study together with a mathematical model. The process starts with the case itself. This is a real-world problem which should be simplified before it can be used. Two simplifications occur, one of which is the mathematical model. Translating the real-world phenomenon to a mathematical model should be done with much care, as explained in subsection 3.2.3. The other simplification is that of the case towards the data. Data can be very detailed, and these details sometimes have to be simplified to ensure the mathematical solver can find a solution. An example of this is that a company has all the specific addresses of customers, but using all individual addresses as input is too complex for the model. In this case, clusters have to be made to simplify the input data. Other than simplifying the data, sometimes data also has to be adapted to the correct units. The mathematical model and the collected data together are used for the solver. An mathematical solver will be used for this project. Examples of mathematical solvers are CPLEX or Gurobi. When solving a model, different problems can occur. These can be linked to the mathematical model and the collected data. Implications can be that the time to solve the problem takes too long or that there is no optimal solution. For both of these problems, there must be a reflection on the mathematical model and collected data, and adaptations must be done to resolve these implications. The mathematical solver will give the optimal network design solution when no implications occur. This network design solution consists of depot location, depot capacity, allocation to these depots, the volume of flows and their modes. Validation should be done to know that the model and its outcomes are correct.

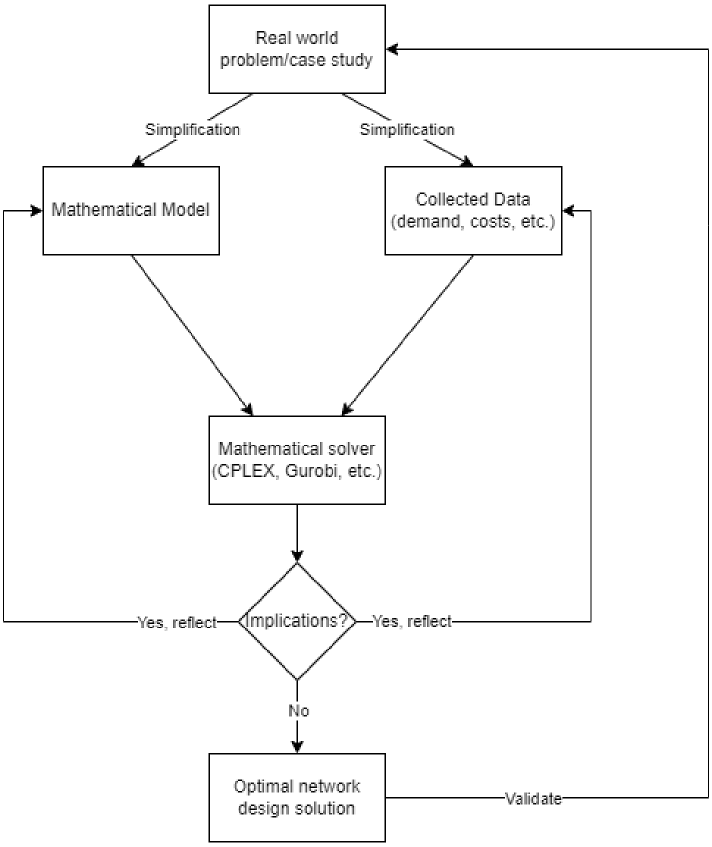


Figure 3.2: *Process of performing a case study, adapted from Zeytun et al. (2016)*

4. System description

This chapter goes further in depth on the system that is analysed in this research. The network decisions that are made are discussed in the following sections.

4.1 System decision level

optimising a network deals with many different decisions. When discussing an optimisation problem for a transport network, three primary types of models can be taken into account: operational, strategic, and tactical models. These three types can determine vehicle routes, capacity planning strategies and facility locations. The three models are discussed in the following sections. Next to the three decision levels, combined levels can also be made. This is also known as vertical integration, while horizontal integration is when decisions within the same level are joined together (Pishvaee et al., 2010).

4.1.1 Strategic

Strategic planning is on the long-term horizon (2 to 5 years) (Sheriff et al., 2012). Strategic decisions cannot simply be changed after implementation, one of the reasons for this is that high investment costs are linked to strategic decisions. With strategic decisions, questions like where to locate a depot or what vehicle types to invest in are answered. The existing flows in a network can influence these types of decisions. For example, if both the forward stream and the returning stream of products are taken into account, the location of depots might be different compared to a model where only one of them is taken into account. Other decisions taken in a strategic network are the optimal number of opened facilities, the capacity of these facilities and the flows allocated to these facilities (and between facilities).

4.1.2 Tactical

On the slightly shorter-term planning than strategic decisions lie the tactical decisions. Tactical decisions are made for the next year or two. Decisions on the tactical level consist of how often trucks should drive between a depot and a production facility to fulfil demand, while also considering that the depots' capacity is not exceeded. The decisions made on the strategic level influence this. On the strategic level, the capacity of a depot is chosen, while the tactical level has to consider this capacity when making the network. Consolidation-based decisions, like which products of different customers can be grouped in the same transport vehicle, are also part of decisions made on a tactical level. This is done to aim for a balance between economies of scale and service quality (Crainic and Hewitt, 2021).

4.1.3 Operational

The operational model is the most detailed. All decisions made in the strategic and tactical models set the foundation of the operational model. Moreover, it concerns the shortest-term planning (day-to-day decisions). With an operational model, decisions on vehicle routes and departure and arrival times can be made (Misni and Lee, 2017). The vehicle routing problem can be for both a forward and a returning stream of products. A vehicle can for example deliver a package to a customer and pick something up at a supplier near that customer to return to the depot. The flow allocated to depots can impact the size of a truck needed for the last-mile delivery. Moreover, a product's delivery window also influences this last-mile delivery.

4.1.4 Chosen system decision level

From the literature review, it became apparent that investigating the effects of considering both the forward and returning flow when performing network optimisation has not been researched often. The effect of considering both flows on the location of depots, their capacities and on the choices made for transport (like consolidation opportunities and transport frequencies) is researched in this paper. The facility location problem is part of a strategic level, since this is on the long-term planning horizon. However, consolidation opportunities and transport frequencies fall under the tactical network decision layer. This is why a service network design is formulated together with a location problem in this paper. A service network design is used to model tactical-level decisions. It can be expanded with the choice of opening certain facilities, depending on characteristics like location and costs. With a general, static service network design, results can show how many vehicles are needed to satisfy demand efficiently. For a static design, it is assumed that in each time step, the same things happen. For example, the same demand needs to be fulfilled at the same nodes in each time step (Crainic and Hewitt, 2021). However, the model analysed in this paper is time-dependent. This means that the model also needs to represent when services leave, when they arrive, when demand is created and when it needs to be fulfilled. This is important for models where in each time step, different activities happen. When wanting to perform consolidation, time is an important aspect. The departure time of a transport type (i.e. a truck) has to be known for consolidation. When a truck leaves, it can transport all products available to depart at that time. A scheduled service network design (SSND) can show the network costs for a scenario where products are ordered randomly by customers and have to arrive before a particular due time.

A scheduled service network design can be composed on a time-space graph. In this model, demand is characterised by the product's availability time and due time. Furthermore, the time it takes to transport goods through the network is also considered. By integrating time in the network, the schedules of the services can be retrieved. Moreover, when a product has a specific promised delivery date, the network can be optimised in such a way that this delivery date is considered. The network of a SSND is much more extensive than that of a static SND. This is because each node is modelled on a time-space graph, meaning there is a node for each location per time step. An example of a time-space graph is shown in Figure 4.1. In this example, there is a production facility at node 1. Customer 4 (i.e. node 4) orders a commodity on day 1, and customer 3 does this on day 2. In this case, the goods can be consolidated towards depot node two (i.e. node 14), after which they are separated again for the last-mile delivery. For this example, services are opened on arc (9,14), (18,23) and (18,24) on the time-space network. On the physical network, these arcs represent arcs (1,2), (2,3) and (2,4) at different time steps.

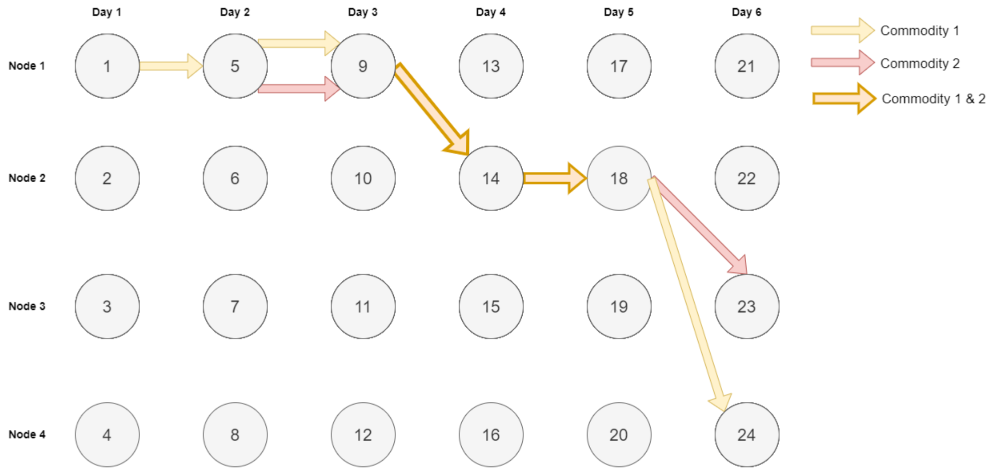


Figure 4.1: *Time-space graph example*

An important choice that has to be made for such a time-space graph is the time-discretization. This is discussed in the following section.

4.1.5 Time-discretization

Time-discretization means that time is partitioned into discrete time intervals on a time-space network (Boland et al., 2019). For example, Figure 4.1 shows a time interval of 1 day, but one could also choose a discretization in hours or weeks, depending on the problem one wants to analyse. When choosing a very large discretization size, a loss of quality occurs. However, when choosing a very small discretization size, the network size grows significantly. The choice for this has to be balanced, the level of detail that the model has to achieve and the size of the problem have to be taken into account when making this choice. Next to the time-discretization, a rounding scheme has to be deployed. When one hour is used as a discretization length, and the travel time between two nodes is 25 minutes, it needs to be determined if this rounds up to one hour or down to zero hours. Three rounding schemes are mentioned in the paper by Boland et al.: optimistic, regular and conservative. Optimistic schemes overestimate availability, meaning that they round down travel times. When looking at the example of 25 minutes, it is rounded down to 0 minutes, which increases the availability of the delivery time window. If a product has to be delivered at time step 3, the truck can also leave at time step 3, while in reality it arrives after time step 3. Conservative schemes do the opposite, they underestimate availability. In this case, it is possible that certain feasible solutions for the model are seen as unfeasible, which leads to a loss of quality in the model. A regular scheme rounds to the nearest discretized value, thus zero hours when in reality the time is 25 minutes. As said before, the length of the discrete time intervals is dependent on the type of model used and on what the model wants to achieve. The length of the interval chosen is discussed in Chapter 5.

4.2 Network characteristics

The current practice model is a scheduled service network design with only direct flows. To this model, other network characteristics are added. These characteristics are described below.

4.2.1 Modalities

An interesting possibility that is researched is adding the train as a modality to the model next to the already existing trucks. Trains are more beneficial in terms of costs since they have the opportunity to carry more goods than trucks. This increase in capacity is interesting since more goods can be consolidated in one service type. An important consideration when using trains is that depots should be located near railway stations. Moreover, extra handling costs are necessary to move the products from a train towards a depot, since the train station is not always right next to the depot. In the case study, the usefulness of the train as a mode of transportation is investigated in the scenarios.

4.2.2 Demand

Another characteristic that can change over time is the volume of demand. In the case study it is investigated how the model functions with larger volumes. It is interesting to see how the network design changes, and which services are used.

4.2.3 Depots

In the network as shown in Figure 4.1 there is a depot: node 2. This depot makes sure that goods can be consolidated. However, the location of the depot is dependent on the mode usage, since a train station is only located near certain places. Furthermore, the size is dependent on the demand for products in the network. Building a depot can have multiple benefits, the first one is that a depot is a place where goods can be stored. Moreover, the goods can be sorted, consolidated and separated from each other. It may be useful for products to travel the first part of their journey together in a big truck, after which the last-mile delivery is completed in several smaller trucks. In this case, the products are sent to a depot in bulk, which is cheaper than separate distribution. If this is indeed cost-effective depends on the costs of a depot. These costs can for example be the rental costs of the depot itself, the handling costs of products flowing through it or the inventory costs of products staying in a depot. When opening a depot, part of the investment goes to renting the building. In addition, the people that work in the depot also have to be paid. When handling products or storing them, employees and various machinery are necessary, which all add up to the cost of using a depot.

Figure 4.2 gives an overview of the network that is used in the current practice, and the network that includes depots (the extended network). Both are networks with a forward and returning flow of products in which the forward flow can go to all customers, and the returning flow can come from customers and suppliers. In the current practice model, none of these flows can be combined, since there are no intermediate facilities. In the extended network, a depot is added as a layer to the network. As shown in the figure, flows can either go directly to their destination, or go to the intermediate facility whilst consolidated, and be split up afterwards (or the other way around for returning flows). The location of these depots, the size and the service types that are used to transport goods are all part of the decisions in the network study. The model can also choose to not open depots, in this case, the extended network is the same as the current practice network.

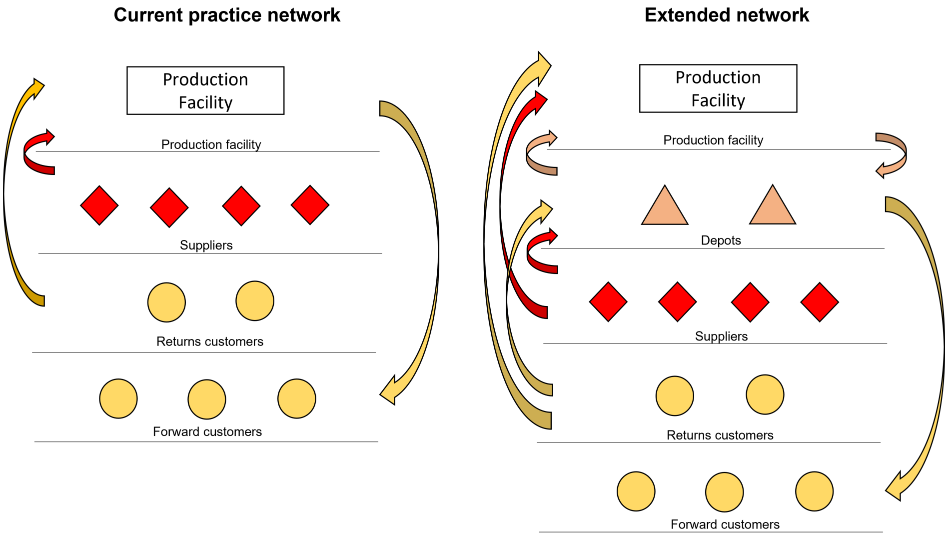


Figure 4.2: *Current practice network compared to the extended network with a depot*

5. Mathematical model

This chapter presents the composed mathematical model is used to analyse the case study.

5.1 Type of mathematical model

There are two ways of modelling the flow of products in a network. One is the path-based model, and the other is the arc-based model. The figure below shows the representation of an arc-based and path-based model for this system. For an arc-based model, a decision must be made for each transportation arc that the product uses. For path-based, only one decision has to be made so that the product flows from the origin to its destination (Ohmori et al., 2019). For this research, an arc-based model is used to design the service network.

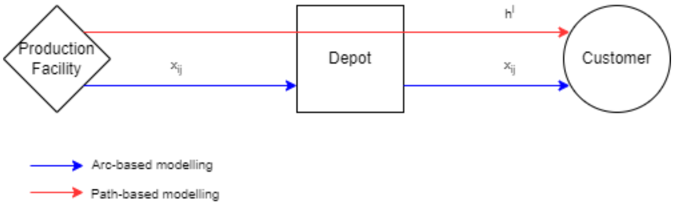


Figure 5.1: *Arc-based and path-based modelling, adapted from Ohmori et al., 2019*

5.2 Goal of the mathematical model

This research aims to investigate if a network can be optimised more in terms of costs if the forward and returning flow of products is taken into account simultaneously instead of sequentially. To analyse this, a mathematical model is composed. This model should make the following decisions:

- Will a depot be opened or not?
- What should the capacity of this depot be?
- On which arcs will a product travel to reach its destination?
- To what type of service will an arc be connected (i.e. train, small truck, large truck)?
- How many services are necessary to fulfil the network's demand?

A conceptual version of what the mathematical model should solve is shown in Figure 5.2. The mathematical model is solved with Gurobi, a software that can optimise these models. To create the decision variables, inputs have to be put in Gurobi. These inputs are also shown in the figure, where parameter values are aspects like the costs and capacity of services or the delivery time available to send a product.

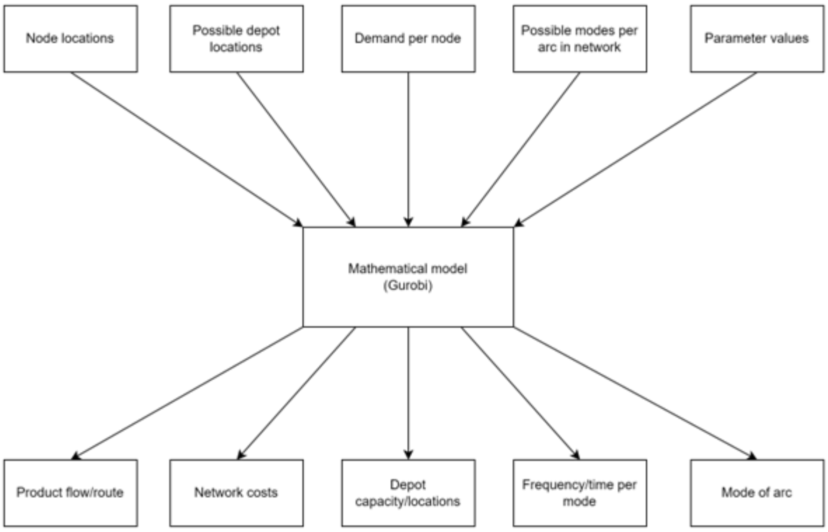


Figure 5.2: *Inputs and outputs of the mathematical model*

5.3 Mathematical formulation

Three types of optimisation methods are compared in this research. The three methods are listed below:

1. Current practice: only direct services are possible for both forward and returning flow, i.e. no depots are used.
2. Sequential optimisation: model with depots, first forward stream is optimised, afterwards returning stream is added to the existing infrastructure.
3. Simultaneous optimisation: model with depots where returning and forward flow of products is optimised simultaneously.

The first method is the 'current practice', where no depots are built. It may be true for the case study that building a depot is too expensive and thus not beneficial for the current situation. However, in the future, it could be more useful if, for example, the volume of products grows. That is why a mathematical model that can use depots is developed as well. The model shown in the following paragraph is for the second and third optimisation methods. Adaptations that have to be made to apply the model to the first method are also explained in this section. The difference between the second and third methods is the inputs. For the second method, the infrastructure of depots is built with only the forward flow of products after which the returning flow of products is optimised with the existing infrastructure.

To formulate a model where there is a choice of opening a depot, the facility location model is used together with the scheduled service network design model as described in section 2.2. The facility location problem elements were retrieved from Maknoon and Arslan, 2021. The model is developed to eventually answer the main research question:

How can a combined forward and returning transport network for a production facility be designed effectively and efficiently?

The mathematical model used in this research is shown in this section. This model is the most elaborated model used throughout this research. There is already a possibility to build depots through which products can be consolidated. Moreover, a train can be an extra mode if a depot is built near a facility to transport goods on trains. When using the first optimisation technique, where only direct flows are possible, all aspects that involve opening depots are not used. Which constraints are not applied in the model without depots is further explained throughout the mathematical model.

The model that is formulated should do the following things:

1. Minimize network cost
2. Deliver all demand in the network on time
3. Consolidate goods into one chosen vehicle (if cheaper)
4. Calculate the trip frequencies per mode per time frame
5. Take transport time from i to j into account
6. Take direct and indirect flow possibilities into account

These actions should be performed with the following assumptions:

1. Commodities for the same customer arrive at the same time, so products cannot be split into multiple trucks that drive different routes
2. Transportation between depots is possible
3. No transportation between customers possible
4. It is a multi-modal network
5. The depots are not built yet

The first assumption is that a flow can pass a depot or go directly from the origin to the destination. If it is a direct flow, there is no consolidation. When going through a depot, the flow can be consolidated. Moreover, commodities cannot be split into multiple trucks. The main reason is that customers should not receive their single order over multiple days. Customer experience is an essential aspect of this study, also resulting in the fact that all products must be delivered on time. Furthermore, it is possible to transport products between depots. However, it is not possible to transport between customers. This is because an external logistics provider is used to transport products. The company that sends the products with this provider does not influence the routing of products, so they cannot force a vehicle of that external logistics provider to drive past two points. Moreover, it is a multi-modal network that could also use trains as a transport mode if a depot is built near a train terminal. Lastly, it is assumed that the depots are not built yet. The model can decide from a list of possible locations which one it wants to open and with what capacity. The sets, parameters and decision variables, together with the mathematical model, are described in Table 5.1. Afterwards, the mathematical model with its objective function and constraints are shown.

Set	***Description***
N	All nodes (index: i,j)
$N+$	Succeeding nodes
$N-$	Preceding nodes
A	Arcs
A^h	Holding arcs
A^d	Arcs from the production facility to a depot (or the other way around)
A^m	Moving arcs
DN	Depot nodes on the time-space network (index: i,j)
D	Depot nodes on the geographical network (index: p)
V	Services (index: v)
K	Commodities (index: k)

Parameter	***Description***
u^v	Capacity of service v
V^k	Volume of commodity k
c_{ij}^v	Cost of service v on arc (i,j)
FC	Fixed costs of renting depot
VC	Variable costs of extra capacity in depot
HC	Handling costs of commodity k
IC	Inventory costs of keeping commodity k in a depot for a time step
M_1/M_2	Very large numbers

Decision variable	***Description***
x_{ij}^k	Binary variable, 1 if commodity k flows on arc (i,j), 0 otherwise
y_{ij}^v	Number of vehicles of type v used as a service on arc (i,j)
z_i	Binary variable, 1 if a depot is opened at location i, 0 otherwise
DC_p	Binary variable, 1 if a depot is opened at location p, 0 otherwise
CAP_p	Capacity necessary for the depot at location p

Table 5.1: *Sets, parameters and decision variables of the mathematical model*

Objective function

The objective function is to minimize the total costs. These costs include the services used to transport goods, the depot rental costs, the inventory costs of products and the handling costs. The service costs are per used service type for each arc. The depot rental costs consist of a fixed charge for opening a depot and extra variable costs for capacity. The handling costs are per product, while the inventory costs are per product but also dependent on the volume. For the model without depots, only the service and inventory costs are considered.

$$min \sum_{(i,j)\in A} \sum_{v\in V} (y_{ij}^v c_{ij}^v) + \sum_{(i,j)\in A^h} (x_{ij}^k V^k IC) + \sum_{p\in D} (DC_p FC + CAP_p VC) + \sum_{(i,j)\in A^d} \sum_{k\in K} (x_{ij}^k HC) \tag{5.1}$$

Flow conservation constraints

There are three flow conservation constraints, one for if a node is an origin, one for if it is a destination, and the last one for a node that is not the origin nor the destination.

If a node is the origin of a commodity, then there should be one outgoing arc on which the commodity travels:

$$\sum_{j\in N^+(i)} x_{ij}^k = 1 \quad \forall k \in K, i = o^k, i \in N \tag{5.2}$$

If a node is the destination of a commodity, then there should be one incoming arc on which the commodity travels:

$$\sum_{i \in N^-(j)} x_{ij}^k = 1 \quad \forall k \in K, j = d^k, j \in N \tag{5.3}$$

If a node in the time-space network is not the origin nor the destination, then the following equation applies:

$$\sum_{j \in N^+(i)} x_{ij}^k = \sum_{j \in N^-(i)} x_{ji}^k \quad \forall k \in K, i \in N \backslash \{o^k, d^k\} \tag{5.4}$$

Capacity of service cannot be exceeded

The capacity of a service cannot be exceeded, thus if a commodity travels in a truck, then this truck should be large enough to carry this commodity. If more products are transported in one service type, then the sum of products in this service type should be smaller than the capacity of all services on that arc.

$$\sum_{k \in K} (V^k x_{ij}^k) \leq \sum_{v \in V} (u^v y_{ij}^v) \quad \forall (i,j) \in A \tag{5.5}$$

Return deliveries cannot be controlled

If products are part of the returning flow, then they are sent to a different location immediately (it cannot be held at a customer, since it is not controlled).

$$\sum_{j \in N+} x_{ij}^k = 1 \quad \forall k \in K_{return}, i = o^k, (i,j) \in A^m \tag{5.6}$$

Depot should be open if it is used

If a service goes towards a depot, that means that the depot should be open. This constraint is not used for the model without depots.

$$M_1 z_i \geq y_{ij}^v \quad \forall (i,j) \in A, i = DN, v \in V \tag{5.7}$$

Calculate if a depot is open

Due to the time-space network, a depot can be opened at any of the time steps. Since the depot is opened or not throughout the whole planning period, a new variable is needed. This variable is 1 if the depot is open at any of the time steps, and 0 if it is closed at all of the time steps. This constraint is not used in the model without depots. Note that i is on the time-space network, p is on the geographical network.

$$\sum_{i \in D^+(p)} z_i \leq M_2 DC_p \quad \forall p \in D \tag{5.8}$$

Depot capacity

This constraint decides the necessary capacity of the depot. DN_p are all nodes on the time-space network that are the same geographical location as depot p. For example, if there are 3 days, then depot node 1 has 3 nodes on the time-space network. DN_p shows which three nodes belong to depot node 1. This constraint is not used in the model without depots.

$$\sum_{k \in K} \sum_{i \in N^-(j)} (x_{ij}^k V^k) \leq CAP_p \quad \forall p \in D, j \in DN_p \tag{5.9}$$

Pallet transportation

There are two types of products: pallets and parcels. This constraint states that pallets always have to be transported in a pallet vehicle, and cannot go into a regular vehicle.

$$\sum_{k \in K_{pallet}} (x_{ij}^k V^k) \leq \sum_{v \in V_{pallet}} (y_{ij}^v u^v) \quad \forall (i,j) \in A^m \tag{5.10}$$

Boundaries

For the model without depots, only Equation 5.11 and Equation 5.12 are used.

$$x_{ij}^{k} \in \{0,1\} \quad \forall (i,j) \in A, k \in K \tag{5.11}$$

$$y_{ij}^{v} \in \mathbb{Z}^{+} \quad \forall (i,j) \in A, v \in V \tag{5.12}$$

$$z_i \in \{0,1\} \quad \forall i \in DN \tag{5.13}$$

$$DC_p \in \{0,1\} \quad \forall p \in D \tag{5.14}$$

$$CAP_p \in \mathbb{Z}^{+} \quad \forall p \in D \tag{5.15}$$

6. Case study analysis and results

This chapter provides a description of the case study along with the data necessary to perform the case study. Furthermore, the results of the case study are presented.

6.1 Case study description

The case study is carried out with the distribution network and data of Quooker, a company that sells boiling water taps. Quooker started selling its products in the Netherlands but has been growing ever since. As of today, Quooker is selling its taps throughout Europe and even in Hong Kong, the United Arab Emirates and Israel. Figure 6.1 shows a map of the countries where Quooker is currently active.

Quooker distributes these taps and parts for repairs through external logistics providers. They can either transport products in boxes or on pallets. Sometimes Quooker delivers a large pallet of products to a store that sells the taps or to a service point of Quooker. When sending it to a service point, the pallet mainly consists of products used to repair Quookers in that country. Moreover, they can directly send parcels to individual customers, which are transported in boxes.

Since the introduction of the Quooker CUBE®, the return stream of products from customers has grown. This is because the CUBE® also gives the opportunity to get sparkling water from the tap directly. This is possible because of a CO_2 cylinder. These cylinders eventually need to be refilled. This means that the customer can send a cylinder back to the production facility, after which they receive a new, filled cylinder in return. Another product that customers can return is the cold water filter. The same process applies for these products as for a CO_2 tank.

Currently, Quooker has some service points to store service parts. However, they do not have depots yet that they use for consolidating products. In the future, Quooker would like to know if building depots can be a useful way to reduce transportation costs.

One of the most important things for Quooker is service quality. This means that if a customer orders a product, it has to be delivered in the promised time frame. These time frames are more flexible for a large customer like a kitchen store than for an individual customer. Furthermore, they would like to minimise costs, but only if that is possible within the set service quality objectives.

For this case study, Germany and Austria are the focus area for the sales of Quooker. For the returning pallets, Italy is also added to this area because Italy has a considerable share of pallet supply within Europe. Germany is currently a significant customer of Quooker, and Austria is still small but growing.

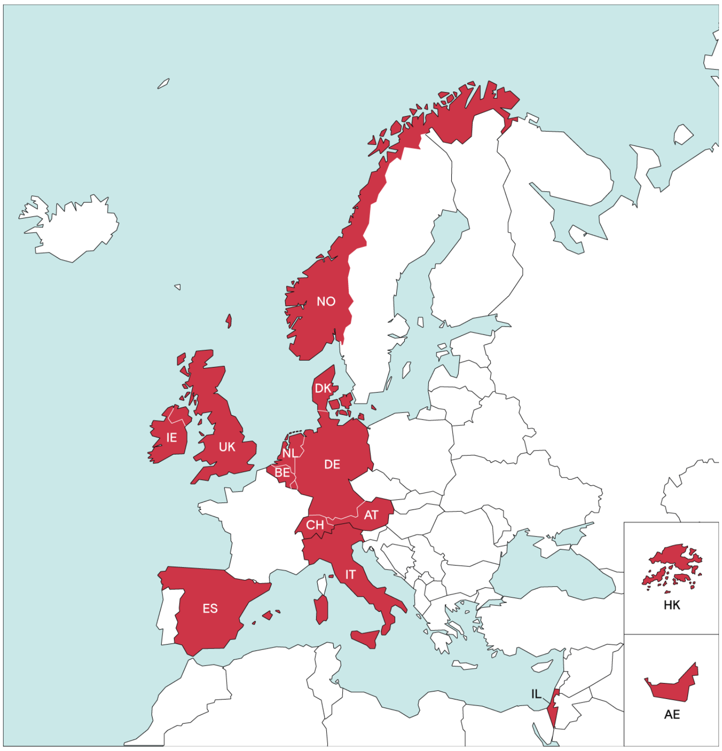


Figure 6.1: *Countries where Quooker is active, retrieved from Quooker B.V., n.d.*

6.2 Data

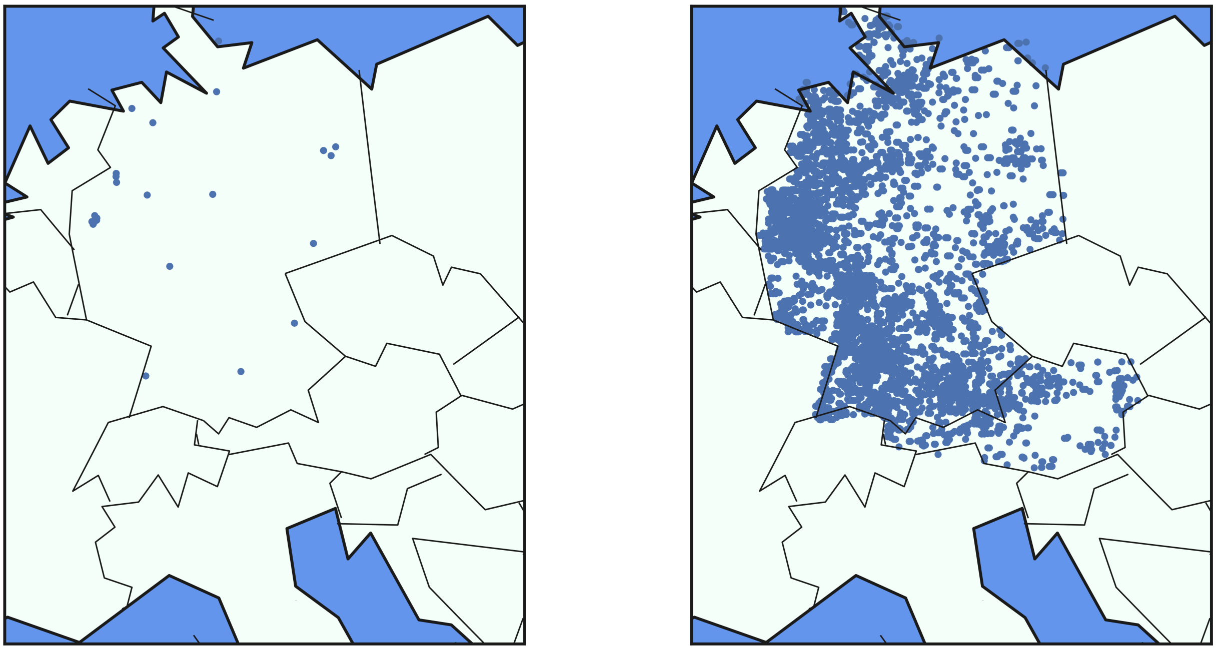
In the following section, data is gathered and input parameters are discussed. All data is from Quooker, assumptions are made when the data is unavailable. Note that the input parameters can change for the different scenarios, but these values are used as a starting point. An overview of all necessary data for the model is discussed in the following sections, after which it is used as input parameters for the scenarios that are analysed in this paper.

6.2.1 Time period of data

The figure below shows the sales in 2021 for Austria and Germany, which are the focus areas for this case study. The sales for 2021 are used since 2022 was not yet available. For this research, the data collected in March is used for the analysis. This is done because the sales in this month are pretty average when looking at the entire year. However, Quooker is significantly growing, so it can be expected that the sales in March 2023 will be much higher than what is shown in this graph.
Graph not available for repository version

6.2.2 Demand per region

An important aspect is that the model cannot be solved when all individual sales of Quooker are added. This means that the sales must be consolidated into clusters, and one large node should represent these clusters. When looking at the sales of March 2021, a geographical map can be made that shows the sales in that month. Figure 6.2b shows the sales of parcels (thus the forward flow), and Figure 6.2a shows the sales of pallets. Pallets are only sold to Germany, not to Austria. Since there is no detailed data about the parcel returns, it is assumed that the returns of parcels are distributed in the same way as the forward flow since customers that order a Quooker with sparkling water also contribute to the return flow by sending their empty CO_2 tanks back as well as their water filters.



(a) *Demand of pallets for forward flow* **(b)** *Demand of parcels for forward flow*

Figure 6.2: *Demand shown geographically for the forward flow of products in March 2021*

Pallets bought by Quooker are part of the return flow. In Europe, Quooker buys its pallets from multiple countries. However, this research focuses on pallets bought from suppliers in Germany and Italy since these countries are in the right location to be consolidated in possible depots in Austria and Germany. No suppliers are located in Austria, and this is why this country has not been taken into account for pallets in the return flow.

The following two subsections discuss the location of the depots and the demand nodes in the model. These locations are used in all analyses made for this case study.

6.2.2.1 Depot locations

First, the depot locations are decided on. Quooker's preference for possible depot locations in Germany is one in the West, one in the East and one in the South. For Austria, one possible location is added in the North since that is where the highest demand is. These are the only depots that the model can choose from, and the model is not able to build one in a different location.

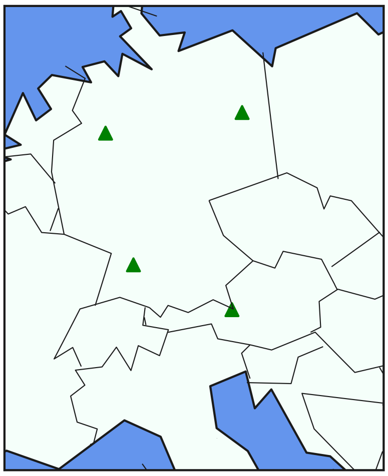


Figure 6.3: *Possible future depot locations in the Austria/Germany region for Quooker*

6.2.2.2 Nodes

For this model, 61 nodes are used, of which 1 is the production facility of Quooker, 4 are depot locations and the other 56 nodes can be used as nodes for a forward and return demand in either pallets or parcels. It is not possible to have many depot possibilities, or that all orders are a separate demand point, since these factors can result in a model that is too large and complex to solve (which is further explained in subsection 6.2.8). This is why there are only four depot nodes and 56 demand nodes. Demand points represent a larger area of demand in reality. For example, all of the orders made in Berlin can be represented by one, larger demand point instead of many small points. To keep the model realistic to Quooker's data, the demand nodes are distributed in the same proportion as the data shows in March 2021. The nodes can be either parcel or pallet demand nodes, and can be either forward or return nodes. Table 6.1 shows the ratios of the nodes that are from the data in March 2021. This means that almost 70% of the volume sold that month by Quooker was a parcel going from the Netherlands to Germany or Austria.

Type	**Share**	**# Nodes in model**
Forward parcel	69,5%	39
Returning parcel	12,5%	7
Forward pallet	9%	5
Return pallet	9%	5

Table 6.1: *Node distribution in model*

The nodes in the model are be distributed geographically based on the demand in March 2021. To do this, an adaptation to the k-means clustering method is used. The K-means clustering algorithm determines clusters and their centroids (i.e. the central point of a cluster) based on the distance of all nodes towards this centroid. However, for this research, it is important that the clusters are not based only on location but also on the size. All demand points must be grouped in a cluster, and each cluster has to be around the same size. This means that each cluster has around the same amount of demand points. A more extensive explanation of this method and its results can be found in Appendix B.

The clustering method has been applied to all demand points for the forward flow of parcels. The number of clusters made 39, since this is how many demand points represent this forward flow. However, there is also a split between Germany and Austria. Based on the volume of orders for each country, Austria has a total of 3 forward parcel nodes, and Germany has 36 forward parcel nodes. This is a large difference, but it is the current situation for Quooker. The results of the cluster analysis are presented in Appendix B. Moreover, since it is assumed that the return flow of parcels is distributed evenly over the forward flow, the same can be done for the return flow, but with fewer clusters. The return parcel flow accounts for 7 nodes, so this is the number of clusters made. The results for this can also be found in Appendix B.

The pallet flow at Quooker is a much smaller flow compared to the parcel flow. The forward pallet flow is also based on the cluster method. Quooker's biggest suppliers are chosen as a node in the model for the supply of pallets. Since pallets in Europe are mostly from Italy and Germany, only these countries are used in the network.

Each cluster has a centroid, which is the centre of a cluster. All cluster centres form the final network. Figure 6.4 shows the final network of nodes on the map. Note that the larger nodes are pallet nodes, and the smaller ones are parcel nodes.

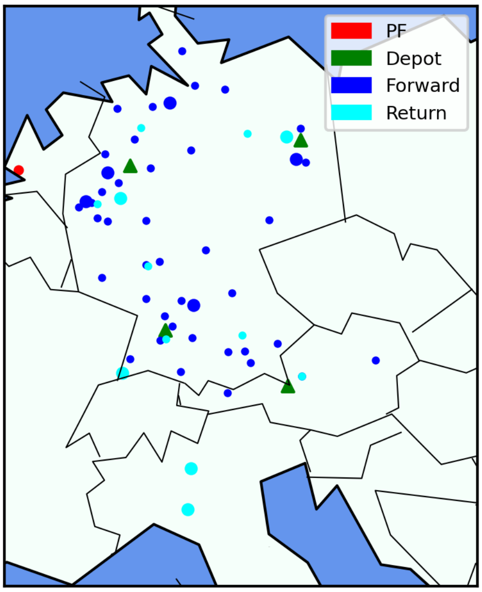


Figure 6.4: *All nodes, larger nodes are pallet orders, smaller are parcel orders*

6.2.3 Modes

Different mode types are used throughout the scenarios researched in this paper. There are different truck types for parcels, each with a different capacity. Moreover, there is a truck type for pallets. In this truck, parcels can also be transported. Pallets can however not go into trucks destined for parcels (as stated in Equation 5.6 in the mathematical model). Moreover, there is an option to transport products by train in one of the scenarios. Trains are not able to drive freely, thus the train is only connected to two depots. This is the depot in the West of Germany and the one in the East of Germany. These are connected through the same rail line, meaning the load does not have to be transferred from one train to another. This is based on the map of European freight train tracks, which can be found in Appendix C. Table 6.2 shows the overview of the different modes and their capacity. Note that in the model, the same mode can be used multiple times. Thus the fact that the capacity of a truck is 2 kg does not mean that that is the limit of what can be transported by that truck. More goods can be transported if more trucks are used of that type.

Mode	Capacity
Parcel Truck	2 kg
Parcel Truck	5 kg
Parcel Truck	15 kg
Parcel Truck	32 kg
Pallet Truck	200 kg
Train	4800 kg

Table 6.2: *Mode types used in model with their capacity*

6.2.4 Costs

The depot and inventory-related costs are shown in Table 6.3. These costs are based on Quooker's current costs, and assumptions were made if costs were unclear. For the depot, there are different types of costs. The fixed costs have to be paid to rent a depot, and these costs are yearly. The variable costs are the extra costs for renting a pallet place, and these costs come on top of the fixed costs. The handling costs are the extra costs that must be paid when consolidated products have to be sorted again or when different products have to be consolidated. This takes an extra handling step, which costs money. Inventory costs are the costs for storing a pallet for a day in the depot.

Type	Costs	Unit
Fixed costs	150.000	€/year
Variable costs	17,5	€/pallet/month
Handling costs	1	€/order
Inventory costs	5	€/pallet/day

Table 6.3: *Depot and inventory costs*

There are two cost structures that are used for the services. The first is a country-based system, where a price is determined based on which country a parcel goes to. The second is a distance-based system, where the price is determined by the total amount of kilometres driven. Costs for transporting pallets are the same for both cost structures.

There are six different country-based service costs. First of all, there are service costs for sending a parcel to a country. These parcels can be sent from the Netherlands to Germany, from the Netherlands to Austria, from Germany to Austria, and the other way around. Moreover, parcels can also be sent within a country, thus from Germany to Germany or Austria to Austria. The costs are different for different capacities. For example, sending a parcel of 2 kilos is more expensive per kilo than sending a parcel of 32 kilos. The country-based costs are shown in Table 6.4.

Type	Costs	Unit
Service costs NL to DE	[...]	€/kg, capacity:[2;5;15;32]
Service costs NL to AU	[...]	€/kg, capacity:[2;5;15;32]
Service costs DE to DE	[...]	€/kg, capacity:[2;5;15;32]
Service costs AU to AU	[...]	€/kg, capacity:[2;5;15;32]
Service costs AU to DE	[...]	€/kg, capacity:[2;5;15;32]

Table 6.4: *Country-based service costs*

Costs for transporting pallets are distance-based, although the prices stay mostly the same if the distance is longer because the variable costs are low. Prices of pallet transport range between 80 and 100 euros. The fixed costs of transporting a pallet for Quooker are quite high. For the pallet transport in a truck, the following formula is used: $palletcosts = 0,011 * distance + 79,4$

To develop the distance-based model, pallet costs stay the same, since they are already based on the distance travelled. For the parcel trucks, the cost structure is made in such a way that for the same volume, the total service costs are the same as the country-based service costs. The costs for each truck can be found in Table 6.5. According to a logistics service provider, the fixed costs for transporting goods is 10%, and the variable costs 90%. The values used for the distance-based cost structure have the same ratio, depending on the distance travelled by a truck. The average distance between all origin and destination nodes is 453 km. This distance is used to ensure that, on average, the fixed costs are 10% of the variable costs. Thus for a truck driving the average distance, the fixed costs are 10%, and the variable costs are 90%, but if a truck drives a longer distance, the fixed costs become relatively lower. Furthermore, there are different truck capacities which have different prices. For the distance-based model, the same price increase is used as what is used for the country-based system. For example, the price of a 5 kg truck is 8% more expensive than that of a 2 kg truck. This calculation can be done for all truck types.

Truck	**Capacity**	**Fixed costs**	**Variable costs**
Truck 0	2 kg	€[...]	€[...]/km
Truck 1	5 kg	€[...]	€[...]/km
Truck 2	15 kg	€[...]	€[...]/km
Truck 3	32 kg	€[...]	€[...]/km

Table 6.5: *Distance-based service costs*

For transporting a container by train, the costs are not known by Quooker. To estimate the costs for transporting a container by rail, the information from the Netherlands Institute for Transport Policy Analysis (KIM) is used (2020). When transporting a 40ft container by train with a capacity of twenty-four pallets, it is assumed that this is five times more expensive than transporting one pallet by truck. This is based on the operating costs of a truck and a train in the paper. The operating costs are not directly connected to the price paid by the customer, but in this research, this is assumed.

6.2.5 Volume

Quooker sells different products, for this research six products are taken into account. These products are shown in Table 6.6. The shares show how often this product was ordered in March 2021 compared to the other products in the table. The products sold are a combination of a tap and a boiler, or are a CO_2 tank or a water filter. The return parcel nodes consist of a CO_2 tank and a water filter, since this is what customers send back and get a new one sent to them. For the forward parcel flow, the volume distribution is decided by the shares in the table. An overview of the demand volume per node is shown in Appendix D.

Product	**Weight**	**Share**
FusionCombi	[...]	[...]%
FusionPro	[...]	[...]%
FlexCombi	[...]	[...]%
FlexPro	[...]	[...]%
CO2	[...]	[...]%
filter	[...]	[...]%

Table 6.6: *Product types, weights and shares*

6.2.5.1 Volume factor

Knowing the total volume of products that Quooker sells is also necessary for the analysis. The total amount of products sold in March 2021 was [...]. These are the monthly sales and consist not only of the 6 products shown in Table 6.6, but for the case study it is assumed that the total sales do consist of only those products. Moreover, these are single products that are sold, while products are not sent individually. In total that month, there were around [...] parcels sent. This means that in two weeks, it is assumed in the model that [...] parcels are sent. Each demand point in the model is coupled to a product and an order size. One demand point in the model can represent multiple orders in real-life. Since this model has 46 demand points for parcels, each parcel demand point should represent [...] real-life parcel orders when representing the current situation of Quooker.

For pallets, this is different since there are more products on one pallet. In March 2021, [...] pallets were sent to Germany. In total, there are [...] pallet nodes in the model. This means that each pallet node should represent around [...] pallets in the real situation with a model that plans for a time period of two weeks.

This volume factor is used to calculate the actual costs of Quooker in their transport network. In the model, this volume factor is used when calculating the total volume of products, the truck capacity and costs are also be multiplied by this factor. This has to be done because if the volume of a node is multiplied by this factor, then this product does not fit in an original truck anymore since these capacities range from 2-32 kilos for regular trucks. To ensure that the services and their costs also represent the real-life situation, these also have to be multiplied by this factor.

6.2.6 Delivery time

For the delivery time of a product, Quooker's promised delivery days are used. The promised delivery time is two working days for parcels from the Netherlands to Germany. It is three working days for parcels going to Austria from the Netherlands. Pallets are promised to be delivered in five working days for the locations involved in this model. For the return flow, there is no specific delivery date. As discussed in the mathematical model, the products are sent immediately for the return flow. This is because Quooker has no control over at what moment products get returned to them. However, they do have control over to what location these products are sent (a depot or directly to the production facility).

6.2.7 Node characteristics

The previous sections have described all characteristics that are inputs to the model. The locations of all nodes used for most scenarios are shown in Figure 6.4. Each node has different characteristics, like order dates and order volumes. A complete overview of all commodities' characteristics is given in Table D.1. These characteristics are used as an input in the model for most of the scenarios.

6.2.8 Complexity of the model

The amount of depot and demand nodes used in the model is decided based on how fast the model can optimise the network. During the case study, the goal is to find the best solution. The optimal solution is found when the gap between the upper and lower bound solution is at 0%. When increasing the complexity of the model, optimising in such a way can take a very long time. In this research, Gurobi is used for optimisation. An other important aspect to consider when deciding on the number of nodes is that the model has to be run many times due to the different scenarios and sensitivity analyses. Because of this, it is preferable to have a short solution time.

How fast gaps are reached for different model sizes is shown in Table 6.7. When running the different sizes for depot nodes, sixty demand nodes are used. When running the different demand nodes, four depot nodes are used. There is a difference between depot nodes and demand nodes, as depot nodes are connected to all other nodes in the network. In contrast, demand nodes are only connected to the depots and the production facility. The number of depots has a very large impact on the solution time of the model. If the distance-based model is run with the node characteristics as described in Table D.1, a 0% gap is reached after 65 seconds. If only two depots are used, the optimal solution is found after 6 seconds. The gap between solutions decreases slowly when the number of depots is increased to eight, resulting in a significantly longer time to solve the model. the model reaches a gap of 3,82% after an hour. Running the model for an hour for many scenarios takes up much time, so that is why it is chosen to implement four depots in the model. Moreover, these four locations are in line with what the potential locations for Quooker can be (3 depots in Germany and 1 in Austria). When adding more demand nodes, the solution time increases as well, although not as much compared to adding more depots. If a network of 90 nodes is analysed, there is still a gap of 0,8% between the upper and lower bound after 65 seconds, after which the gap decreases very slowly. Due to the impact of having more nodes on the solution time, the number of nodes used in this research is 61 (of which 1 is a production facility).

Gap	**2 depots**	**4 depots**	**8 depots**
5% gap	2s	8s	2534s
1% gap	4s	40s	n/a
0,5% gap	6s	60s	n/a
Gap after 1 hour	0,00%	0,00%	3,82%

30 nodes	**60 nodes**	**90 nodes**	**120 nodes**
1s	8s	9s	14s
4s	40s	41s	427s
4s	60s	739s	n/a
0,00%	0,00%	0,41%	0,74%

Table 6.7: *Gap reached over time for different nodes sizes*

6.3 Analysis

This section discusses the results of the different scenarios and the sensitivity analyses. The focus lies on six scenarios, further explained in the following sections. The input data used in these scenarios is based on the information in section 6.2. If variables change, this is discussed in the description of each scenario.

The key performance indicators (KPIs) that are measured throughout these scenarios are the following:

- Network costs: these are the different parts of objective function, i.e. all costs shown in Equation 5.1. This KPI is measured in euros.
- Depot open/closed: this is one of the decision variables in the model. This variable states if a depot is open and if so, which one.
- Depot capacity: this is also a decision variable of the model. This calculates how much capacity is needed for inventory and the handling of products. This is measured in the number of pallets places.
- Services: the number of services and possibly trains used to transport all goods.
- Distance travelled by services: this calculates how far each service has travelled. This is measured in kilometres and is based on the celestial distance between two nodes.
- % utilization rate: this calculates how efficiently the available capacity of a truck is being used. For example, if there is a capacity of 5 kilos and the service is transporting 3 kilos, the utilization rate would be 60%. It is the weighted average over all trucks per kilometre travelled, such that a truck that drives very far but empty weighs more than a full truck that travels a short distance.
- Inventory volume: gives the number of pallets that stay in the depot for a day. This is measured in pallet days, so if one pallet stays in inventory in a depot for three days, this KPI would be 3.

This research focuses on the effect of integrating the return flow and forward flow when optimising the network. It also looks at the effect of opening a depot. This means that within each scenario, there are three optimisation methods that are compared (also discussed in section 5.3). Those three methods are the following:

1. Current practice
2. Sequential optimisation
3. Simultaneous optimisation

The following sections discuss the scenarios, their results, and the applied sensitivity analyses. Moreover, the model is verified in Appendix E, where all parameters used in the model are adapted and checked if the model responds as expected.

6.3.1 Scenario 1: current situation

Scenario 1 represents the current situation of Quooker in terms of volume and available modes. Quooker currently has no depots, but the option of building a depot is available for the sequential and simultaneous optimisation methods. In this scenario, only trucks exist as a mode of transport. The cost structure of these trucks is country-based in this scenario, and this means that a truck costs money based on which country it drives to, not based on where exactly in the country they drive to. So if a truck drives from the Netherlands to Germany, this costs a set amount of money, no matter if it goes to the West or East of Germany. Furthermore, all characteristics of each commodity (i.e. each demand node) are shown in Appendix D. All these nodes represent one order, but this needs to be converted to the realistic volume of Quooker. All nodes have to be multiplied by a certain factor: the volume factor. To represent the realistic volume of Quooker, the volume factor for parcels is 185 when running the model over a time period of 2 weeks (i.e. 10 working days), and for pallets, this factor is 3. This is also explained in subsection 6.2.5.

The main results of scenario 1 can be found in Table 6.8. A more detailed version of the results is shown in Appendix H. The results show that for Quooker's current volumes and parameter values, it is not useful to open a depot, and therefore the results are the same for all the modelling approaches. When optimising the model with the possibility of opening a depot, the model does not choose to do so. Moreover, 56 trucks are used and these trucks drive a total distance of 25.379 km. The trucks are not filled efficiently, around 56% of a truck is full. A contributing factor to this is a mismatch between the volumes of the products considered in this research and the capacity of trucks. The most sold product (the CO_2 tank) weighs 5,5 kilos, meaning that it has to go in a truck of 15 kilos. This causes a low usage of available capacity, especially when no goods are consolidated. More detailed results are presented in Appendix H.

Scenario 1: current situation	**Total costs**	**Service costs**	**Depot costs**	**Depot open?**	**Depot capacity**	**Inventory volume**	**#Services**	**Distance traveled**	**Utilization rate**
All 3 optimisation techniques	63.032,06	61.527,04	0	no	n/a	n/a	56	25.379	56%

Table 6.8: *Results scenario 1: current situation*

These results are depicted on a map as shown in Figure 6.5. This map clearly shows that there are only direct connections between the production facility and the demand nodes (or the other way around), and depots are not used.

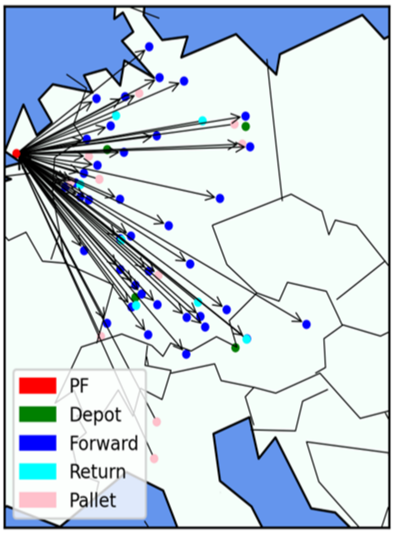


Figure 6.5: *Network results scenario 1 for all optimisation techniques*

6.3.1.1 Validation

To validate the model, the results of the current situation can be compared to the real situation for Quooker. With the data available, the validation can be done by looking at the amount that Quooker has paid a logistics service provider for transporting their products. A logistics service provider does both the forward flow of parcels and the returning flow of parcels. The pallet flow is done by a different company. The price paid to a logistics service provider in two weeks in March for the forward parcels was around [...]; in the model, this is [...] euros. For the returning parcel, Quooker paid a logistics service provider around [...] euros. For the return flow of products, these costs were around [...] euros in the model. These differences are small. This means that the model for the current situation represents the real situation of Quooker in terms of costs quite well.

There are no specific invoices for pallets since this is done through multiple companies. However, it is known that in March, [...] pallets were sent to customers in Germany, and Quooker received around the same amount of pallets from suppliers in Germany and Italy. Each pallet costs between 80 and 100 euros. With a model that plans for two weeks, around [...] pallets should be sent and received, which means the costs should range between [...] and [...] euros for the forward and returning flow. The cost of transporting pallets in the model is around [...] euros, which is between the bounds.

6.3.2 Scenario 2: train as a mode

For the second scenario, a future situation for Quooker is investigated. In this scenario, Quooker can move their products by train in addition to trucks. Moreover, since it is a future situation, demand has grown since the company has been growing rapidly over the last few years, a trend that is expected to continue. The main differences between the train and the truck are that much higher volume is needed for a train since a full container has to be filled. However, transporting this container is much cheaper compared to transporting this by truck. As discussed in subsection 6.2.3, for the train, it is only possible to go to the depots in the East and West of Germany since these are connected to the same railway as the production facility in Rotterdam. Moreover, only pallets are transported by train since parcel transportation has to be done in two or three days, so there is not enough time to ensure that parcels can be sent by train and still arrive at the customer in time.

For this scenario, it is assumed that 30% growth continues for the following five years. The fifth year is analysed. Compared to the current situation, there is a growth in the volume of 371%.

Upon running this scenario, it becomes evident that using a train for transportation is not a viable option, regardless of the adjustment of the volume and depot parameters. The reason being that the fixed transportation costs for pallets are very high. Therefore, in this model, transporting a pallet directly is always more efficient than consolidating them in a train. This is because after the train arrives at a depot, the pallet has to be transported for the last mile, for which the high fixed costs are paid. Hence, using the train is not a viable option in this model.

To explore the threshold for when a train does become a cost-efficient option, the fixed transport costs are adapted, and the number of pallets in the model is increased. The extra pallets are distributed around the first depot. If eventually the fixed costs of pallet transport by truck are 40 euros, and the variable costs are 10 cents, the train as a mode is used. Note that there are more fixed and variable costs combinations for which the train is used as an option, but all options are not in line with reality. The results of optimising the model with these input parameters are shown in Table 6.9, the Δ represents the difference compared to the optimisation without any depots. For this scenario, there is a difference in the optimisation techniques. Only depot 4 is opened for sequential optimisation, while for simultaneous optimisation, depots 1 and 4 are opened. The depot is opened in the wrong place for sequential optimisation since most pallet transport is located near depot node 1 for this scenario. Moreover, there is not enough capacity in depot 4 to also include the return flow of products. What the network looks like with a train as a mode is shown in Appendix H in section H.2. The pallets originating from the Southern part of Germany and Italy still use the direct transport flow, but the ones near the depot are consolidated.

Scenario 2: train as a mode		**Total costs**	**Service costs**	**Depot costs**	**Depot open?**	**Depot capacity**	**Inventory volume**	**Services**	**Distance traveled**	**Utilization rate**
Current practice (no depot)	value	244.583	236.328	n/a	no	n/a	n/a	66	29.299	65%
Depot possibility sequential optimisation	value	214.964	185.442	20.496	Yes, 4	109	0	71	23.225	73%
	Δ	-13,7%	-21,5%	n/a	n/a	n/a	n/a	7,6%	-20,7%	12,3%
Depot possibility simultaneous optimisation	value	209.419	176.503	37.367	Yes, 1 and 4	176, 160	565	75	17.883	74%
	Δ	-14,4%	-25,3%	n/a	n/a	n/a	n/a	13,6%	-39,0%	13,8%

Table 6.9: *Results scenario 2: train as a mode*

To review, many parameter values have to change to make the train a feasible option for Quooker. The thresholds lie quite far from the current situation, thus it is not likely that Quooker will transport its products by train in the future.

6.3.3 Scenario 3: distance-based model

To extend the research, a distance-based cost model is investigated. In the previous scenarios, only the pallet or the train transport were distance-based, and parcel costs were country-based. For a country-based model, it does not matter where a depot is built in terms of travel costs, but for a distance-based model, this would matter. This is because consolidated goods are transported over a long distance, and the more expensive last-mile deliveries is a short distance. For the distance-based model, the same inputs are used as for the current situation model. The only difference is the pricing system.

The main results are shown in Table 6.10, in which the Δ represents the difference compared to the optimisation without any depots. With the same inputs as the current scenario model, the distance-based model does open a depot: depot 4. The results are also shown on a map in Figure 6.6. In this figure, it can be seen that the nodes nearby the production facility in the North are transported directly, but for the nodes that are further away in the South, consolidation towards the depot is used, and for the last-mile direct services are used. For the return nodes, the same happens. The Northern nodes are directly transported, and the Southern ones are transported through the depot. The return flow is shown separately in Figure H.4a in section H.3. The fact that a depot is opened in the distance-based model and not in the model in scenario 1 can be explained since transporting products in the distance-based model is more expensive for long distances. This means that consolidation efforts on long-distance movements are beneficial. For the model in scenario 1, the same price was paid for all distances, thus consolidating for long-distance trips did not specifically pay off. What is also interesting to see is that the pallet flow does not go through a depot. The reason for this is that the fixed costs of transporting pallets are too high, which is why using two trucks when consolidating is not beneficial instead of one when it moves through a direct line. More extended details of this model are shown in Table H.2 in section H.3. In the two figures of the return flow in the appendix, it also becomes clear what the exact difference is between sequential and simultaneous optimisation. Figure H.4 shows the difference in sequential and simultaneous optimisation flows. Here it becomes clear that four demand nodes can go through the depot when optimising it simultaneously, whereas only two can go through the depot for sequential optimisation. This is because there is not enough capacity in the depot since more capacity was not necessary for the forward flow, thus a smaller depot was built. For this model, the money that is yearly saved by opening a depot compared to simultaneous optimisation is €116.895. Moreover, the difference in the efficiency of sequential and simultaneous optimisation causes a yearly savings of €27.350.

Scenario 3 distance-based		**Total costs**	**Service costs**	**Depot costs**	**Depot open?**	**Depot capacity**	**Inventory volume**	**#Services**	**Distance traveled**	**Utilization rate**
Current practice (no depot)	value	62.716,71	61.208,68	0	no	n/a	n/a	56	25.379	56%
Depot possibility sequential optimisation	value	58.985,7	47.492,62	9780,40	Depot 4	30	0	61	19.335	63%
	Δ	-6,0%	-22%	n/a	n/a	n/a	n/a	8,9%	-23,8%	12,5%
Depot possibility simultaneous optimisation	value	57.846,1	46.181,55	9977,30	Depot 4	35	35	61	18.744	63%
	Δ	-7,8%	-24,6%	n/a	n/a	n/a	n/a	8,9%	-26,1%	12,5%

Table 6.10: *Results scenario 3: distance-based model*

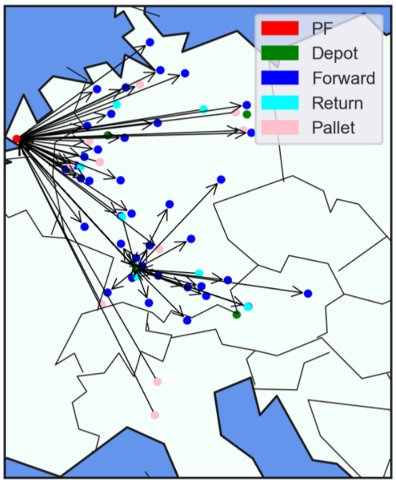


Figure 6.6: *Network results simultaneous optimisation for scenario 3*

6.3.4 Sensitivity analyses

A sensitivity analysis is performed for two reasons, the first being that it is interesting to see the model's limits and thresholds for changing decision variables. The second one is because certain input parameters are based on assumptions or are expected to change in the future, and for these parameters, a sensitivity analysis is valuable. First of all, the depot costs are based on assumptions, so it is checked how sensitive the model is towards these costs. Moreover, seeing the effect on the model for different service costs is interesting. This is also a variable that can change in the future. It can go up due to the increasing gasoline prices or decrease if Quooker's volumes go up. Lastly, a sensitivity analysis of the volume is performed. Quooker's goal is to grow by 30% each year, which has been achieved over the last few years. To see the effect of this growth on the model, a sensitivity analysis of the volume is done.

The sensitivity analysis is performed on two aspects, one is the sensitivity on the objective function itself when optimising the model simultaneously. The other is how the difference between optimising simultaneously and sequentially changes when changing the input parameters. The sensitivity analyses are performed on the current situation and the distance-based model.

Volume sensitivity

Firstly, the sensitivity to the volume is checked. The analysis shows that the model is sensitive to this input variable. In this case, that means that if the volume increases by 10%, the total costs increase by 10% as well for scenario 1. The distance-based model is slightly less sensitive, that is because this model opens a depot for consolidation in the current situation scenario, and when the volume increases, the total costs do not increase by as much. The figures in section I.1 show this relation.

This sensitivity was tested with a volume growth of up to 400%. The current situation model opens a depot when the volume is increased to 3,3 times its original value. At this volume, the depot costs are relatively small compared to the service costs, which is why the model opens a depot. However, since a depot also has handling costs, which depend on the volume, increasing the volume also indirectly increases the depot costs. This is why the volume must grow much before the model opens a depot.

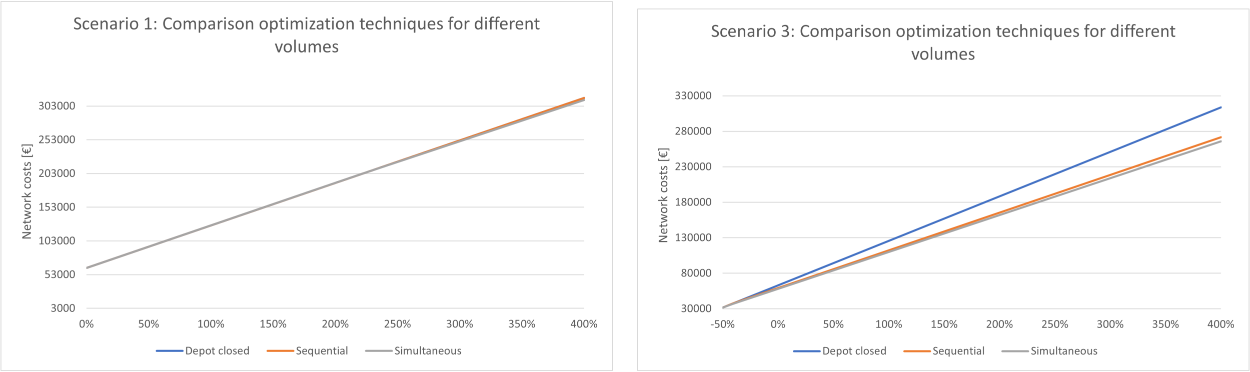
A depot is already opened for the distance-based model with the regular parameter values. The threshold for opening a depot is when the volume drops to 50% of the current volume. Moreover, when the volume is increased by 400%, two depots are opened: depot 1 and depot 4. For these volumes, pallet transportation is still not used for consolidation. The model's sensitivity for a volume change is shown in Figure I.8 in section H.3.

The other sensitivity investigated is the difference in optimising sequentially versus simultaneously. These results are also compared to the scenario when no depot is opened, i.e. the current practice. For the volume, Figure 6.7 shows the results of both scenarios. Both figures are provided in a larger size section I.2. For scenario 1, all lines overlap almost completely, and this is because there is a delicate balance between opening a depot at a larger volume and not opening one, which is partially due to the handling costs that also increase when increasing the volume. At the largest tested volume, optimising the model simultaneously has a 1% lower cost than optimising it sequentially. For the sequential optimisation, no depot is opened, while for the simultaneous optimisation, depot 1 is opened. It is expected that the volume grows quite a lot in the future. However, it takes some time before a 400% growth is reached. When this growth is reached, a 1% cost reduction with this growth could mean a yearly savings of €37.313 for scenario 1.

In scenario 3, more differences can be seen in the Figure 6.7b. Every time a change occurs in opening a depot, this can be seen in the sensitivity. The graph below shows the change in the volume parameters and the results for the three optimisation techniques. Since the changes are minimal (0%-2%), it is difficult to see the differences. The changes that occur are the following:

- -50%: no depot is opened for any of the cases, thus all lines are on top of each other
- -40%: a depot is opened for the simultaneous optimisation, but not for the other techniques, this results in a small change between the techniques, where the grey line is slightly underneath the orange line.
- -25%: a depot is opened for simultaneous and sequential optimisation, but there is a difference in optimising it since the depot's capacity for forward optimisation is insufficient for the return flow. This is what happens at the other volume increase percentages as well.

When the volume increases by 50% in the distance-based model, using a simultaneous optimisation is 2% more efficient in terms of network costs. This means that in a year, 41.000 euros can be saved by doing this. An increase in the volume of 50% is most likely reached quite quickly by Quooker. Thus it would be beneficial for Quooker to optimise it simultaneously and open a depot if they used a distance-based pricing model.



(a) *Scenario 1: current situation model*

(b) *Scenario 3: distance-based model*

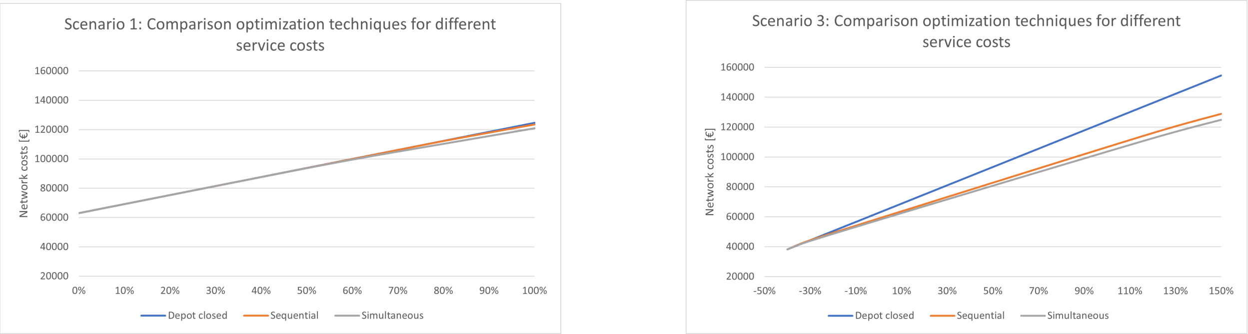
Figure 6.7: *Comparison of the three optimisation techniques for changing volumes*

Service costs sensitivity

For the service costs, both models respond slightly in the same way as for the volume. In section I.1, the effect of changing the service price on the total network costs is presented. In scenario 1, with regular parameters, no depot is opened. However, when increasing the service costs by 60%, a depot is opened. This is because the costs for services increase by such an amount that the cost of opening a depot becomes relatively cheaper, and consolidation is more cost-beneficial. The distance-based model does not open a depot if the service costs drop to less than 60% of the original costs.

Figure 6.8 shows the differences between the optimisation techniques for changing service cost parameters. Both figures are shown larger in section I.2. Again, it shows that the distance-based model can operate more efficiently with a depot compared to the country-based model. For scenario 1, if the service price would increase by 80% to 100%, optimising the forward and return model simultaneously would reduce the total costs by 2% when comparing this to optimising it sequentially. In the most extreme case, i.e. a service cost increase of 100%, this would mean a yearly savings of around €60.000. However, it is not very likely that the service costs will double in the near future. Figure I.3 in section H.1 show in more detail the cost development of a closed depot optimisation, a sequential optimisation and a simultaneous optimisation.

For scenario 3, when the service costs decrease by 40%, no depot is opened. In this case, it is cheaper only to use direct transportation routes. When the costs of services increase, the difference between the lines also increases. For a price increase of 30%, the difference between optimising the model simultaneously versus sequentially is 2%, and the difference between simultaneous optimisation and a network with only direct routes is 11,6%. Thus if the prices increase by 30%, which is not an unrealistic value, it is definitely beneficial to build a depot. Not using one would increase the network costs on a yearly basis by a bit more than 225.000 euros. The difference between simultaneous and sequential optimisation is smaller, but the yearly benefits are still quite high for the distance-based model: €34.000.



(a) *Scenario 1: current situation model*

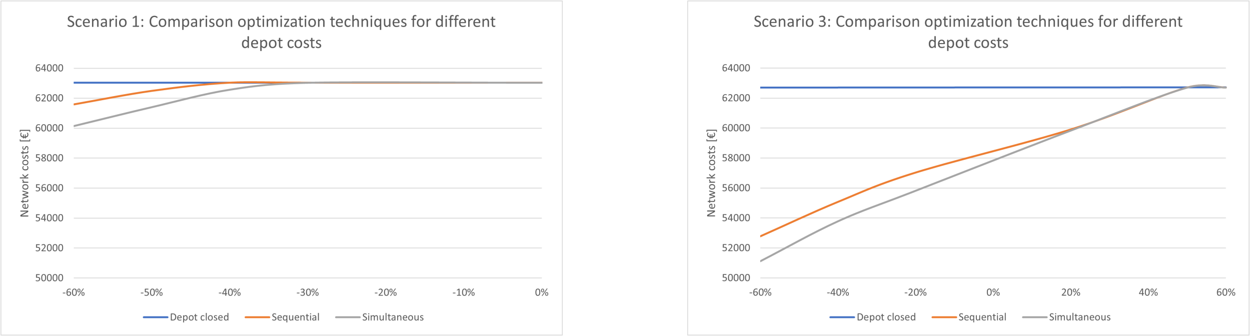
(b) *Scenario 3: distance-based model*

Figure 6.8: *Comparison of the three optimisation techniques for changing service costs*

Depot costs sensitivity
For the depot costs, both models are not very sensitive. Section I.1 show the sensitivities of both models to the depot price. The distance-based model is more sensitive than the model in scenario 1 for the depot costs. When decreasing the depot costs in scenario 3 by 60%, the network costs decrease by 16%, while for scenario 1 this is 5%. For scenario 1, a depot is only opened if the price decreases by 40%. For scenario 3, a depot is already opened with the current parameters. However, if the price is increased by 60%, only direct transport lines are used, and the model avoids opening a depot.

When comparing the optimisation techniques, Figure 6.9 shows the comparison for scenarios 1 and 3, again displayed larger in section I.2. What is interesting to see is that for scenario 1, when the depot price decreases by 40%, in the simultaneous optimisation, the depot is opened, but for the sequential one, it is not opened. This results in a slight difference in network costs (1%). In the most extreme situation, where the depot prices decrease by 60%, the difference in optimising the model sequentially versus simultaneously is 2%. This means a yearly cost savings of €30.000. However, a cost reduction of 60% is very much and not likely to be realistic in scenario 1.

As seen in the graph, no depot is built when the depot costs increase by 60% for the distance-based model. From this point, it is more efficient only to use direct routes for transportation. On the other hand, when the depot costs are decreased by 60%, the model opens two depots for both simultaneous and sequential optimisation. However, for the sequential optimisation, the depot capacity is not high enough to consolidate the return flow, which is why the costs of sequential optimisation are 3% higher in this case. This equals 40.000 euros per year. For this distance-based scenario, it is quite likely that one depot is opened, even if the depot costs are not estimated correctly. Only if the real depot costs lie 60% lower or higher than the estimated one, a change in the number of depots that are opened occurs.



(a) *Scenario 1: current situation model*

(b) *Scenario 3: distance-based model*

Figure 6.9: *Comparison of the three optimisation techniques for changing depot costs*

6.3.5 Scenario 4: return flow

A scenario that is interesting to investigate is a future situation where Quooker's growth has stabilized. For this scenario, the variables and pricing system of scenario 1 are used as a basis. However, some things do change compared to scenario 1. It is assumed that Quooker has reached all its potential customers, and only a few new orders are made in Germany and Austria. However, all these existing customers still order the products that must be replaced. This means that the flow only consists of CO_2 tanks and water filters in this scenario. This flow is 50/50 since each time a product is sent back by a customer, one needs to be sent forward again as well. Moreover, in this scenario, the pallet flow has also reduced, so only the parcel flow is considered. It is assumed that in this scenario, 35% of the households have a Quooker, and of all people that have a Quooker, 75% have a Quooker with a cold water filter or a CO_2 tank. Moreover, the share of products going to Austria is 10% and the share to Germany is 90%, which is based on the number of households in Austria versus Germany (Eurostat, 2022).

For this model, a new cluster analysis has to be made. The same amount of nodes as before is used: 56 demand nodes. With a 50/50 split in return versus forward parcels, and a 10/90 split for Austria/Germany, the amount of nodes used in the model per country is the following:

Type	Share	# Nodes in model
Forward Germany	45%	25
Returning Germany	45%	25
Forward Austria	5%	3
Returning Austria	5%	3

Table 6.11: *Node distribution in model*

With these shares, a new cluster analysis can be performed. For Austria, the cluster centroids stay the same since 3 nodes are used, just like in scenario 1. For Germany, new clusters are made, the details of this are in section B.1 in Appendix B. For the costs, the location of the nodes does not matter since the model is not distance-based but country-based. However, for the KPI of the travelled distance, it does matter.

According to Quooker, a cold water filter has to be replaced each year, and it is assumed that a CO_2 tank that has a capacity of 60 litres has to be replaced two times a year. Based on the number of households in Germany and Austria, Quooker will have 498.750 customers in Germany and Austria when growth has stabilized. This means that per year, 831.125 orders are made by customers for the forward flow and the same amount for the return flow. If there are 25 nodes representing this volume, this means that the volume factor in the model should be 33.235.

Since Quooker is now a very large customer of the external logistics provider, and it only transports two types of products, the transport capacities have changed. The truck capacities are now more customized towards the CO_2 tanks, since this is the largest share. The new capacities and prices are shown in Appendix F. Moreover, the final commodities and their characteristics are shown in the same appendix.

The results of this scenario can be found in the table below, where the Δ represents the difference compared to the optimisation without any depots. Moreover, the network design when using a simultaneous optimisation is shown in Figure 6.10. Interesting to see is that when performing simultaneous optimisation, two depots are opened. This happens while there are no limits to the depot capacity and the model is not distance-based, so opening two depots seems illogical at first glance. However, it can be explained by the fact that holding a product in inventory costs money, while holding a product in a truck for a day avoids those inventory costs at a depot or at the production facility. When the model opens a second depot, this means that the extra depot costs and handling costs are lower than the inventory costs for a day. This only happens when a substantial volume is transported, so that the fixed depot costs become relatively low. This second depot is being used only by the return flow in this model. This is because this flow cannot be controlled in terms of when it is being sent, and this flow does not have a specific delivery time (while for forward parcels, this is 2-3 days). So the return flow is being sent, and the model wants to delay the product to decrease inventory costs. For the forward flow, the model wants to send the products as quickly as possible to a customer since Quooker does not pay inventory costs for a product located at a customer. In this scenario, simultaneous optimisation is 3,2% more efficient than sequential optimisation.

Scenario 4 return flow		**Total costs**	**Service costs**	**Depot costs**	**Depot open?**	**Depot capacity**	**Inventory volume**	**#Services**	**Distance traveled**	**Utilization rate**
Current practice (no depot)	value	13.770.008	12.970.956	n/a	no	n/a	n/a	56	25.917	92%
Depot possibility sequential optimisation	value	13.180.574	11.241.739	1.082.120	Yes, 1	5368	0	60	22.075	93%
	Δ	-4,3%	-13,3%	n/a	n/a	n/a	n/a	7,2%	-14,8%	1,1%
Depot possibility simultaneous optimisation	value	12.752.255	10.353.367	1.658.662	Yes, 1 and 3	5368 & 16.369	33.451	62	26.640	93%
	Δ	-7,4%	-20,2%	n/a	n/a	n/a	n/a	10,7%	2,8%	1,1%

Table 6.12: *Results scenario 4: return flow*

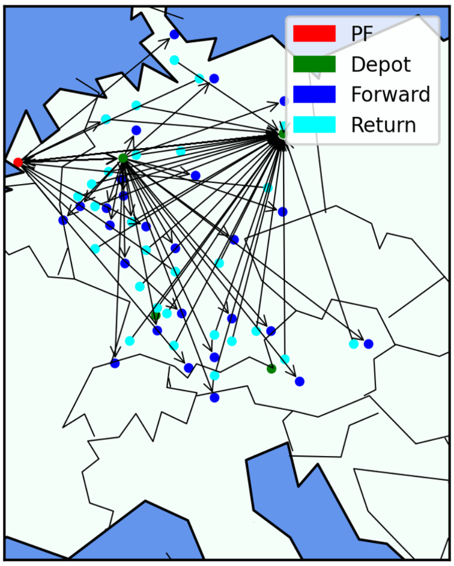


Figure 6.10: *Network results simultaneous optimisation for scenario 4*

6.3.6 Scenario 5: fixed costs pallet transportation

To further investigate the sensitivity of the distance-based model, a possible future scenario for Quooker is investigated. In this scenario, Quooker does their transport internally. It is assumed that the ratio of fixed and variable costs for pallets is the same as for parcels, thus 10% fixed and 90% variable. In the distance-based model, this was already included for the parcel transport. However, the pallet flow costs are very high in fixed costs and low in variable costs in the distance-based scenario. External logistic providers have higher costs due to administration and because they have to drive to a pick-up location, which are included in the fixed costs for the customer. When Quooker does its own transport, these aspects can be handled more efficiently. It is assumed that the costs of transporting pallets for Quooker is the same as when doing it with an external logistics provider. This is assumed because Quooker will only start doing this by themselves if it is indeed around the same price (or cheaper). This means that for deciding the pallet transportation costs, the same method is used as for making the parcel distance-based costs, meaning that the network costs for transporting pallets in the current situation for Quooker is the same when only using direct transport services.

For this scenario, it is assumed that Quooker has two types of trucks: a smaller truck that can carry up to 6 pallets, and a larger truck that can carry up to 12 pallets. Moreover, it is also possible for Quooker to still use the external logistic provider as a means of pallet transportation. For the trucks of Quooker, it is assumed that a truck carrying 12 pallets is 17% more expensive than one carrying 6. This is the same ratio as shown in the paper by the Netherlands Institute for Transport Policy Analysis (KIM) that compares a truck and a truck + trailer, which has around double the capacity (2020). Moreover, since this is a future scenario, so the volume has grown according to the predictions made by Quooker, which is a yearly growth of 30%. This scenario is 5 years later, meaning that Quooker has more than tripled in size (371%). The price of depots stays the same in this scenario. The final price for pallet trucks are the following:

- truck with 6 pallets (truck 5): 5 + 0,1 * distance
- truck with 12 pallets (truck 6): 5,8 + 0,12* distance
- truck of external logistics provider (truck 4): 79,40 + 0,011 * distance

The results of this scenario are shown in the table below, the Δ represents the difference compared to the optimisation without any depots.

Scenario 5 own pallet transportation		**Total costs**	**Service costs**	**Depot costs**	**Depot open?**	**Depot capacity**	**Inventory volume**	**#Services**	**Distance traveled**	**Utilization rate**
Current practice (no depot)	value	229.014	223.431	0	no	n/a	n/a	56	25.379	46%
Depot possibility sequential optimisation	value	199.395	172.544	20.496	yes, 4	109	0	61	19.335	56%
	Δ	-12,9%	-22,8%	n/a	n/a	n/a	n/a	8,9%	-23,8%	21,7%
Depot possibility simultaneous optimisation	value	194.231	166.816	21.325	yes, 4	150	248	62	17.872	49%
	Δ	-15,2%	-25,3%	n/a	n/a	n/a	n/a	10,7%	-29,6%	6,5%

Table 6.13: *Results scenario 5: own pallet transportation*

The final network design when performing simultaneous optimisation is shown in Figure 6.11. It can be seen that part of the pallet flow now indeed is consolidated in the depot, which results in lower network costs. In this scenario, the difference between a network that does not have a depot and a network where depots are used (and simultaneous optimisation is performed) is 15%, which is a substantial amount. On a yearly basis, this would mean a cost reduction of €850.000. Moreover, the difference between sequential optimisation and simultaneous optimisation is 2,6%. Therefore, optimising your network simultaneously would reduce yearly costs by €123.921. Specifically for the pallet transport costs, a reduction of 18% in pallet transport costs is made when optimising it simultaneously versus sequentially. This is mainly due to the fact that when optimising sequentially, no pallets of the return flow fit in the depot anymore. This means that all returning pallets are transported directly instead of consolidated, which is what happens in simultaneous optimisation. These differences are shown on a map in Figure H.9 in section H.5.

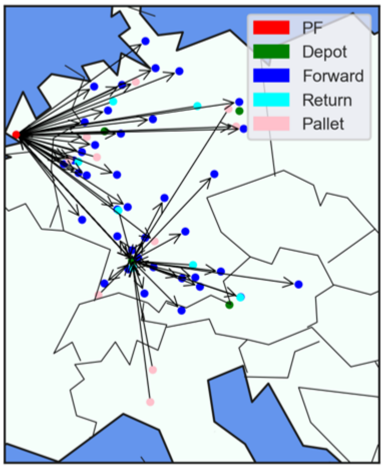


Figure 6.11: *Network results simultaneous optimisation for scenario 5*

6.3.7 Scenario 6: generic network

This last scenario is not based on the network of Quooker specifically but is a more generic case. An additional production facility is added to the model, and random demand nodes are composed. Furthermore, an important change to this model is that all demand is requested on the first day, while in the previous models, this was on a random day. This means that all demand nodes can immediately be consolidated if this would be beneficial. The distance-based model is used in this scenario, and the volume factor is six times larger than in the current situation scenario. The volume per demand node is created randomly. The network characteristics are shown in Appendix G. With an additional production facility, the forward and return flow of products can be consolidated between two depots, which could increase the impact of simultaneous optimisation. The positive impact of simultaneous optimisation is also expected to be larger because all demand becomes available on the first day, and smaller volumes are used per demand node.

The results in Table 6.14 show that there is a larger difference between sequential and simultaneous optimisation in this network compared to the previously analysed scenarios. The extended results are shown in Table H.5. Using simultaneous optimisation compared to sequential optimisation would result in a yearly savings of €555.028,80. This cost-reduction is because of multiple reasons. This network consists of two production facilities, and because of this the forward and return flow are consolidated into the same truck between depots 2 and 3. Moreover, this generic network has more consolidation opportunities, which means that the use of depots is very effective. Consolidation possibilities increase because the volume per demand node is smaller, so more orders can fit into one truck. Moreover, all orders are made on the same day, so products do not have to wait in inventory if they are consolidated with other products. There is a disadvantage to all orders being made on the first day, and this is that the inventory costs are higher, as all returning flow products arrive at the production facility earlier than in the previously used models.

Scenario 6 generic case		**Total costs**	**Service costs**	**Depot costs**	**Depot open?**	**Depot capacity**	**Inventory volume**	**Services**	**Distance traveled**	**Utilization rate**
current practice (no depot)	value	447.939,50	439.309,25	0	no	n/a	n/a	56	28.089	79%
Depot possibility sequential optimisation	value	424.906,00	378.214,60	12.864,42	yes	2 and 3	333 & 178	60	23.361	80%
	Δ	-5,1%	-14,0%	n/a	n/a	n/a	n/a	7,1%	-16,8%	1,3%
Depot possibility simultaneous optimisation	value	401.779,80	346.695,16	12904,64	yes	2 and 3	267 & 261	61	20.937	81%
	Δ	-10,3%	-21,1%	n/a	n/a	n/a	n/a	8,9%	-25,5%	2,5%

Table 6.14: *Results scenario 6: generic case*

6.4 Computational time for other cases

The complexity of the input factors is further analysed to find out for what other network types this research can be performed. Subsection 6.2.8 already described the impact on the solution time when increasing the number of depots and the number of demand nodes. This section investigates the impact of the following factors on computational time:

- Total volume in the network increased
- Cost of service increased
- Different weight distribution
- Increased time window for delivery

For this analysis, a random network is created and the distance-based model is used to investigate the computational time. The demand nodes and depot nodes are based on random coordinates. This network has sixty nodes in total, of which four are demand nodes. The results of the analysis can be found in Table 6.15. Moreover, in Appendix J, the gap over time is shown in a graph for the different factors. As shown in section 6.5, the results of using different optimisation techniques are quite close. This means that the model quickly finds a gap of 1% between the upper and lower bound solution. However, decreasing that gap even further is difficult in some cases. This lies in line with the results from this section. It can also be noticed that this model already takes a longer time to run compared to the model used in the case study, so changing the coordinates already impacts the computational time. The optimal solution for this case is found after 780 seconds. However, a gap of 1% is reached after 90 seconds, after which it decreased very slowly. The total volume in the network increased the computational time as well. If the volume was increased by six, the gap after running the model for one hour is still at 0,66%. Increasing the prices also caused an increase in complexity, but the optimal gap is reached within an hour. The weight distribution in the random network is quite wide. The weight distribution is changed to investigate how fast the model is solvable for companies with only one product type. For this, the weights of all nodes are changed to 1 kg and 7 kg. Both of these models are easily solved by Gurobi. Lastly, a larger delivery window is tested. This increases the number of available arcs and nodes on the time-space network. As expected, this indeed increases the difficulty of solving the model.

	Base case	**Larger network volume**	**Higher service price**	**Weight distribution**	**Increased delivery window**
1% gap reached	90s	2168s	615s	81s	266s
0,5% gap reached	472s	-	1514s	82s	975s
Gap after 1 hour	0,00%	0,66%	0,00%	0,00%	0,00%

Table 6.15: *Solution time and optimality gap for different variables*

As presented in subsection 6.2.8, increasing the number of depots has the most significant effect on computation time. This can be explained by the fact that a depot is open throughout the whole planning period, and that a depot is connected to all nodes in a network (whereas a demand node is only connected to the other depots and the production facility). These two factors significantly increase the number of arcs on the time-space network, making the model more complex to solve. Increasing the number of demand nodes also increases the gap of the model, just like increasing the network volume. Furthermore, increasing the delivery window of products in turn increases the number of arcs in the model and thus the complexity. If nodes are available for a longer time, the time-space network will become larger, and the solution space of the model will grow as well. The model has to make a decision with more available options, making it more complex to solve. Lastly, a factor that decreases the computational time is having an even distribution of weights per order, although it is interesting to test this with more weights than done in this section. Although Figure J.1 shows that a gap under 5% is quickly found for most cases, decreasing this gap further has proven to be difficult, specifically for a large volume and higher service costs. In this research, a short solution time is preferred as many analyses are performed. Yet, when applying this model to other cases, a longer solution time may be accepted as the model has to be run less often.

6.5 Comparative results

In the previous sections, the different scenarios were analysed individually, and in this section, they are compared. Note that not all aspects can be compared since the scenarios are different. Figure 6.12 shows the five scenarios that were analysed and the differences in the optimisation methods. Since the train scenario has proven to be unrealistic, it is not shown in the comparison.

Extensive sensitivity analyses were performed for the current situation and distance-based model. These analyses make it clear that the distance-based model opens a depot much earlier than the current situation model. The distance-based model even opens two depots when parameters are changed significantly. When comparing the sensitivity analyses, it can be noticed that the sensitivity for volume and service costs is higher for the current situation model. This means that when increasing those two parameters, the model increases by (almost) the same amount. The distance-based model changes less when changing the parameters by the same amount. This is because the distance-based model uses the depot more often and for more products. To compare, the current situation opens a depot when the volume increases by 230%, while the distance-based model opens a depot even when the volume drops to 40%. When looking at the sensitivity of the depot costs, the same applies. The threshold for opening a depot for the current situation is when the price decreases by 50%. For the distance-based it closes the depot when costs increase by 60%. To conclude, the distance-based model can use the depot much more effectively, which is why it opens one quicker.

The differences in optimisation techniques can be compared for all scenarios. The first four scenarios in Figure 6.12 are based on Quooker's network, and these scenarios are first compared. For the current situation, there are no effects. For the return flow scenario, the effects are the largest when looking at the differences in sequential and simultaneous optimisation. This makes sense since the return flow in this scenario is a larger percentage of the total flow. Thus when optimising it sequentially, the depot capacity is not large enough to incorporate a large part of the return flow, while this is possible when optimising it simultaneously. The effect of opening a depot is the largest for the scenario where pallet transport is done internally. These percentages are converted to costs in Table 6.16. This table shows the annual savings per kilo of volume that is transported. This was not the same for all scenarios, as not all scenarios had the same order size and total volume. This table also shows that opening a depot is very effective for all scenarios except the current situation, just as using a simultaneous optimisation technique.

The generic case scenario has the largest difference in sequential versus simultaneous optimisation. It is also the most effective in terms of savings/kg for simultaneous optimisation compared to the current practice optimisation. Reasons for this are that there are two production facilities, all orders are made on the same day and the order size was smaller.

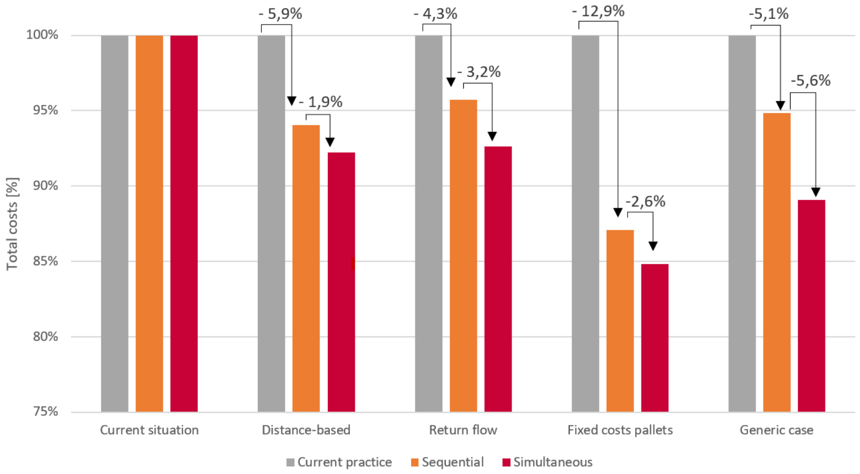


Figure 6.12: *Comparative results for different optimisation techniques, first 4 scenarios based on Quooker's network, last scenario on a random network*

Results of all scenarios	**Current situation**	**Distance-based**	**Return flow**	**FC pallets**	**Generic case**
Volume in model	60.380	60.380	7.644.050	224.010	134.310
Savings/kg simultaneous vs. current practice (no depot)	€ 0,000	€ 0,080	€ 0,133	€ 0,155	€0,350
Savings/kg simultaneous vs. sequential	€ 0,000	€ 0,019	€ 0,056	€ 0,023	€0,172

Table 6.16: *Comparison of the different scenarios in savings per kilo of volume transported*

It is also interesting to see which depots are opened for the different scenarios. For all distance-based scenarios that are based on Quooker's networks, first depot 4 is opened, and when the parameters change such that two depots are opened, depot 1 is added. This is because most of the demand is located near these two depots. For the fourth and fifth scenarios, where the return flow increases, depots 1 and 3 are opened. In this scenario, depot 3 is opened because the return products have a longer travel time, and a longer travel time means lower inventory costs, as discussed in subsection 6.3.5. However, when the model uses sequential optimisation, it only opens depot 1. Thus there are some important differences in which depot the model opens when using sequential or simultaneous optimisation.

A challenge in analysing this problem is that there are only a limited number of nodes available that can be used to represent the whole demand network. To ensure this representation is accurate, each demand node in the model represents multiple, smaller demand nodes in reality, which reduces consolidation opportunities in the network. Where in reality thousands of nodes can be consolidated, in this model only sixty can be used for consolidation. A limited number of nodes representing a larger network means that increasing the volume in the model does not increase the consolidation opportunities, since no new nodes are added to the model, but the available nodes only increase in size. This limitation is a common challenge when optimising a service network design model, as also discussed in previous literature (Wieberneit, 2007). In the scenarios based on Quooker's network, these nodes also all have a different ready and due time. If the ready time of a node is later than the due time of another node, these can never be consolidated. The generic network creates a larger opportunity for consolidation, where all ready times are the same. Additionally, the complexity of the model increases quickly when the number of depot possibilities is increased. This makes it difficult to perform this study on a larger network with more depot nodes.

7. Discussion, conclusion and recommendations

This chapter first discusses the results presented in the previous chapter. It also discusses the limitations of this research. Afterwards, a conclusion and recommendations for future research are given.

7.1 Discussion

As the results show, introducing a depot and simultaneously optimising flows can be beneficial in some cases. While consolidation of goods can reduce transportation costs, additional costs arise when a depot is opened. There is a fine balance between these aforementioned costs, and it is important to know in what cases the benefits are greater than the losses. In the following paragraphs, the findings are discussed in greater detail.

One of the results of this research is that opening a depot used for consolidation can effectively reduce transportation costs, which is consistent with papers previously written on service network designs with depot opportunities (Sung and Song, 2003). However, how to make use of such a depot on an operational level can be challenging. This model could choose between a direct flow between the origin and destination or an indirect flow through the depot. This decision can only be made when it is known what the spare capacity is of that depot, and if other products can be consolidated as well. These factors are not always known, making it difficult to determine which route a product should take. Nonetheless, there are also opportunities. A depot can function as a small station where the returning products can be refilled or replaced instead of sending them back to the production facility. Furthermore, once a depot is built, a simultaneous optimisation strategy can pay off in certain scenarios. This result aligns with what other research has stated before in a different network design model (Zhang et al., 2014). For some scenarios, simultaneous optimisation pays off more than for others. For example, when the return volume increases, the order volumes are smaller or a distance-based cost structure is used, it is more beneficial compared to the current situation scenario discussed in subsection 6.3.1.

An interesting point of discussion is how willing the external logistic service providers are in changing their cost structure. The model proved that is more beneficial to use a distance-based cost structure, but external logistics providers are the ones that can implement such a structure. All consolidation carried out by Quooker reduces transportation costs, while this money previously went to a logistics provider. It can be assumed that a logistics provider may be hesitant to switch to an option that reduces their income. Nevertheless, on the other side, the network is also more efficient for the logistics providers since they will drive shorter distances to deliver the same amount of parcels. Thus although their revenue will decrease, their costs will as well. Another potential motivating factor for logistics providers to move to a distance-based model is their environmental goals. If environmental factors are important to a logistics provider, or if new regulations require them to operate in a more environmentally friendly way, then there is a strong incentive to move to such a distance-based model since this reduces the emissions of transportation due to efficient consolidation.

Even if the country-based model stays in place, opening a depot has some reduction in costs if the volume grows, just as using simultaneous optimisation instead of sequential. However, the results showed that the cost differences are small, even if the volume grows. This is because increasing the volume and opening a depot will also cause an increase in necessary depot capacity and handling costs. The benefits of consolidating are slightly larger than the handling costs, but this is quite balanced (with a difference of 1% when the volume is quadrupled). This is because external logistics providers can offer low transport rates. They have a very large volume of all types of companies that they can consolidate within their own distribution network. Further reducing those costs is challenging since a logistics provider has a large benefit in terms of economies of scale, allowing them to offer transport services at a lower price. Moreover, if the volume that a company has to transport yearly is very large, these logistics providers can even offer lower rates compared to companies that only transport small volumes. When transport prices decrease, the effects of opening a depot for consolidation are less evident.

Lastly, the model revealed that for some instances, a depot far away from the product's origin and destination is opened so that the travel time towards that depot is very long, causing products to stay in a truck during that time instead of in inventory. This came to light in the scenario where the return flow was increased (subsection 6.3.5). It became apparent in this scenario because the increased return flow is a flow that cannot be planned. A return flow gets send the moment a customer decides to do so. This means it was heading towards the depot or production facility, where it costs money to store products. As a response, the model ensured that the product would stay a day or two more in transport to reduce inventory costs. This phenomenon can be compared to a current trend in the logistics market, which is described in The Wall Street Journal, where retailers are using transport equipment as inventory (2022). This occurrence can be even more effective on larger networks, such as those involving intercontinental product transportation. A product may arrive multiple days later by prolonging travel time, meaning that inventory costs are avoided during that period.

7.1.1 Limitations

Throughout this research and specifically in the case study, an attempt was made to represent reality as best as possible. However, exactly representing reality is very difficult due to the many details that occur in reality. In the model, simplifications were made, both of the model itself and of the data used in the model.

Firstly, the limitations of the input data of the model are discussed. The data used in the model was from one month in 2021, while it is a fast-growing company. This means that data from 2022 may be very different already. Since this was not yet available at the start of the project, it was not possible to use more recent data, but this was a limitation. Secondly, not all products and their volumes were taken into account. A more realistic representation could have been made by involving more products in the model, but this also would increase the complexity of the data and the model. Moreover, the research area was all transport between the Netherlands, Germany and Austria. For some scenarios, the distance travelled was important for the results. Throughout this research, the distance was based on the coordinates between two nodes, not on the actual travel time it would take. Especially in Germany and Austria, countries with hills and mountains, using the celestial distance would mean a shorter travel time than in reality.

Next to the limitations of the data, there are also limitations in the model. First of all, the model could not handle each demand point as a separate node for a short computation time. Nodes had to represent multiple demands in reality, which reduced consolidation opportunities. Moreover, this model has not considered any global factors, like what was done in the paper by Amin and Baki in 2017. Effects of crossing borders or toll rates were not implemented in the model. This sometimes impacts the cost of transportation and the duration. Another limitation is that the distribution of returning nodes across a country was spread the same way as the distribution of forward notes when considering parcel demand. However, this is not necessarily realistic, especially between the two countries. This return demand may be higher in some regions since other products with more returning attributes are popular there. Lastly, the model rounded the travel time. This means that if it took three hours to reach a location, the model would round it to zero days since the time interval used in the model was days. If a product would stop at an intermediate depot, and afterwards go to the destination, the travel time of those separate journeys could be less than a day when rounded. The model then assumed that the travel time would be zero for the total journey, while in total, this could add up to a day. The same effect can be the other way around, where the model would overestimate the travel time. This point is also discussed in subsection 4.1.5.

7.2 Conclusion

After having discussed this research, this section will conclude with the answers to the (sub)-research questions asked in chapter 1. The main research question is: “How can a combined forward and returning transport network for a production facility be designed effectively and efficiently?”. Forward flows originate from the production facility, and return flows end at the production facility. This question was answered with the help of mathematical modelling and optimising this model with Gurobi. Different models and optimisation techniques were used to find out the best designs. These techniques were one with no possibility of opening a depot, or a technique with the possibility to open a depot where sequential or simultaneous optimisation was performed. Simultaneous optimisation meant that the forward and return flow were optimised at the same time, and based on that, depot locations and their capacities were chosen. Sequential optimisation first optimises the forward flow, after which the return flow was added to the existing depot infrastructure.

Only when a depot would be built in a scenario, there could be a difference in simultaneous and sequentially optimising the flows. Opening such a depot for consolidation was useful in terms of cost minimisation if the volume would be around twice as high as the volume used in the current situation case study, or when a distance-based model would be used with the same volume. For the scenarios where a depot was opened, the total network costs could reduce by 1,9% - 5,6% when simultaneous optimisation was performed instead of sequential. During sequential optimisation, either insufficient space was left to also process the return flow, or the depot was built in a place that was not as efficient for the return flow as for the forward flow. Moreover, simultaneous optimisation resulted in an increased usage of trucks, but in most cases they drove a shorter distance. The only scenario where the distance driven was larger, is in the return flow scenario. This was done to reduce inventory costs, as mentioned in the discussion. Furthermore, the experimental results showed that using a train for multi-modal transport was ineffective under the analysed setting since the fixed costs of pallet transportation were too high. Lastly, when making a generic network with two production facilities and lower order volumes that were made on the same day, the differences between simultaneous and sequential optimisation were the largest.

Trying to optimise this model for larger-sized networks is difficult since this quickly increases the complexity of the model. Especially when more nodes that are connected to all other nodes in the network are added (like a depot node), the solution time increases quickly. However, throughout this research, a short computation time was preferable as the model had to be run many times for different analyses. When applying this model to other cases, a longer solution time can be accepted since the model only has to be applied once, in contrast to this research where it had to be applied multiple times. If a longer solution time is tolerated, a more complex network can be analysed. Other cases that the results can be generalised to are cases that also deal with both a forward flow of products and returning flow of products. This case study was performed on a network where for parcels, 12,5% was part of the return flow. If the return flow takes up a larger percentage, the network results of optimising simultaneously are even more beneficial. Moreover, this study can also be used in cases where transport is arranged internally. However, more research has to be done, since the model will change when applying it to a case like this. For that situation, it is also necessary to ensure enough services are available and that they return to their origin node, which was not necessary for this research.

To conclude, opening a depot that can be used to consolidate goods is in most cases effective. It is especially promising when volumes are large or a distance-based pricing system is used with low fixed costs. Moreover, performing simultaneous optimisation when designing a service network design is more effective and efficient than sequential optimisation, as this reduces the total network costs.

7.3 Recommendations

Recommendations can apply to practice or future research. First, the recommendations for practice are discussed. These help with what steps have to be taken to implement the results of this research. After that, recommendations for future research will be given.

Recommendations for practice apply to Quooker, the company that was analysed for this case study. With their current network and demand level, building a depot is inefficient; thus, optimising the forward and return flows simultaneously is ineffective. However, since Quooker's volume is expected to grow, the benefits of opening a depot will also grow. A first recommendation would be to further investigate the costs of building a depot, as this research relied on estimations that need to be studied further. According to this research, it is always beneficial to use a simultaneous optimisation technique when building a depot. Thus, when deciding on the location and capacity of a depot, looking at both the location of forward and return demand nodes is advantageous. Moreover, it does not add extra costs to the system. It is also worth exploring the benefits of a distance-based model. Such a model could significantly reduce the total network costs. However, discussions with the external logistics provider first have to be made to determine their cooperation for this new pricing system. Since these providers have the final say in their own cost structures, discussing the benefits of distance-based system for both parties is recommended. As it is expected that cost structures are often evolving due to new developments in regulations and changing company strategies, it is wise to design a pricing system that is robust for future changes. Additionally, it is important to note that this research has focused only on products in Germany and Austria, whereas Quooker sells in more countries. Therefore, it is interesting to determine whether opening a depot and optimising flows simultaneously will be even more effective if the company expands to additional countries. For a larger network, depots can be shared by an even larger flow, and more products can be transported together. While investigating the opportunities of analysing the network with more countries, the challenges should also be considered. Moving products through different countries can result in higher costs due to taxes or tolls. Moreover, it will increase the complexity of the problem, resulting in a longer solution time (or a larger gap between the upper and lower bound solution).

While this research provides new insights on optimisation of forward and returning flows, several valuable matters are not yet analysed but could be very interesting for future research. First of all, several papers have been written on algorithms that improve the calculation time of problems like the one researched in this paper. Using such an algorithm to solve problems described in this research could improve calculation time compared to the commercial solver used. This could create opportunity to expand the network and, increasing the number of nodes and scheduling length. The effects of different parameters on computational time are analysed in this research, but it is recommended that this analysis is expanded for more generic cases, because in this research only one network is analysed to examine the computational time for different parameters. Secondly, this paper only discussed cost minimisation as a goal, while it is also interesting to assess the environmental impact of simultaneous optimisation. On the one hand, less distance is driven by trucks, which has a positive environmental effect. On the other hand, a depot will be opened, which harms the environment. Therefore, assessing the environmental factors and examine how they can motivate logistics providers to move towards a more environmentally friendly distance-based model would be interesting. This would reduce the distance travelled, but also the total network costs. Furthermore, this research focused on optimising this problem for a company that sends products through a logistics service provider. In addition to this, a new research area can focus on optimising this problem for companies that have their own transport system. This creates an interesting new angle to the problem. New aspects of the problem would be that service vehicles do not pop up somewhere as they did in this paper. Because of this, the problem owner must also consider the costs of getting to a location. Moreover, there is not an unlimited amount of services available, as was the case for this research. Lastly, an important extension of this research could be focused on optimising this on different network types, as this study mainly focused on one type of network. Changing aspects like the location of nodes, demand quantities, and costs impact the results.

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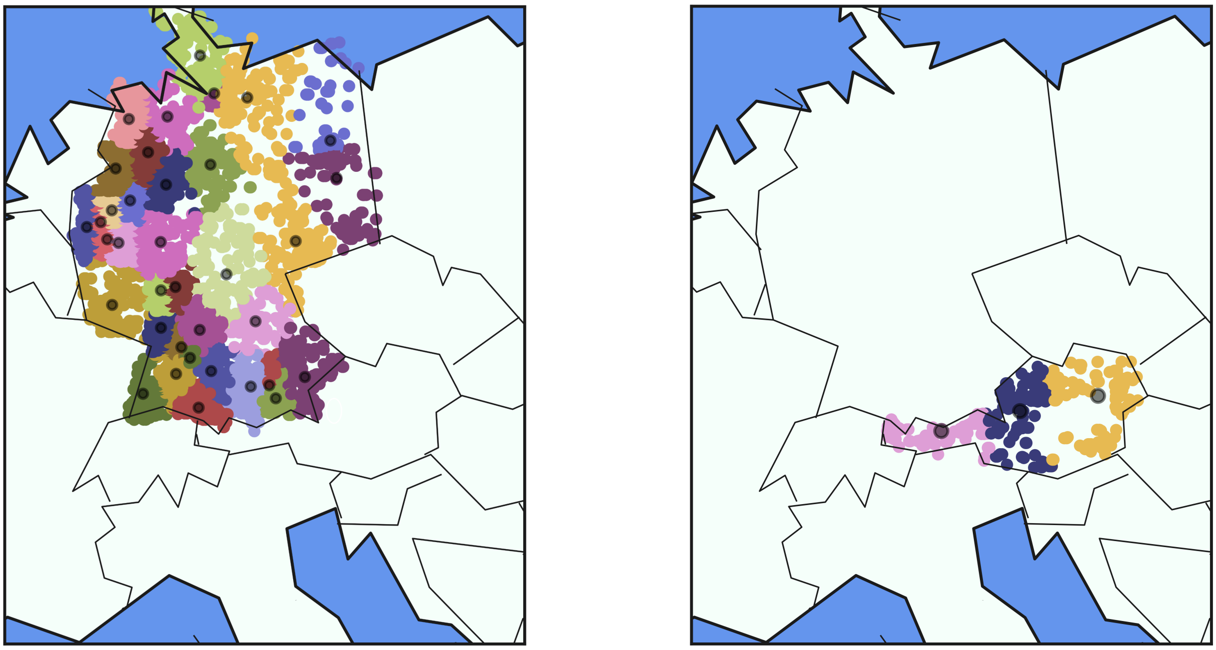
A. Scientific paper

The scientific paper starts on the next page.

B. Cluster method for node locations

To decide the location of the demand nodes in the model, the K-means clustering method is used. This is a method clusters data into larger groups, where each point fits in only one group. The data points are placed in subgroups (i.e. clusters) based on the sum of squared distances from the centroid of a subgroup (Yogeesh, 2021). For this case, each cluster will consist of around the same amount of demand points. This is because each demand point should represent around the same amount of volume. The results of the k-means method are described below.

The forward parcel flow is divided into the two focus countries of this research: Germany and Austria. All demand points in March 2021 are added to the model, and the k-means algorithm makes the clusters. The amount of clusters that has to be made is decided based on the volume of demand in a country. The results are shown in Figure B.1. What can be noticed is that the West and South of Germany have a higher cluster density. This is because in these regions, more orders are placed and the cluster sizes should be around the same size. For Austria, three clusters are made. For Austria the demand is higher in the North of the country, which is why the centroids are located a bit more to the North of the country. Each centroid location is used as the location of the demand point in the model.

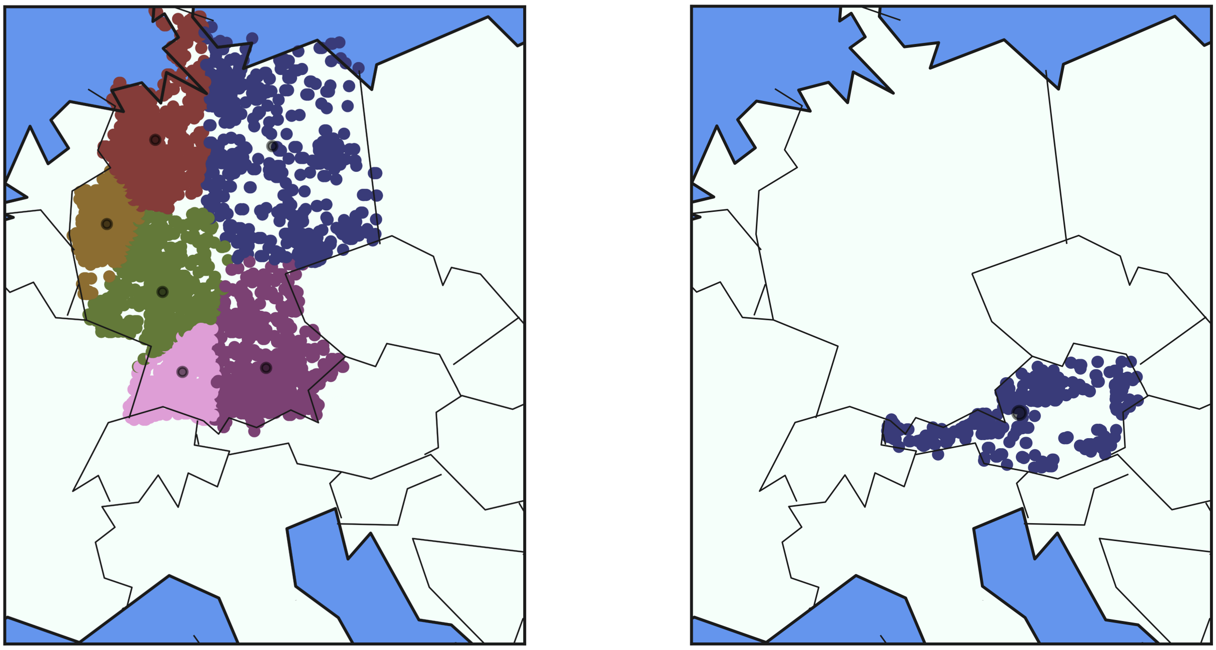


(a) *Clusters and their centroids for Germany's forward parcel flow*

(b) *Clusters and their centroids for Austria's forward parcel flow*

Figure B.1: *Clusters and its centroids for the forward parcel flow for Germany and Austria*

For the return flow of parcels, it is assumed that it is distributed in the same way as the forward flow. This assumption has to be made since there are no specific addresses available for the return parcel flow of Quooker's products. The return flow for parcels in Germany consists of 6 nodes, this means that 6 clusters have to be made. For Austria it consists of just 1 node, meaning that the center of all orders made in Austria is used as a demand point. The clusters of the return flow and its centroids are given in Figure B.2.



(a) *Clusters and their centroids for Germany's returning parcel flow*

(b) *Clusters and their centroids for Austria's returning parcel flow*

Figure B.2: *Clusters and its centroids for the returning parcel flow of Germany and Austria*

Pallets are only sent to Germany. There are much less pallet orders compared to parcel orders, but in terms of volume they are much larger. For the pallet orders, 5 clusters are made in Germany. This results in the centroids displayed in Figure B.3. Note that the cluster sizes of pallets are much smaller than the ones for parcels. This is taken into account throughout this research.

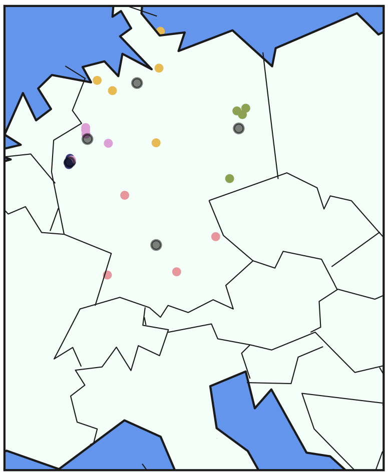


Figure B.3: *Clusters for forward pallet flow Germany*

B.1 Clustering scenario 4: return product flow

For scenario 4, new clusters have to be made since now 25 nodes will represent Germany's forward flow, and also 25 nodes will represent its return flow. The same method is applied as the one described at the start of this appendix. Although this scenario is a future situation for Quooker, it is still assumed that the demand locations are the same as they are right now. Thus the clustering method for scenario 4 is performed on the same demand nodes as was done for scenario 1. The results are shown in Figure B.4. The centroid locations are used in scenario 4. This is done to calculate a realistic travel distance by the trucks, which is one of the KPI's in the model. For the costs the node locations do not matter, since the model in scenario 4 is not distance-based.

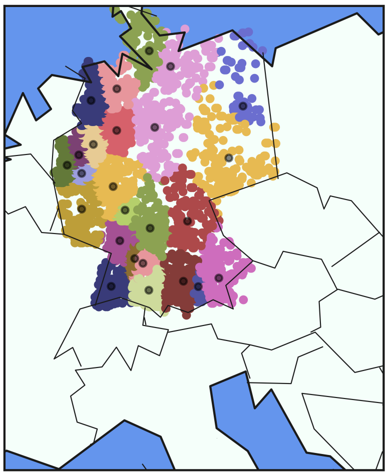


Figure B.4: *Clusters and their centroids for Germany's forward and returning parcel flow of scenario 4*

C. Map of European rail freight tracks

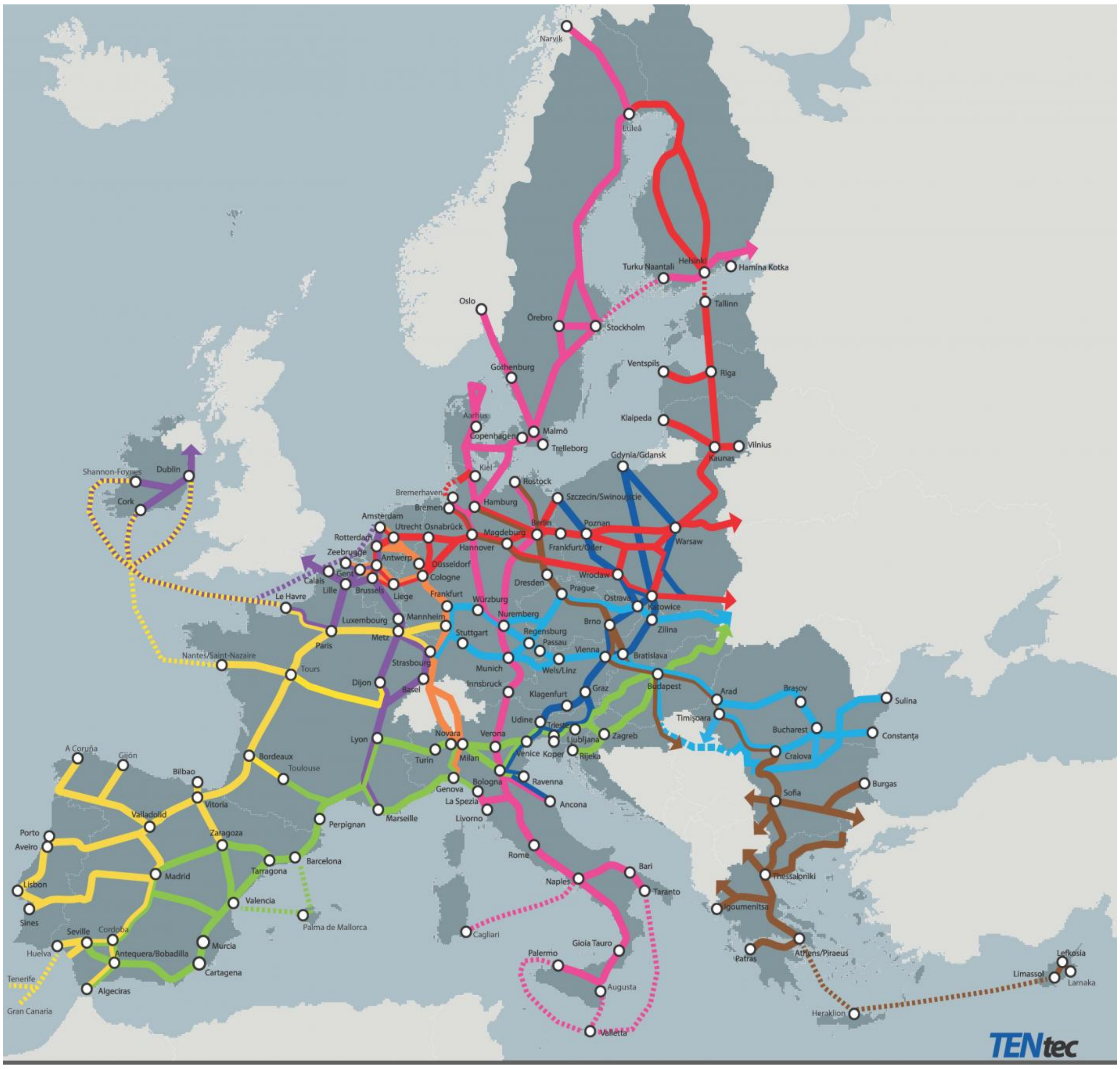


Figure C.1: *Train tracks for freight in Europe (retrieved from European Commission, n.d.)*

D. Commodity characteristics

Commodity	Origin	Destination	Volume	ReadyTime	DueTime	Route	Type	Country
0	0	5	5,5	4	6	forward	parcel	Germany
1	0	6	5,5	3	5	forward	parcel	Germany
2	0	7	1,6	4	6	forward	parcel	Germany
3	0	8	11	3	5	forward	parcel	Germany
4	0	9	5,5	0	2	forward	parcel	Germany
5	0	10	11	0	2	forward	parcel	Germany
6	0	11	5,5	0	2	forward	parcel	Germany
7	0	12	5,5	0	2	forward	parcel	Germany
8	0	13	8,7	2	4	forward	parcel	Germany
9	0	14	11	7	9	forward	parcel	Germany
10	0	15	8,7	0	2	forward	parcel	Germany
11	0	16	9,58	6	8	forward	parcel	Germany
12	0	17	5,5	7	9	forward	parcel	Germany
13	0	18	8,7	4	6	forward	parcel	Germany
14	0	19	5,5	3	5	forward	parcel	Germany
15	0	20	8,7	1	3	forward	parcel	Germany
16	0	21	5,5	5	7	forward	parcel	Germany
17	0	22	5,5	2	4	forward	parcel	Germany
18	0	23	11	3	5	forward	parcel	Germany
19	0	24	5,5	1	3	forward	parcel	Germany
20	0	25	5,5	1	3	forward	parcel	Germany
21	0	26	7,23	0	2	forward	parcel	Germany
22	0	27	8,7	6	8	forward	parcel	Germany
23	0	28	5,5	5	7	forward	parcel	Germany
24	0	29	8,7	3	5	forward	parcel	Germany
25	0	30	1,6	1	3	forward	parcel	Germany
26	0	31	8,7	4	6	forward	parcel	Germany
27	0	32	7,23	2	4	forward	parcel	Germany
28	0	33	5,5	2	4	forward	parcel	Germany
29	0	34	8,7	5	7	forward	parcel	Germany
30	0	35	5,5	5	7	forward	parcel	Germany
31	0	36	7,23	6	8	forward	parcel	Germany
32	0	37	9,58	0	2	forward	parcel	Germany
33	0	38	5,5	5	7	forward	parcel	Germany
34	0	39	1,6	4	6	forward	parcel	Germany
35	0	40	5,5	1	3	forward	parcel	Germany
36	0	41	5,5	0	3	forward	parcel	Austria
37	0	42	11	6	9	forward	parcel	Austria
38	0	43	5,5	3	6	forward	parcel	Austria

39	0	44	180	1	6	forward	pallet	Germany
40	0	45	150	0	5	forward	pallet	Germany
41	0	46	200	4	9	forward	pallet	Germany
42	0	47	165	2	7	forward	pallet	Germany
43	0	48	165	4	9	forward	pallet	Germany
44	49	0	5,5	0	9	return	parcel	Germany
45	50	0	5,5	1	9	return	parcel	Germany
46	51	0	5,5	2	9	return	parcel	Germany
47	52	0	5,5	0	9	return	parcel	Germany
48	53	0	5,5	0	9	return	parcel	Germany
49	54	0	5,5	0	9	return	parcel	Germany
50	55	0	5,5	1	9	return	parcel	Germany
51	56	0	140	1	9	return	pallet	Germany
52	57	0	100	2	9	return	pallet	Germany
53	58	0	180	2	9	return	pallet	Germany
54	59	0	180	0	9	return	pallet	Italy
55	60	0	170	0	9	return	pallet	Italy

Table D.1: *Commodity characteristics*

E. Verification

During the verification process, the current situation scenario is analysed. Since the parameters that relate to the depot also have to be verified, the volume has increased such that a depot is opened. The verification results are shown in the table below. As presented in the table, the model passes all verification tests.

Parameter	**Description**	**Change in parameter**	**Expectation**	**check**
t	Days modeled	+5	higher depot costs OR depot closed	✓
		-5	no possible outcome	✓
FC	Fixed depot costs	2000	higher costs OR depot closed	✓
		0	lower costs, depots open	✓
VC	Variable depot costs	50	depot not used	✓
		0	more OR same number of products through depot	✓
HC	Handling costs	50	Depot not used	✓
		0	more OR same products through depot	✓
IC	Inventory costs	500	higher inventory costs	✓
		0	reduced inventory costs	✓
u^v	Capacity	first truck cap 200kg	only that truck used for parcels	✓
		all cap /10	more trucks used	✓
c_{ij}^v	Service costs	*5	service costs increases	✓
		/5	service costs decreases	✓
V^k	Volume	*50	larger trucks used	✓
		/50	smaller trucks used	✓

Table E.1: *Verification tests for parameters used in model*

F. Inputs scenario 4

Commodity	**Origin**	**Destination**	**Volume**	**ReadyTime**	**DueTime**	**Route**	**Type**	**Country**
0	0	5	1,6	4	6	forward	parcel	Austria
1	0	6	5,5	3	5	forward	parcel	Austria
2	0	7	5,5	4	6	forward	parcel	Austria
3	0	8	1,6	3	5	forward	parcel	Germany
4	0	9	5,5	0	2	forward	parcel	Germany
5	0	10	5,5	0	2	forward	parcel	Germany
6	0	11	1,6	0	2	forward	parcel	Germany
7	0	12	5,5	0	2	forward	parcel	Germany
8	0	13	5,5	2	4	forward	parcel	Germany
9	0	14	1,6	7	9	forward	parcel	Germany
10	0	15	5,5	0	2	forward	parcel	Germany
11	0	16	5,5	6	8	forward	parcel	Germany
12	0	17	1,6	7	9	forward	parcel	Germany
13	0	18	5,5	4	6	forward	parcel	Germany
14	0	19	5,5	3	5	forward	parcel	Germany
15	0	20	1,6	1	3	forward	parcel	Germany
16	0	21	5,5	5	7	forward	parcel	Germany
17	0	22	5,5	2	4	forward	parcel	Germany
18	0	23	1,6	3	5	forward	parcel	Germany
19	0	24	5,5	1	3	forward	parcel	Germany
20	0	25	5,5	1	3	forward	parcel	Germany
21	0	26	1,6	0	2	forward	parcel	Germany
22	0	27	5,5	6	8	forward	parcel	Germany
23	0	28	5,5	5	7	forward	parcel	Germany
24	0	29	1,6	3	5	forward	parcel	Germany
25	0	30	5,5	1	3	forward	parcel	Germany
26	0	31	5,5	4	6	forward	parcel	Germany
27	0	32	1,6	2	4	forward	parcel	Germany
28	33	0	1,6	0	9	return	parcel	Austria
29	34	0	5,5	0	9	return	parcel	Austria
30	35	0	5,5	0	9	return	parcel	Austria
31	36	0	1,6	0	9	return	parcel	Germany
32	37	0	5,5	0	9	return	parcel	Germany
33	38	0	5,5	0	9	return	parcel	Germany
34	39	0	1,6	0	9	return	parcel	Germany
35	40	0	5,5	0	9	return	parcel	Germany
36	41	0	5,5	0	9	return	parcel	Germany
37	42	0	1,6	0	9	return	parcel	Germany
38	43	0	5,5	0	9	return	parcel	Germany

39	44	0	5,5	0	9	return	parcel	Germany
40	45	0	1,6	0	9	return	parcel	Germany
41	46	0	5,5	0	9	return	parcel	Germany
42	47	0	5,5	0	9	return	parcel	Germany
43	48	0	1,6	0	9	return	parcel	Germany
44	49	0	5,5	0	9	return	parcel	Germany
45	50	0	5,5	0	9	return	parcel	Germany
46	51	0	1,6	0	9	return	parcel	Germany
47	52	0	5,5	0	9	return	parcel	Germany
48	53	0	5,5	0	9	return	parcel	Germany
49	54	0	1,6	0	9	return	parcel	Germany
50	55	0	5,5	0	9	return	parcel	Austria
51	56	0	5,5	0	9	return	parcel	Germany
52	57	0	1,6	0	9	return	parcel	Germany
53	58	0	5,5	0	9	return	parcel	Germany
54	59	0	5,5	0	9	return	parcel	Germany
55	60	0	1,6	0	9	return	parcel	Germany

Table F.1: *Commodity characteristics scenario 4*

The customised truck prices and capacities can be found in the table below.

Type	**Costs**	**Unit**
Service costs NL to DE	[...]	€/kg, capacity:[2;5,5;16,5;33]
Service costs NL to AU	[...]	€/kg, capacity:[2;5,5;16,5;33]
Service costs DE to DE	[...]	€/kg, capacity:[2;5,5;16,5;33]
Service costs AU to AU	[...]	€/kg, capacity:[2;5,5;16,5;33]
Service costs AU to DE	[...]	€/kg, capacity:[2;5,5;16,5;33]

Table F.2: *Costs of trucks in scenario 4*

G. Inputs scenario 6

Commodity	Origin	Destination	Volume	ReadyTime	DueTime	Route	Type
0	1	5	2	0	6	forward	parcel
1	1	6	1	0	6	forward	parcel
2	0	7	4	0	6	forward	parcel
3	1	8	2	0	9	forward	parcel
4	1	9	3	0	9	forward	parcel
5	0	10	5	0	7	forward	parcel
6	1	11	2	0	9	forward	parcel
7	1	12	1	0	9	forward	parcel
8	1	13	1	0	6	forward	parcel
9	1	14	2	0	7	forward	parcel
10	0	15	1	0	9	forward	parcel
11	0	16	4	0	8	forward	parcel
12	1	17	3	0	6	forward	parcel
13	1	18	4	0	8	forward	parcel
14	0	19	1	0	7	forward	parcel
15	0	20	2	0	8	forward	parcel
16	1	21	3	0	7	forward	parcel
17	1	22	2	0	8	forward	parcel
18	1	23	1	0	6	forward	parcel
19	1	24	4	0	7	forward	parcel
20	0	25	3	0	7	forward	parcel
21	0	26	4	0	9	forward	parcel
22	1	27	4	0	8	forward	parcel
23	1	28	5	0	6	forward	parcel
24	1	29	4	0	8	forward	parcel
25	1	30	5	0	9	forward	parcel
26	1	31	2	0	7	forward	parcel
27	0	32	4	0	7	forward	parcel
28	1	33	4	0	8	forward	parcel
29	0	34	3	0	7	forward	parcel
30	0	35	1	0	8	forward	parcel
31	1	36	1	0	7	forward	parcel
32	1	37	2	0	8	forward	parcel
33	1	38	3	0	6	forward	parcel
34	1	39	1	0	7	forward	parcel
35	0	40	1	0	7	forward	parcel
36	0	41	5	0	9	forward	parcel
37	1	42	2	0	8	forward	parcel
38	1	43	5	0	6	forward	parcel

39	1	44	5	0	8	forward	parcel
40	1	45	1	0	9	forward	parcel
41	1	46	1	0	7	forward	parcel
42	0	47	1	0	7	forward	parcel
43	0	48	5	0	9	forward	parcel
43	49	1	1	0	n/a	return	parcel
44	50	0	1	0	n/a	return	parcel
45	51	1	3	0	n/a	return	parcel
46	52	1	5	0	n/a	return	parcel
47	53	1	5	0	n/a	return	parcel
48	54	0	2	0	n/a	return	parcel
49	55	0	5	0	n/a	return	parcel
50	56	1	5	0	n/a	return	parcel
51	57	0	3	0	n/a	return	parcel
52	58	1	3	0	n/a	return	parcel
53	59	1	1	0	n/a	return	parcel
54	60	0	3	0	n/a	return	parcel
55	61	1	2	0	n/a	return	parcel

Table G.1: *Node characteristics scenario 6*

H. Extended results scenarios

H.1 Scenario 1: current situation

The results for all three optimisation techniques are the same, these are shown in the table below.

Total costs	**63.032,06**
parcel service	58.996,5
pallet service	2530,54
inventory costs	1505,03
Depot costs	**0**
Fixed costs	0
Variable costs	0
Handling costs	0
Services used	**56**
Type 0	5
Type 1	0
Type 2	41
Type 3	0
Type 4	10
Total distance travelled	**25.379**
Utilization rate	**56%**

Table H.1: *Extended results of scenario 1*

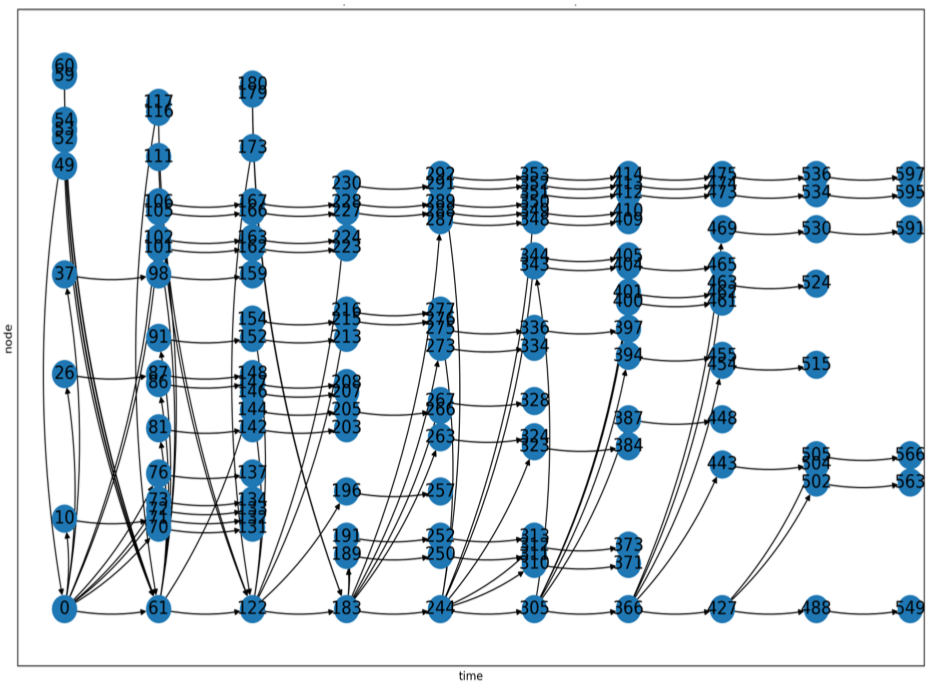
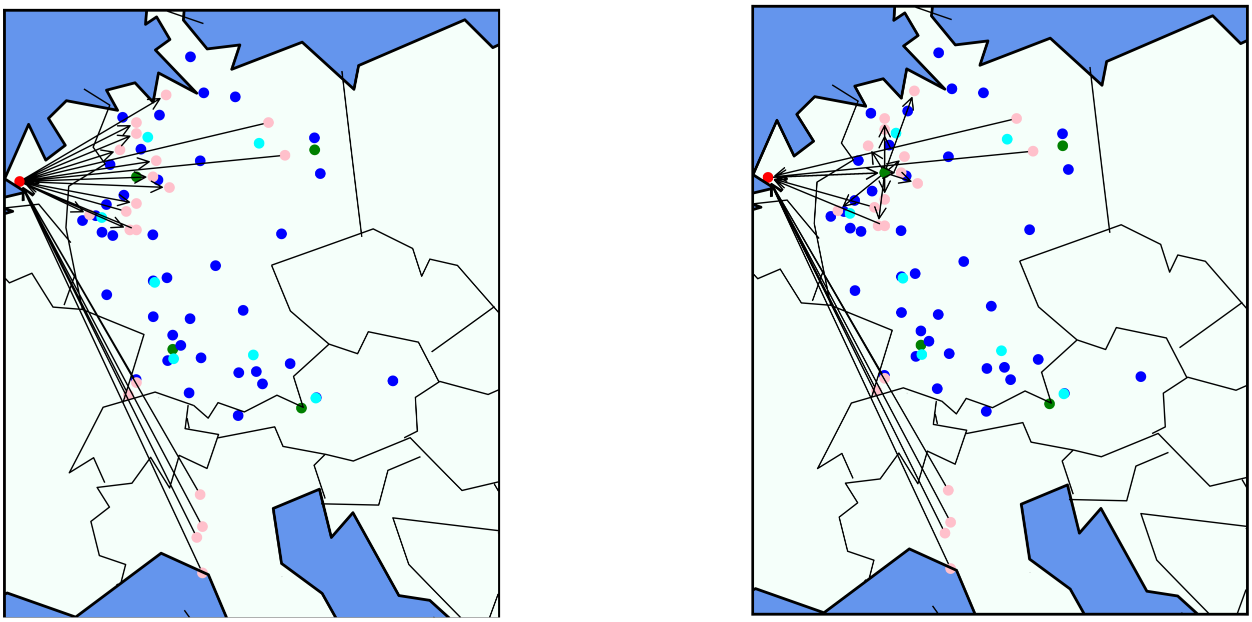


Figure H.1: *Time-space network for scenario 1*

H.2 Scenario 2: train as a mode



(a) *Results of pallet transportation with original pallet fixed costs*

(b) *Results of pallet transportation with reduced fixed costs*

Figure H.2: *The two results for optimising train, with a large fixed costs for pallet transportation (train not used) and a low fixed costs (train is used)*

H.3 Scenario 3: distance-based model

Depot closed	
Total costs	**62.713,71**
parcel service	58.678,14
pallet service	2530,54
inventory costs	1505,03
Depot costs	**0**
Fixed costs	0
Variable costs	0
Handling costs	0
Services used	**56**
Type 0	5
Type 1	0
Type 2	41
Type 3	0
Type 4	10
Total distance travelled	**25.379**
Utilization rate	**56%**

Depot open: sequential optimisation	
Total costs	**58.985,7**
parcel service	44.962,08
pallet service	2530,54
inventory costs	1712,69
Depot costs	**9780,40**
Fixed costs	5824
Variable costs	71,4
Handling costs	3885
Services used	**61**
Type 0	5
Type 1	0
Type 2	42
Type 3	4
Type 4	10
Total distance travelled	**19.335**
Utilization rate	**62%**

Depot open: simultaneous optimisation	
Total costs	**57.846,1**
parcel service	43.651,01
pallet service	2530,54
inventory costs	1687,25
Depot costs	**9977,30**
Fixed costs	5824
Variable costs	83,3
Handling costs	4070
Services used	**61**
Type 0	5
Type 1	0
Type 2	42
Type 3	4
Type 4	10
Total distance travelled	**18.744**
Utilization rate	**63%**

Table H.2: *Extended results of scenario 3*

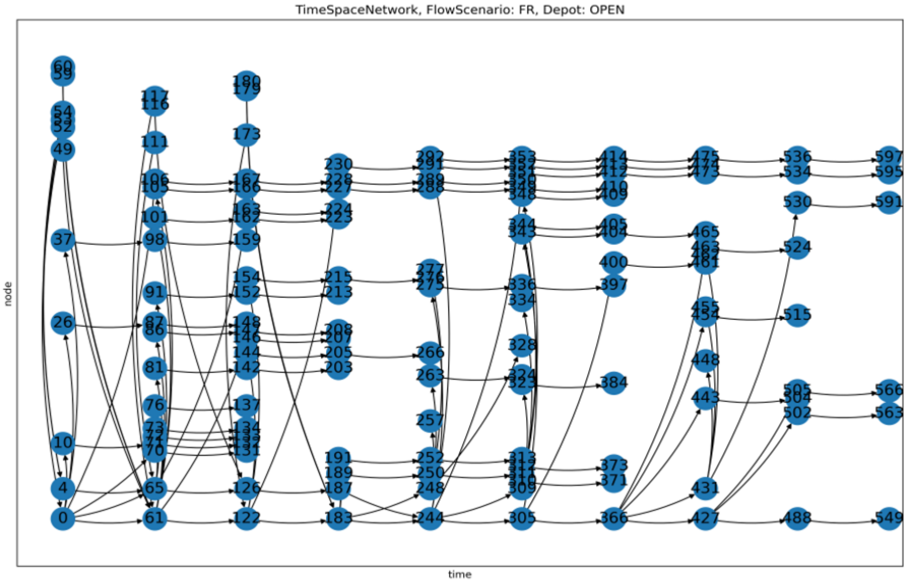
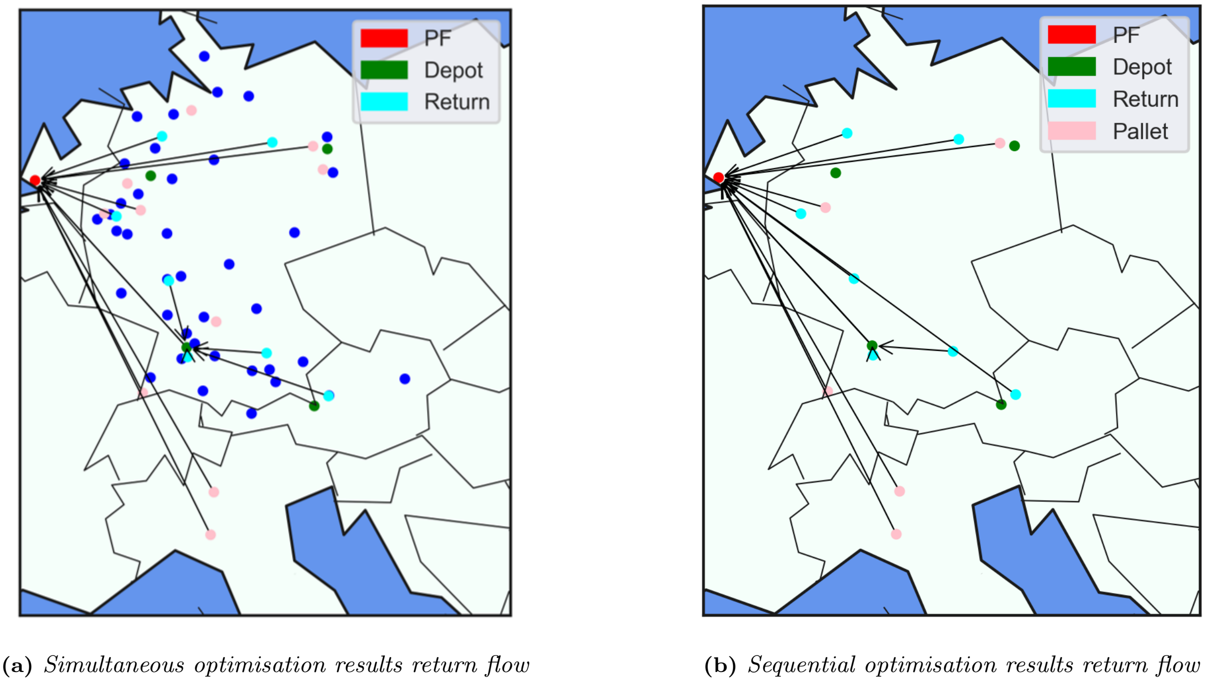


Figure H.3: *Time-space network for scenario 3*



(a) *Simultaneous optimisation results return flow* **(b)** *Sequential optimisation results return flow*

Figure H.4: *Difference return flow for optimising simultaneously versus sequentially*

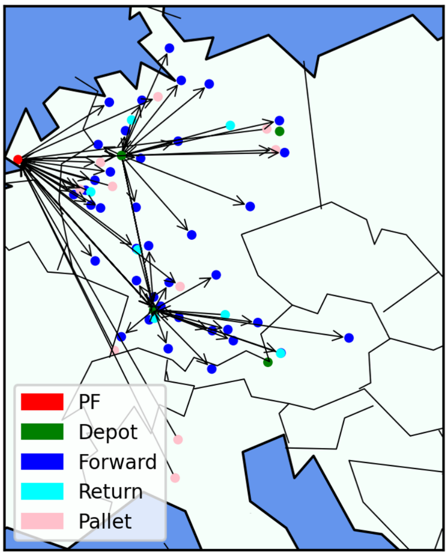


Figure H.5: *Results when parameters are adapted in such a way that two depots are opened in scenario 3*

H.4 Scenario 4: return flow

Depot closed	
Total costs	**13.770.008**
parcel service	12.970.956
inventory costs	799.052
Depot costs	**0**
Fixed costs	0
Variable costs	0
Handling costs	0
Services used	**56**
Type 0	20
Type 1	36
Type 2	0
Type 3	0
Type 4	0
Total distance travelled	**25.917**
Utilization rate	**92%**

Depot open: sequential optimisation	
Total costs	**13.180.574**
parcel service	11.241.739
inventory costs	856.715
Depot costs	**1.082.119**
Fixed costs	5824
Variable costs	12.775,84
Handling costs	1.063.520
Services used	**60**
Type 0	20
Type 1	36
Type 2	0
Type 3	4
Type 4	0
Total distance travelled	**22.075**
Utilization rate	**93%**

Depot open: simultaneous optimisation	
Total costs	**12.752.255**
parcel service	10.353.367
inventory costs	740.226
Depot costs	**1.658.662**
Fixed costs	11.648
Variable costs	51.734,06
Handling costs	1.595.280
Services used	**62**
Type 0	20
Type 1	36
Type 2	0
Type 3	6
Type 4	0
Total distance travelled	**24.640**
Utilization rate	**93%**

Table H.3: *Extended results scenario 4*

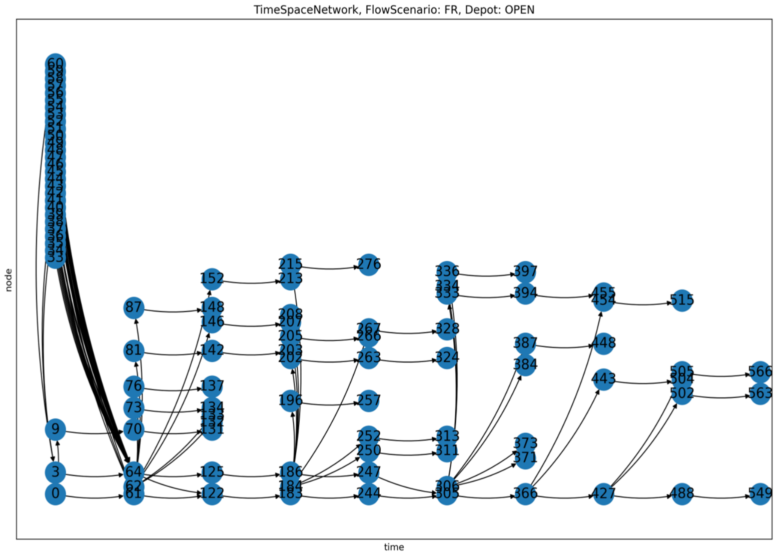
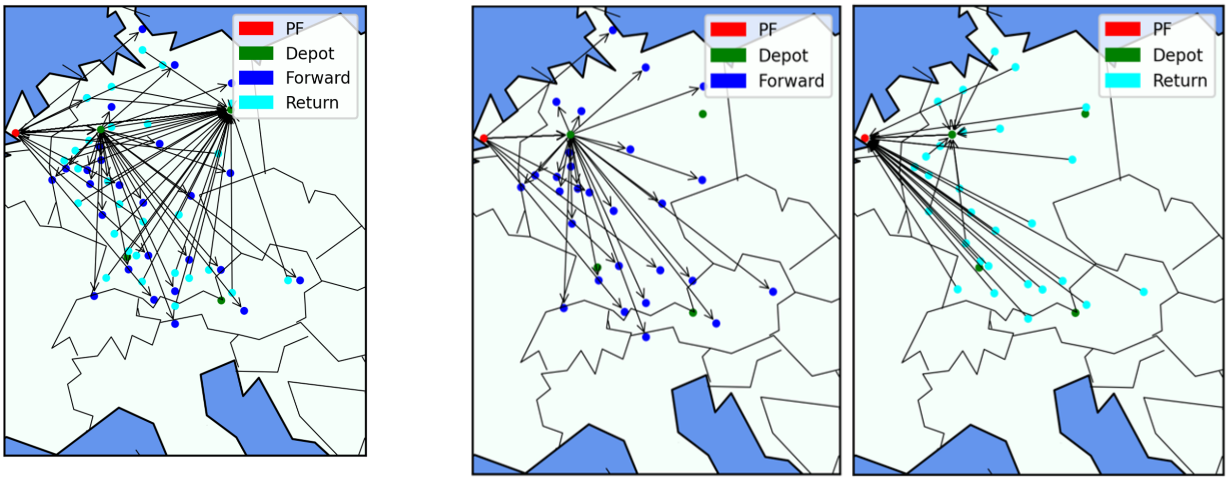


Figure H.6: *Time-space network for increase in return flow scenario*



(a) *Simultaneous optimisation results scenario 4*

(b) *Sequential optimisation results scenario 4 forward flow*

(c) *Sequential optimisation results scenario 4 return flow*

Figure H.7: *Scenario 4 differences between simultaneous and sequential optimisation*

H.5 Scenario 5: fixed costs pallet transportation

Depot closed	
Total costs	**229.014,42**
parcel service	217.695,91
pallet service	5734,86
inventory costs	5583,64
Depot costs	**0**
Fixed costs	0
Variable costs	0
Handling costs	0
Services used	**56**
Type 0	5
Type 1	0
Type 2	41
Type 3	0
Type 4	1
Type 5	9
Type 6	0
Total distance travelled	**25.379**
Utilization rate	**46%**

Depot open: sequential optimisation	
Total costs	**199.395,00**
parcel service	166.809,29
pallet service	5734.86
inventory costs	6354,07
Depot costs	**20496,77**
Fixed costs	5824,00
Variable costs	259,42
Handling costs	14.413,35
Services used	**61**
Type 0	5
Type 1	0
Type 2	42
Type 3	4
Type 4	1
Type 5	9
Type 6	0
Total distance travelled	**19.335**
Utilization rate	**56%**

Depot open: simultaneous optimisation	
Total costs	**194.231,59**
parcel service	161.945,26
pallet service	4871,15
inventory costs	6134,48
Depot costs	**21325,22**
Fixed costs	5824,00
Variable costs	357,00
Handling costs	15.144,22
Services used	**62**
Type 0	5
Type 1	0
Type 2	41
Type 3	5
Type 4	0
Type 5	11
Type 6	0
Total distance travelled	**17.872**
Utilization rate	**49%**

Table H.4: *Extended results of scenario 5*

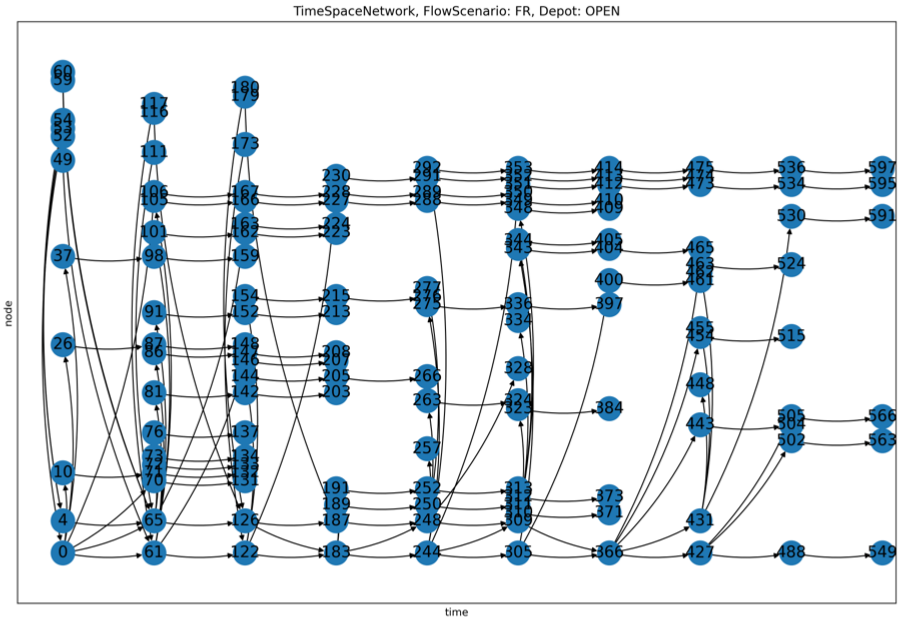
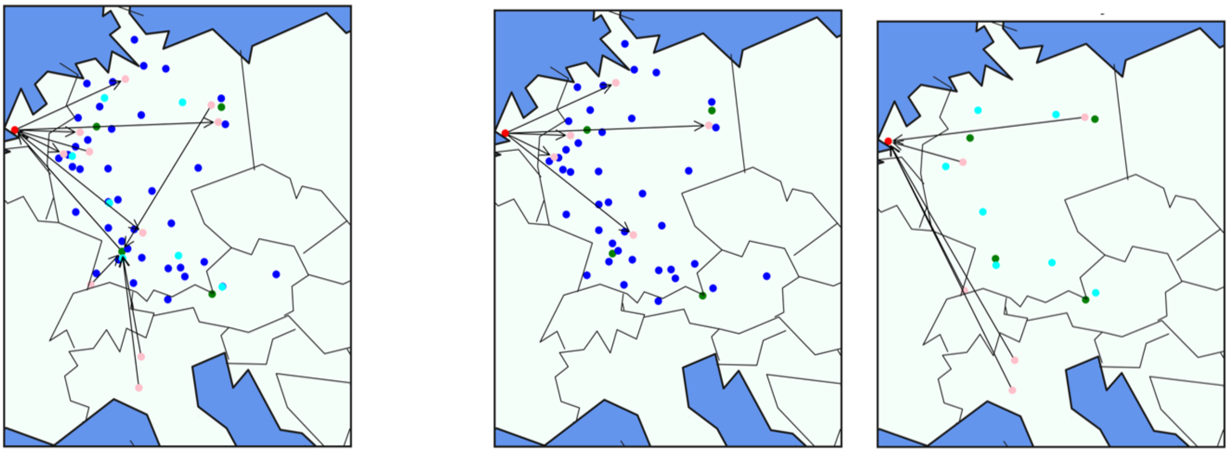


Figure H.8: *Time-space network for scenario 5*



(a) *Simultaneous optimisation results pallet flow scenario 5*

(b) *Sequential optimisation results pallet forward flow scenario 5*

(c) *Sequential optimisation results pallet return flow scenario 5*

Figure H.9: *Pallet transportation difference between simultaneous and sequential optimisation scenario 5*

H.6 Scenario 6: generic network

Depot closed	
Total costs	**447939,50**
parcel service	439309,25
inventory costs	8630,25
Depot costs	**0**
Fixed costs	0
Variable costs	0
Handling costs	0
Services used	**56**
Type 0	22
Type 1	34
Type 2	0
Type 3	0
Type 4	0
Total distance travelled	**28.089**
Utilization rate	**79%**

Depot open: sequential optimisation	
Total costs	**424906,00**
parcel service	378214,60
inventory costs	8297,25
Depot costs	**38394,18**
Fixed costs	11.648
Variable costs	1216,18
Handling costs	25.530
Services used	**60**
Type 0	22
Type 1	34
Type 2	1
Type 3	3
Type 4	0
Total distance travelled	**23.361**
Utilization rate	**80%**

Depot open: simultaneous optimisation	
Total costs	**401779,80**
parcel service	346695,16
inventory costs	9990,00
Depot costs	**45094,64**
Fixed costs	11.648,00
Variable costs	1256,64
Handling costs	32.190,00
Services used	**61**
Type 0	22
Type 1	34
Type 2	1
Type 3	4
Type 4	0
Total distance travelled	**20.937**
Utilization rate	**81%**

Table H.5: *Extended results of scenario 6*

I. Sensitivity analyses

I.1 Sensitivity analysis changes in parameters

Volume

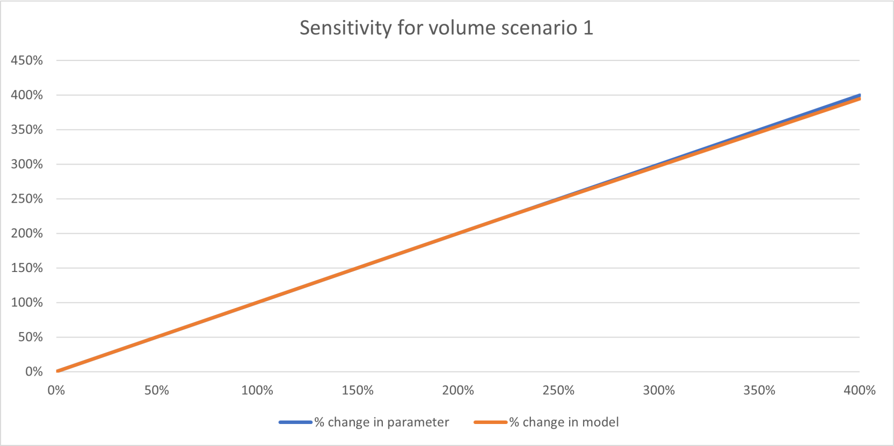


Figure I.1: *Sensitivity for a change in volume for scenario 1*

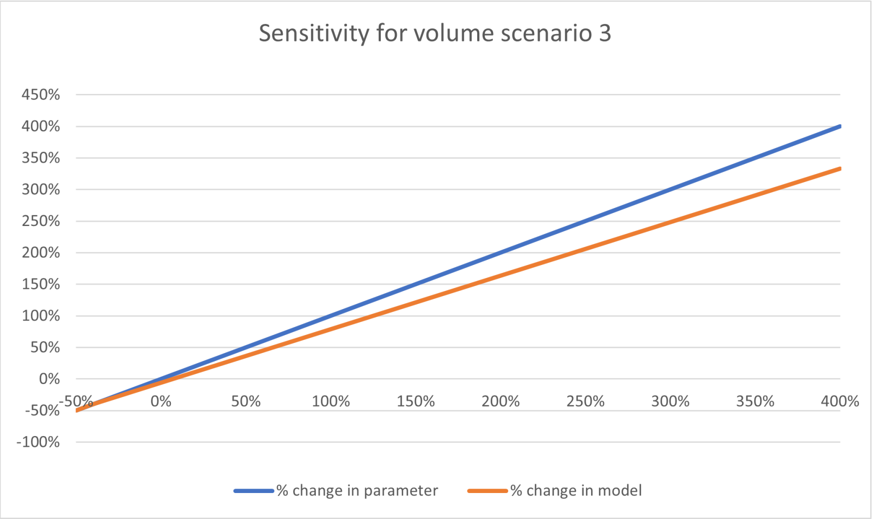


Figure I.2: *Sensitivity for a change in volume for scenario 3*

Service costs

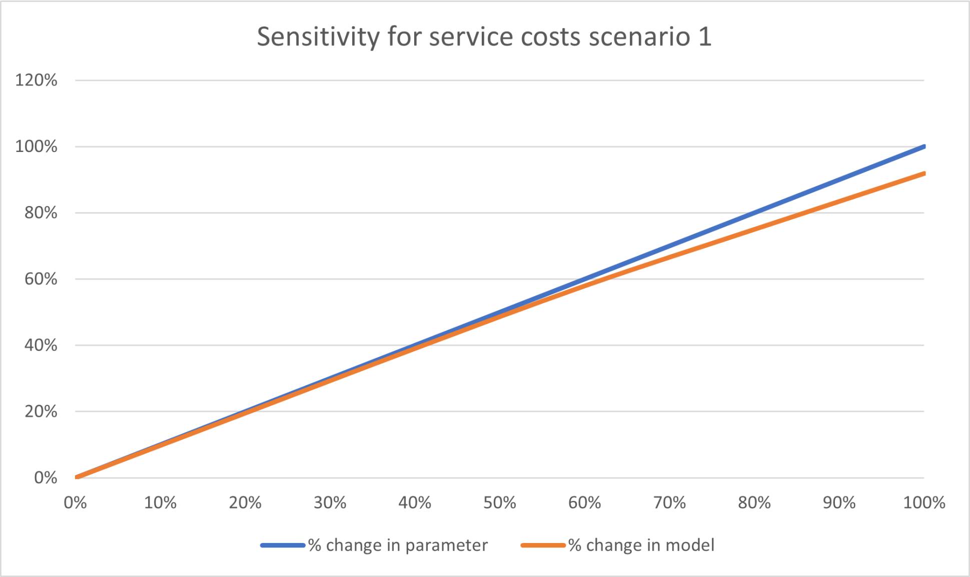


Figure I.3: *Sensitivity for a change in service costs for scenario 1*

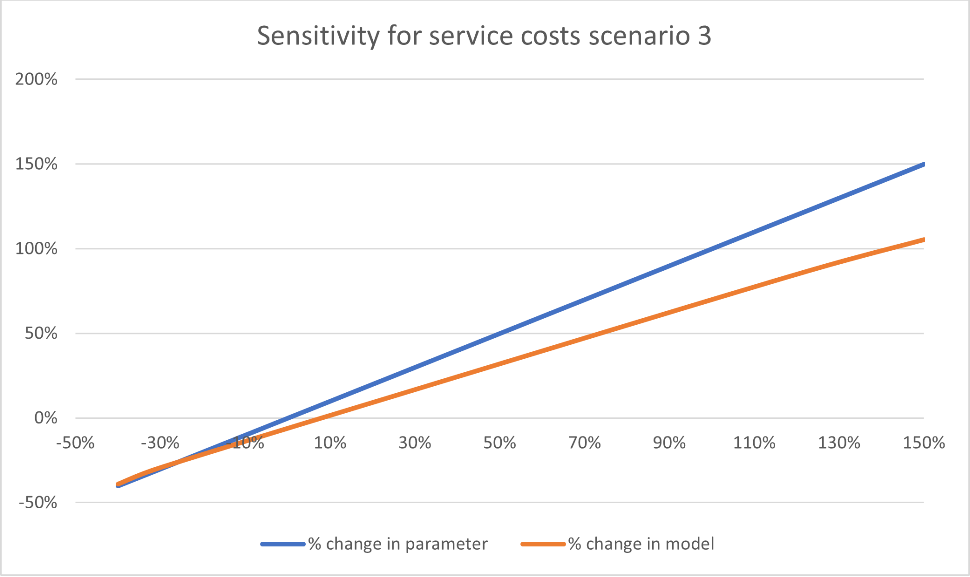


Figure I.4: *Sensitivity for a change in service costs for scenario 3*

Depot costs

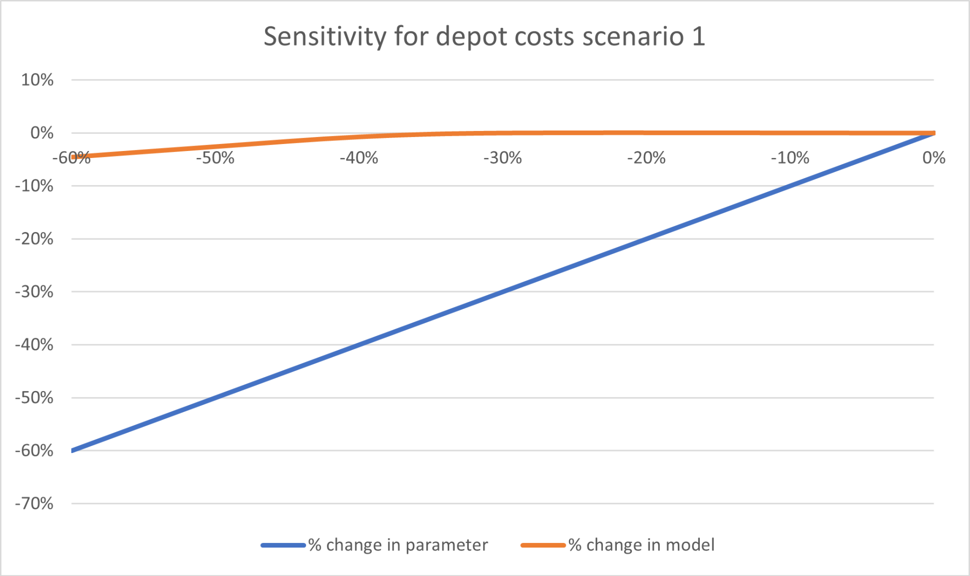


Figure I.5: *Sensitivity for a change in depot costs for scenario 1*

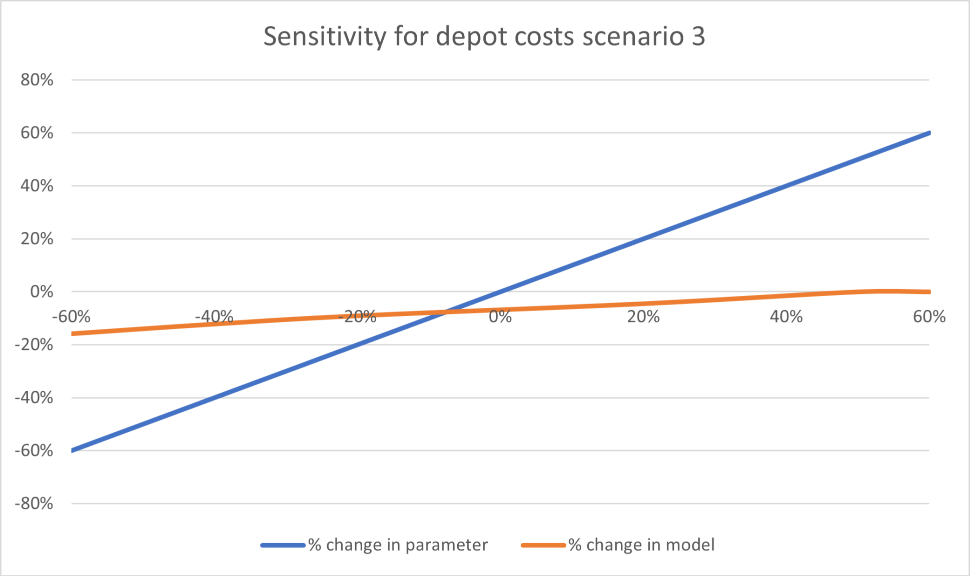


Figure I.6: *Sensitivity for a change in depot costs for scenario 3*

I.2 Sensitivity analysis optimisation technique

Volume

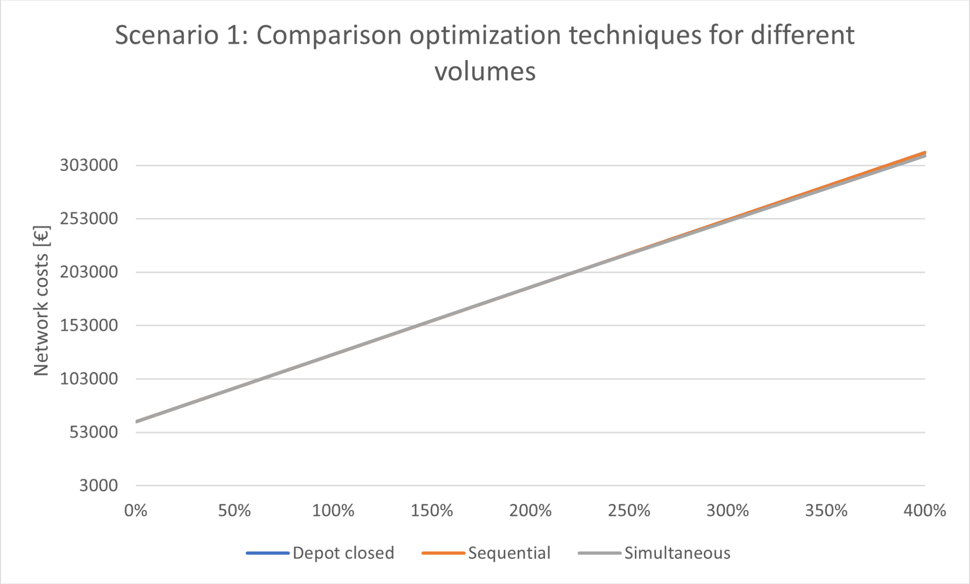


Figure I.7: *Comparison of the three optimisation techniques for changing volumes in scenario 1*

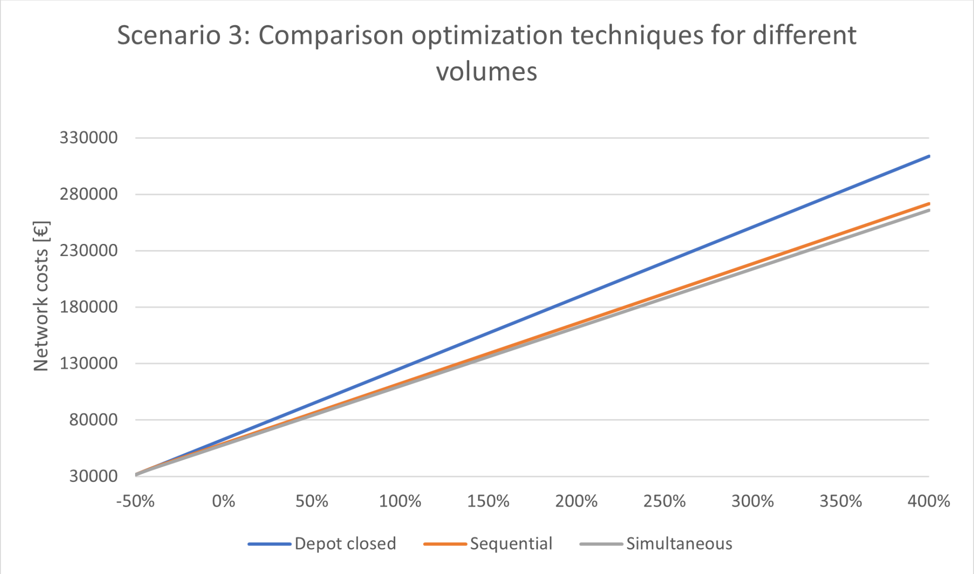


Figure I.8: *Comparison of the three optimisation techniques for changing volumes in scenario 3*

Service costs

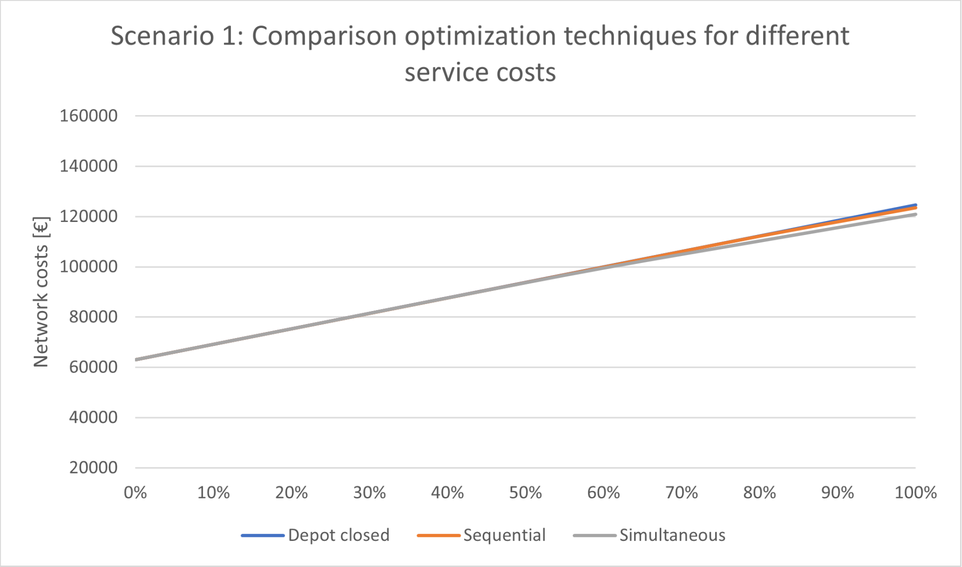


Figure I.9: *Comparison of the three optimisation techniques for changing service costs in scenario 1*

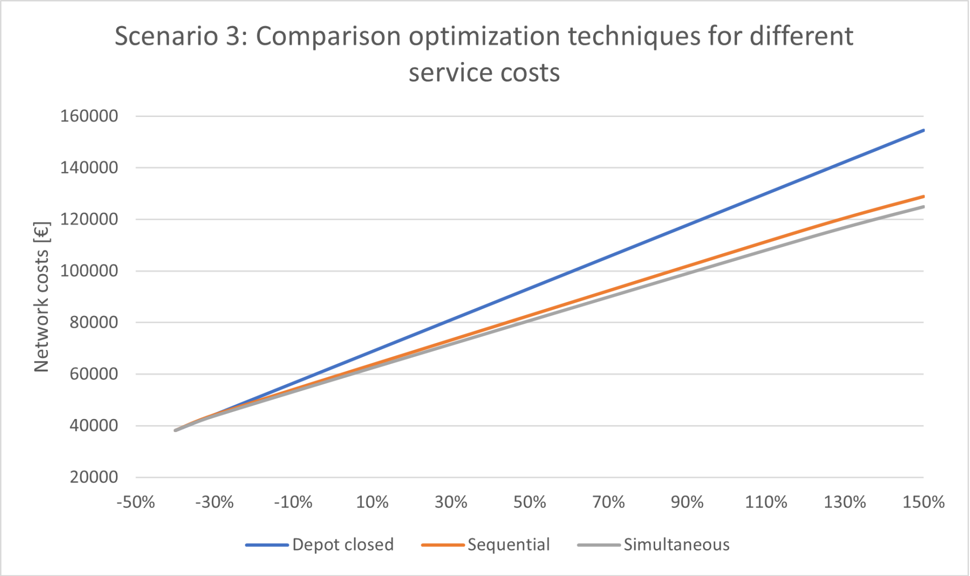


Figure I.10: *Comparison of the three optimisation techniques for changing service costs in scenario 3*

Depot costs

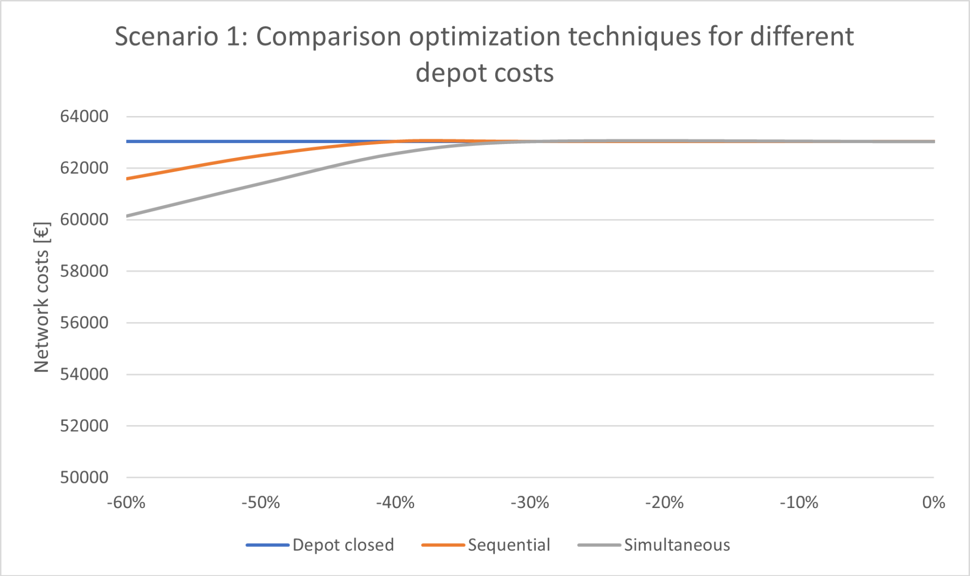


Figure I.11: *Comparison of the three optimisation techniques for changing depot costs in scenario 1*

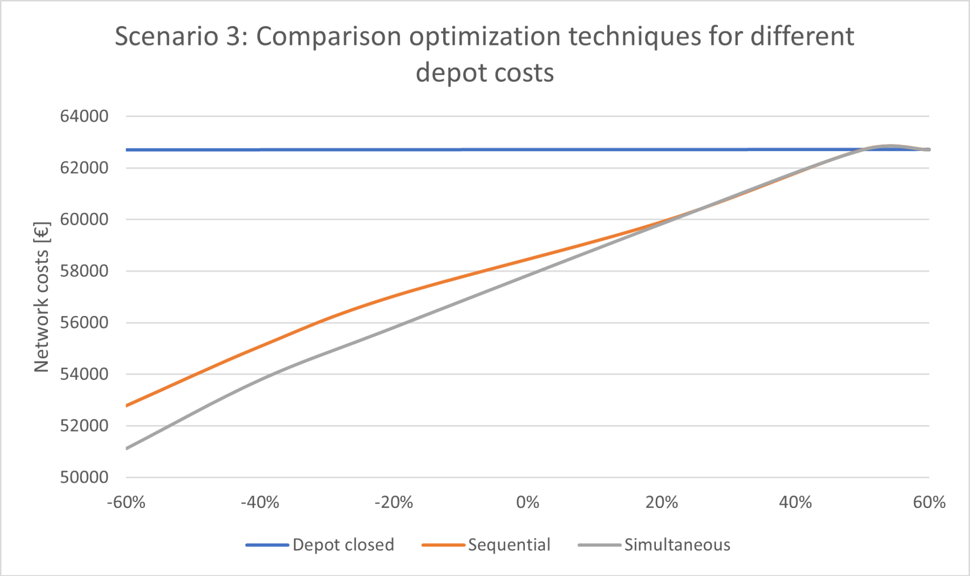


Figure I.12: *Comparison of the three optimisation techniques for changing depot costs in scenario 3*

J. Complexity of model

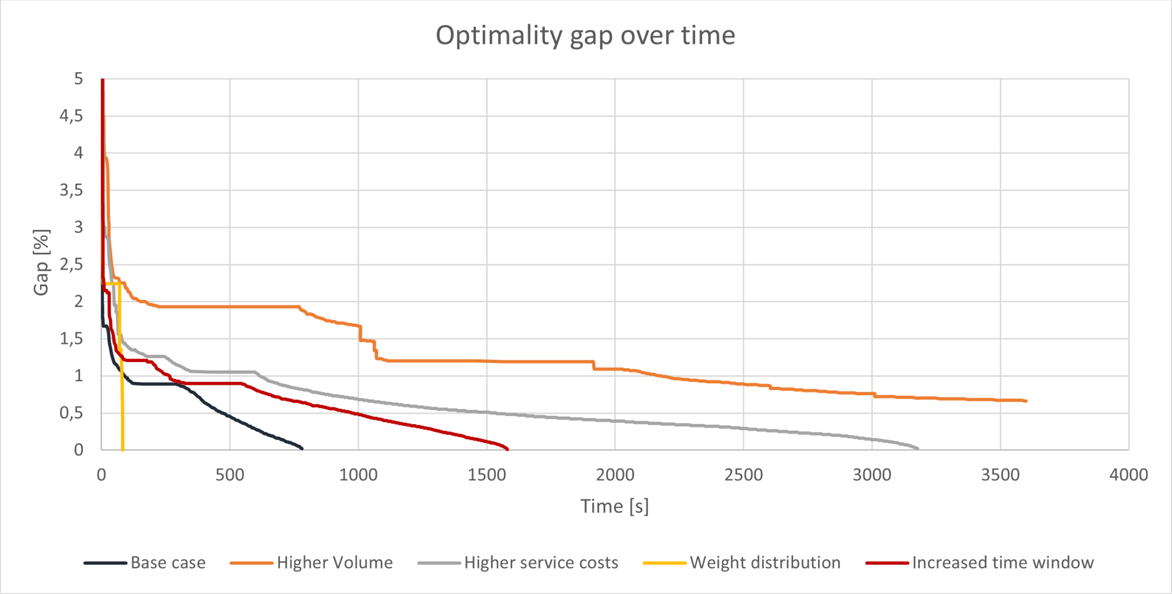


Figure J.1: *Optimality gap over time per parameter tested*