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MASTER

Optimizing the Cross-Docking Operations for the Dutch Flower Logistics

Vahrmeijer, J.C. (Roos)

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Optimizing the Cross-Docking Operations for the Dutch Flower Logistics

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MASTER THESIS

J.C. (Roos) Vahrmeijer
1395246

Supervisors:

dr. S.W. Lai	Eindhoven University of Technology
dr. A.H. Schrotenboer	Eindhoven University of Technology
mr. P.M. van Zaal	Van Zaal Transport BV

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Abstract

This Master Thesis Research presents a method to use existing routing software to schedule routes by standardizing decisions for cross-docking. This study is conducted at a logistic service provider operating in the floriculture industry, named van Zaal Transport (VZT). VZT wants to plan their transports with optimal routes to minimize costs, such as the number of vehicles used and kilometers driven. VZT applies the cross-docking distribution strategy that optimizes labor costs by merging less-than-truckload shipments to full truckloads. However, it turns out that it is most cost-efficient to use direct shipping and cross-docking in combination with one another. The problem of VZT can be described as a Pick-up and Delivery Problem with a Cross-dock opportunity (PDPCD). However, no software is available for solving those route problems in practice. Therefore, this Master Thesis investigates whether operations can be optimized by standardizing cross-docking decisions and creating routes with a Guided Local Search for the Pick-up and Delivery Problem with Time Windows (PDPTW). The study found that a PDPTW can be used to resolve PDPCD. However, the optimal solution was not always found. Lastly, a case study was conducted. Five data sets have been created that present the current situation at VZT. These data sets were subjected to 13 different strategies, 10 for cross-docking and 3 for direct shipping. It was concluded that it is dependent on the situation which cross-docking strategy is most cost-effective. Remarkably, strategies taking the shipping quantity into account were positively influencing the costs for four of the five cases. In addition, the case study exemplifies that direct shipping is most cost-effective.

Keyword: Cross-docking, Pick-up and Delivery with Time Windows, Pick-up and Delivery with Cross-dock Opportunity, Guided Local Search

Summary

Introduction
Since the seventeenth century, The Netherlands has been the dominant player in the global floriculture industry. The world's biggest trading center of floriculture products is located in the Netherlands (Porter et al., 2011). Besides, many different floriculture industry actors operate in The Netherlands and need transportation. The transportation of floriculture products is complex and challenging. Not only because the products need to be transported conditionally, but also swift transportation is required (de Keizer, 2015). Logistic Service Providers operating in this sector want to meet the customers' wishes and transport cost-effectively. Van Zaal Transport (VZT) is one of the Logistic Provides operating in this sector. This Master Thesis Research is conducted at this company.

Problem Definition
The challenge VZT is facing is regarding its routing problem. They want to plan their transports with optimal routes to minimize the costs, for example, the number of vehicles used and the number of kilometers driven. Currently, VZT applies the cross-docking distribution strategy. Cross-docking is a distribution strategy that optimizes the labor costs by enabling the merging of less-than-truckload shipments to full truckloads (Esmizadeh & Mellat Parast, 2021). This is done by temporarily storing shipments at a depot location. A single request is therefore sometimes transported with more than one vehicle (Sampaio et al., 2020).

Currently, VZT cross-docks all shipping requests where previously they made decisions based on fist rules and expertise. However, VZT expects that only cross-docking all shipping requests or transporting everything with direct shipping is not the most cost-efficient. Instead, it seems most cost-efficient to combine the two. This is in line with several studies such as Petersen and Ropke (2011), which investigated a manner to create routes combining cross-docking and direct transport. In conclusion, the main research questions at the heart of this Master Thesis Research is:

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*How can VZT standardize its cross-dock decision in such
a way that they optimize their operations?*

Research
Through the literature, two types of insights were gathered. Firstly routing problems were found with cross-docking or transfer opportunities. Routing problems are problems formulated to plan routes for vehicles to drive optimal. The found routing problems are in line with the problem of VZT. However, no existing software exists in practice to solve such problems. Other approaches need to be investigated to optimally solve such routing problems. The gap found for this research is how a Pick-up and Delivery Problem with Time Windows (PDPTW) can be used to solve Pick-up and Delivery problems with Cross-Docking opportunity. It is found that multiple software and solution approaches exist for solving the PDPTW.

Secondly, different characteristics were found that influence the cost-effectiveness of cross-docking. Characteristics that had an effect were time and distance (Petersen & Ropke, 2011), shipping quantity (Gümüş & Bookbinder, 2004), vehicle capacity(Nikolopoulou et al., 2017), neighbor locations (Nikolopoulou et al., 2017) and Depot location (Nikolopoulou et al., 2017).

Following this, the business analysis was performed. In this analysis, first, the scope of the study was further explained. Then the characteristics found in the literature were examined at VZT to see if the data shows that cross-docking can be cost-effective. The business analysis shows that, in some respects, there are benefits from using cross-docking in the routes of VZT. This is primarily based on geographic distribution. The distances between pick-up and delivery points are large. Moreover, the locations have many neighborhood locations, which is advantageous for cross-docking, according to Nikolopoulou et al. (2017). However, the location of the depot is not conducive to cross-docking. According to the literature, a centrally located depot is more cost-effective for cross-docking (Nikolopoulou et al., 2017).

Next, two model formulations are set for the problem at VZT. Firstly the theoretical formulation of the problem is given, this is a PDPCD. From the literature, it can be concluded that this problem is hard to solve in practice, therefore, a second model is formulated a PDPTW. This second model is used to solve a PDPCD by splitting requests for cross-docking first and subsequently find routes with a PDPTW solution approach.

Subsequently, these model formulations are validated. This is done by using benchmark data. First the PDPCD was solved using self-created data, attached in the Appendix D. The results were evaluated using the PDPTW model formulated. Both solutions were calculated to optimality with Gurobi and programmed in Python. It is concluded that PDPCD model seems correct but that this needs to be ensured by running more tests. Secondly, it is tested if a PDPTW model can be used for PDPCD problems by splitting shipping requests. The PDPTW is heuristically solved with a Guided Local Search (GLS). The GLS was tested using three benchmark data sets. First, the GLS was tested to see if a PDPTW problem properly can be solved, done with benchmark data of Li and Lim (2003). The result is that the GLS can solve the problem properly. Minor differences are seen because the programmed model needs more time to solve.

Next, it was validated if the GLS can be used for problems with cross-docked requests and by fixing the cross-docking time windows. This was done by two benchmark data sets of Nikolopoulou et al. (2017). During the validation, it appears that using the GLS for solving problems with cross-docking translated to a PDPTW is hard. Only solutions can be found for larger time frames. Unfortunately, with the larger time frames still, a difference is seen from the results obtained with the GLS and the results from the literature.

Lastly a case study was conducted. Five data sets were created from the historical data of VZT. These five data sets need to present the current situation at VZT. In addition the data sets were subjected to 13 different strategies, 10 for cross-docking and 3 for direct shipping. From the results, it was concluded that it dependence per situation which cross-docking strategy is most cost effective. Remarkable is that for four out of five cases in the case study, the strategies with shipping quantity has an influence. Larger orders take more time to load and unload, so the cost savings on kilometers do not outweigh the extra costs calculated in time.

In addition, is for the generated cases seen that direct shipping is most cost effective. The lowest objective values have been found for this strategy. The values of distance and time are also the lowest for these solutions. This is in line with the research of Nikolopoulou et al. (2017) which suggests that when the depot is not centrally located cross-docking is not advantageous.

Conclusion and Recommendations

The concluded strategy that is most cost-effective is the direct shipping strategy. The case study showed that fewer vehicles are used when implementing the direct strategy, the number of kilometers is reduced, and the least amount of time is required. However, the question is whether it is realistic to apply this strategy in practice for VZT. Indeed, a reduction in vehicles, kilometers, and time can be achieved. In addition, if VZT chooses to apply only direct shipment, costs can be reduced by eliminating the Venlo Depot or giving the depot other purposes. However, it must be kept in mind that the vehicles depart from this depot, and other operations occur. In addition, in this study, we chose to investigate whether existing software from VZT can be used to solve cross-docking problems with fixed time windows. As concluded, this is possible for problems with a larger time frame but still challenging and not solved to optimality. As a result, it is not known if cross-docking is not advantageous in case of this case study. Therefore, it is not recommended that VZT apply the direct strategy, mainly because this study tolerated multiple visits for locations which is not customer-friendly.

Lastly, it is recommended for VZT not to cross-dock all shipping requests but instead focus more on the shipping quantity by deciding to cross-dock requests. In the case study, the shipping quantity influenced the costs for the different cross-dock strategies. When this variable was included in the decision for cross-docking, better solutions were found than cross-docking all requests.

Preface

This research is conducted at van Zaal Transport and a result of the final project of the master degree in Operations Management and Logistics at Eindhoven University of Technology. Almost a year, I focused on this research and learned a lot about using scientific applications in practice. I am really glad that van Zaal Transport gave me the opportunity to investigate one of their challenges and learn about their company.

First, I want to thank my first supervisor David Lai for his time and advises during my Master Thesis Research. He always made time for me when I needed help during my research. And helped me with his knowledge in the field of transportation. I would also like to thank my second supervisor Albert Schrotenboer for his feedback and guidance in the last stage of my research. This feedback gave me extra energy to complete my thesis and to structure my report well.

Moreover, I want to thank my company supervisor Merijn van Zaal for the opportunity to conduct my master thesis research at van Zaal Transport. Merijn not only taught me things about the company but also showed me how much passion and enthusiasm you can have for your work, something I really admire about him.

Last but not least, I want to thank my family and friends for their mental support during my master thesis process. They had a lot of confidence in me and support me till the end. Besides it is with joy that I can say that my student time is over after 8.5 years and that I have thoroughly enjoyed it. My first years in Delft were great where I did a board year and met friends for life at the study association: Het Bedrijfskundig Genootschap. Followed by an amazing time in Eindhoven where I enjoyed playing hockey with the Assepushters. One last thank you is to all these people.

Roos Vahrmeijer

List of Abbreviations

2E-VRP Two Echelon Vehicle Routing Problem

ALNS Adaptive Large Neighbourhood Search

BBT Box Deliveries

DARP Dial-and-Ride problem

GLS Guided Local Search

GRASP Greedy Randomized Adaptive Search Procedure

LNS Large Neighbourhood Search

LZV Lange Zware Vrachtvoortuigen

MILP Mixed Integer Linear Problem

NNI Nearest Neighbour Index

NV Number of Vehicles

PDP Pick-up and Delivery

PDP-CD Pick up and Delivery Problem with Cross-dock Opportunity

PDPT Pick up and Delivery Problem with Transfer Opportunity

PDPTW Pick up and Delivery Problem with Time Windows

PI Pairing Index

RFH Royal Flora Holland

SD Scheduled Duration

TC Travel Cost

VRP-CD Vehicle Routing Problem with Cross-Docking

VZT Van Zaal Transport

WT Waiting Time

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Chapter 1

Introduction

Since the seventeenth century, the Netherlands has been the dominant player in the global floriculture industry. The Dutch are the largest and most sophisticated cluster globally in terms of technology and international influence in the floriculture industry. The origin of the Dutch flower cultivation is the tulip. Around 1570, the tulip was first imported from Turkey to the Netherlands (Steen et al., 2010). The sandy coastal grounds of the Netherlands were ideal for tulip cultivation. At the beginning of the seventeenth century, the first export of tulips took place and was the start of the Dutch Flower Trade (Porter et al., 2011). Initially, the export was mainly to Germany, France, UK, Russia, and Scandinavian countries, and later expanded to worldwide trade.

In the 20th century, multiple auctions were established by growers to gain a fair trade and reduce the power of middlemen in the industry (Porter et al., 2011). These auctions merged to the organization Royal Flora Holland (RFH), the world's biggest trading center in floriculture Steen et al., 2010. Its mission is to connect players in floriculture and create opportunities for sustainable growth and success in the global market. The different actors in the floriculture value chain growers, florists, garden centers, exporters and retailers. They contributed to 47.6% of the worldwide export and 12% of the worldwide import of floriculture products in the Netherlands in 2019. (Porter et al., 2011). As a consequence, a large number of movements take place to distribute the products. In 2007, around 10% of the trucks driving in the Netherlands carried flowers from or to the auction, excluding the cultivation of plants and direct transport between growers and buyers (Porter et al., 2011).

In addition, transportation of floriculture products is more complex than regular products. Flori culture products are highly perishable and mainly conditionally transported (Steen et al., 2010). To maintain high quality, its transport is executed the same-, or following day (de Keizer, 2015). Subsequently, due to the wide variety that florists, wholesalers, retailers, and garden centers offer, which can be classified as many-to-many transportation problem (Royo et al., 2016), many suppliers serve several customers with small quantities. The many movements, speed at which the products need to be delivered, many-to-many transport, and the small quantities make a complex transport network. In which optimization, sustainability, and cost savings can be achieved.

1.1 Business context

This Master Thesis Research is conducted at Van Zaal Transport (VZT), a transporter specialized in transport of flori culture products. VZT is operating in this sector since 1996 and offers services in the Netherlands, Belgium and Germany. The head office is located in De Kwakel next to their largest depot. Other depot locations are Aalsmeer, Ammerzoden, Lochrisi (Belgium), Naaldwijk, Rhein-Maas (Germany) and Venlo, shown in Figure 1.1. In Figure 1.1 a distinction is made between three types of nodes. Aalsmeer, Naaldwijk, and Rhein-Maas are all auction locations where VZT also has a depot location on the auction site. De Kwakel is near to Aalsmeer, therefor those nodes overlap.

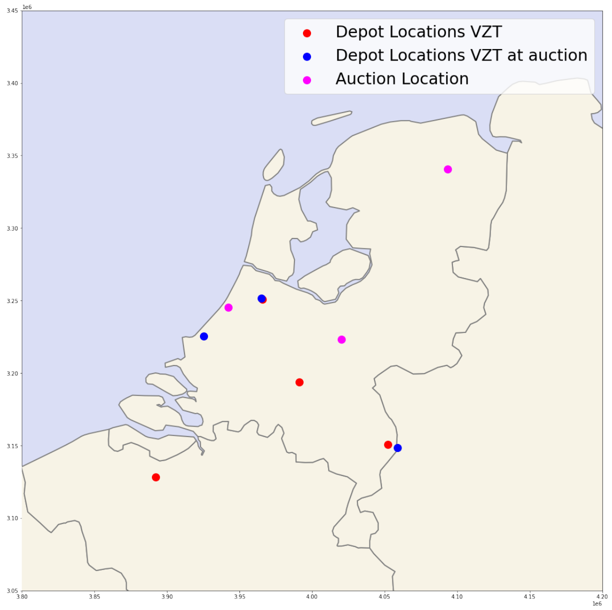


Figure 1.1: Depot and Auction Locations

In Chapter 1 the different actors in the floriculture industry are mentioned. VZT offers different services of transport between those actors. Every service is adapted to the demand and wishes of the actors. In Figure 1.2 an graphical representation of the services of VZT is presented, and an extensive explanation is given below.

1. Firstly, transport is offered from growers to the auctions. Products in this flow are offered at the auction via the clock system. Clock sales start early in the morning an buyers should have the opportunity to pre-evaluate products for quality. Therefore, the products must be delivered before 04:00 AM. This operation flow is called KLOK.
2. Secondly transport is served from growers to exporters or wholesalers. Exporters and wholesalers are mainly located in the neighbourhood of the auction locations. Delivery times are set for these service but are less strict compared with the first flow. The orders that belong to this flow are called Box Deliveries (BBT).
3. National Distribution, is the third flow that is seen in the operations of VZT. Here, products are collected at the growers and transported to garden centers, wholesalers, or florists. As with the first two services, products are collected at the growers and, in most cases, transported to the depot in De Kwakel. Deliveries are planned from the depot to addresses across the country.
4. Fourthly, transport from auctions to exporters and wholesalers. Wholesalers and exporters can purchase at the auctions even if they are not there themselves. Because of this, transport is required from auctions to exporters and wholesalers and is called Remote Buying.
5. Lastly is the reversed logistic flow of special equipment used for the transportation of flowers and plants. These equipment are special carts, called ‘Deense Karren’ (DC) and special buckets called ‘Fust’. To get a better idea of the special logistics resources, they are shown in Appendix A. VZT rents and transports these logistic equipment we refer to these operations as Reverse logistics concerning the DC’s and ‘FUST’ concerning the buckets.

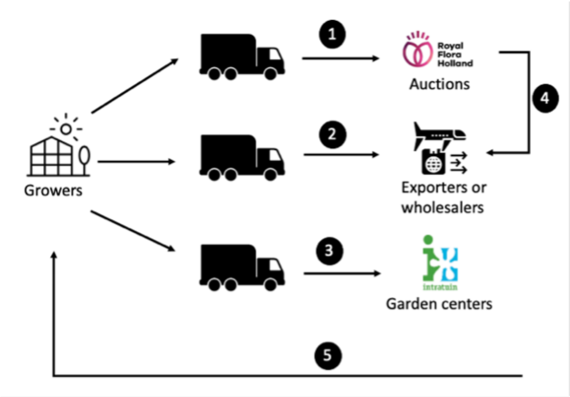


Figure 1.2: Transportation flows VZT

1.2 Problem Definition

VZT has large volumes that require transport on a daily basis. In 2020 VZT transported around 420,000 shipments, translating to a mean of 730 shipment requests per day had together an average load of 3.40 DC. In addition, each day 260 unique load locations and 270 unique unload locations need service. The high amount of shipments together with the previously mentioned characteristics as speed and many-to-many transportation, create a complex routing problem that must be solved every day.

Several ways are implemented at VZT to organize their operations cost efficiently. First, by collecting the shipments, multiple shipping requests are combined, also called milk-run collecting (Hosseini et al., 2014). By combining these shipments, the load factor of a vehicle is increased and resources are utilized. Secondly, cross-docking is applied. Cross-docking is a distribution strategy that optimises the labour costs by enabling the merging of less-than-truckload shipments to full truckloads (Esmizadeh & Mellat Parast, 2021). This is done by temporarily storing shipments at a depot location. A single request is therefore sometimes transported with more than one vehicle (Sampaio et al., 2020).

Everyday shipping requests must be scheduled for transport. It must be ensured that the requests are picked up and delivered on time within less than a day. The shipments are known an hour or two in advance. Concretely this means that many shipping requests have to be planned in a short period. Planning the routes is done manually and with the help of the software ORD offered by Ortec. ORD helps by scheduling routes and by adhering to the customers' wishes. A feature that is not available in ORD is the decision to use a depot for consolidations in routing, or other words, whether cross-docking is applied.

Currently VZT is cross-docking all shipping requests, due to the drivers shortage. However, earlier this was arranged differently, some of the shipping requests were selected for cross-docking and some were transported directly. The underlying idea of VZT was that the extremes of cross-docking all shipping requests or transporting everything with direct shipping are not the most cost-efficient but that it is most cost-efficient to combine the two. This is in line with several studies such as Petersen and Ropke (2011), they investigated a manner to create routes combining cross-docking and direct transport. In literature such problems are are referred to as Pick up and Delivery Problem with Cross-dock Opportunity (PDP-CD) and Pick up and Delivery Problem with Transfer Opportunity (PDPT). However, the decision of cross-docking shipment requests or to transport shipping requests with direct shipping was made by the planner based on fist rules and experience. These rules seem quite logical but are not substantiated with facts and figures. In conclusion the question that arises at VZT is as follows:

When is it beneficial to transport orders via a cross-dock location and when is direct transportation preferred?

VZT would like to have this question answered in the hope that by doing so, decision making can be standardized and the transportation planning can be made more efficient. VZT is interested in a solution whether their transport schedules can be arranged more cost-efficient, in such a way that they decrease their operational costs in terms of kilometers and use of resources.

1.3 Research Questions & Methodology

This section introduces the main research question and support research questions. The questions are formulated based on the Business Context 1.1 and the Problem Definition 1.2. Besides the research questions helping to structure the Master Thesis Research. For this Master Thesis Research the following main question is determined:

How can VZT standardize its cross-dock decision in such
a way that they optimize their operations?

To answer the main research question, several sub questions are formulated. The sub-questions provide structure to the study and ensure that all necessary information is acquired. Below are the sub-questions named and an explanation how they are answered.

1. *What studies are found in literature that provide insights for the problem definition of VZT?*

To answer this first sub question, a systematic literature review is conducted. Relevant literature and publications are sought that can provide insights into the problem of VZT and may also provide solution guidelines. After gathering insights from previous studies, a base of knowledge has been acquired and the next step is performed.The second sub question that is therefore formulated is:

2.What is the current situation of VZT in terms of the promising cross-dock characteristics?

A business analysis is performed to answer this second sub-question. This business analysis is conducted by first having discussions with employees of VZT. In this way we can find out what historical data is needed. The historical data is analyzed and extra attention is given towards the characteristics mentioned in the literature that might influence the cost effectiveness of cross-docking. After the business analysis, an answer is given to the third sub-question is formulated as follows:

3. What mathematical model formulations are applicable to the situation of VZT?

The answers of the first two sub-questions are used as input to formulate the model for VZT. The business analysis ensures that the situation of VZT is clarified and the model limitations can be set as a result of research question 2. Several model formulations are seen in literature that are applicable for VZT. The most appropriate model is formulated as a Mixed Integer Linear Problem (MILP). In addition, a second model is formulated that is closer to the current planning process of VZT. After the models are formulated, they must be tested for correctness. A next question has been formulated for this purpose:

4. How validate the model and approaches formulated in research question 3?

The purpose of this fourth sub-question is to test if the formulated models in research question 3 are formulated correctly. To do so benchmark data from literature is used to test if the formulated models can solve these problems properly. When the models are validated, they can be used for the case study at VZT. To conduct the case study, the following two sub-questions were formulated:

5.How to set-up the case study at VZT to generate promising results?

6.How to generalize the results obtained in the case study of VZT?

These two sub-question are answered in the chapter 7. Firstly the model set up is given to ensure that the study is re-executable. Subsequently the results are presented and conclusions are drawn. Analyzing the results of the case study need to obtain insights in the ways that cross-docking is cost effective. Next a conclusion is drawn on how to translate the results into practice.

1.4 Research Goal & Scope

This section introduces the scope of the Master Thesis Research and presents the goals. The scope of the research is the night transport at VZT with the KLOK and BBT type of shipping requests. The decision for this is because for the National Distribution & Remote Buying transport flows other network structures are seen, Reverse Logistics is also not taken into account because in most cases these quantities are the same. So the amount of DC to be collected is equal to the amount of DC to be delivered. Occasionally this will be different. In addition, it is assumed that all shipping requests are known in advance, so that the decision for cross-docking can be made over all orders at the same time. Further explanation of the scope is given in more detail in chapter 3

The research goals are discussed now that the scope has been established. Two types of research goals are discussed: the academic goals and the practical goals:

- Academic Goals
  - Integrate cross-docking strategies applied in literature in the context of flori-culture products transportation
  - Bridging the gap of theory and practice by solving routing problems for the PDP-CD with a solution approach Pick up and Delivery Problem with Time Windows (PDPTW) and by deciding cross-docking based on rules.
  - Creating new benchmark data based on realistic situations
- Practical Goals
  - Provide options to standardize the cross-dock decision with the current routing plannings-system in mind
  - Gain insights of applications of organizing routing calculation in a different way

1.5 Report outline

This section presents the structure of this Master Thesis Research. The content of each chapter is outlined below:

Chapter 2 : Literature review - A systematic literature review is conducted for routing problems using intermediate facilities to consolidate freight with a detailed explanation of the solution approaches for the Pick-up and Delivery Problem with Transfer Opportunity and Pick-up and

Delivery Problem with Cross-dock Opportunity. In this chapter the first research question is answered.

Chapter 3: Business Analysis - This chapter gives an overview of the current situation at VZT that is used for the case study in this research. Additional attention was given at analyzing characteristics that indicate if cross-docking is effective.

Chapter 4: Model Formulation - A model formulation based on the problem at VZT is given in this chapter. Assumptions are included and the model is formulated according to reality.

Chapter 6: Model Testing - In the fifth chapter the model formulated in chapter 4 is tested. This is done with three different benchmark data-sets.

Chapter 5: Guided Local Search - In the fifth chapter the heuristic solution approach Guided Local Search (GLS) is explained. The heuristic is used for solving the routing problems with Google OR tools.

Chapter 7: Case Study at VZT - In this chapter are the data sets explained that are used in the case study. Besides the cross-docking strategies are described that are applied in the case-study. The set-up is followed by the results of the case study Insights are gained by applying different cross-docking strategies at the set data of VZT.

Chapter 8: Conclusions, limitations and recommendations - The final conclusions on the thesis are presented. Furthermore, recommendations are discussed and future research directions are given.

Chapter 2

Literature Review

This chapter aims to provide literature about the relevant subjects for this Master Thesis Research. The literature is studied to get insights regarding the research objective and to understand the challenges and trends in transportation. The first request is the focus and is set as follows:

1. What studies are found in literature that provide insights for the problem definition of VZT?

Moreover, the review helps to answer the research question and substantiates the purpose of this research. The literature review starts with introducing routing problems with intermediate facilities. Afterward, one of the routing problems is discussed in more detail, and different solution approaches will be discussed. Finally, variables that might influence the optimal use of intermediate points in routing problems are discussed. In the end, an overall summary is given to understand the current knowledge status.

2.1 Network Designs with intermediate facilities

This section introduces the research domain of network designs using intermediate points as temporally storage locations. Many different designs are known in the literature and could apply to the situation of VZT. In the literature review conducted for the master thesis research, three types of network designs were found to be tangentially related to the investigated case. These three types of networks have their specifics and associated routing problems. The different networks are briefly explained in the following subsections.

1. **Hub-and-Spoke**
   Hub-and-spoke is the first network design found in the literature using intermediate facilities in their distribution network. The hub-and-spoke network, is a network wherein central facilities are implemented, called hubs, and are used as switching points (Esmizadeh & Mellat Parast, 2021). The switching points can be used for transferring persons or cargo between vehicles. Besides the network can exist of multiple hubs. These hubs can be interconnected, such a network is called a hybrid network. Lastly, most studies focused on the hub-and-spoke network is usually aimed at determining the hub location. The firstly presented hub location model was by O'Kelly and Miller (1994).

2. **Cross-Docking**
   The second found network design using intermediate facilities is the cross-docking strategy.

This strategy is seen as a basic distribution strategy focused on optimizing transportation by merging less-than truckload shipments to full truckloads at intermediate points Buijs et al. (2014). Products arrive on inbound vehicles at a cross-dock center in a cross-docking network. The inbound vehicles are unloaded, and the freights are divided by destination. Subsequently, outbound vehicles are loaded and transport the freights to the designated destination (Guastaroba et al., 2016). Routing problems that apply for the cross-docking strategy are the Two Echelon Vehicle Routing Problem (2E-VRP) and the Vehicle Routing Problem with Cross-Docking (VRP-CD). Both routing problems ensure that routes are optimized and make use of intermediate centers to exchange freight. Finally earlier studies focused on cross-docking assume that all transportation is arranged through an intermediate facility and that no direct transportation occurs between suppliers and customers.

3. **Pick-up and Delivery**
The third and final network design that is found is the Pick-up and Delivery (PDP). In this network goods are transported between suppliers and customers. The PDP is firstly introduced by Savelsbergh and Sol (1995) and originally uses no intermediate points or facilities. The use of intermediate locations was introduced by Shang and Cuff (1996). They introduced a model that allowed both direct transport between supplier and customer and indirect transport, using intermediate locations for switching passengers or freight between vehicles (Shang & Cuff, 1996). After the study of Shang and Cuff (1996), further studies followed, and two types of routing problems were formulated. These are the PDPT and PDP-CD that are quite similar and consider an intermediate locations as an opportunity and not an obligation (Sampaio et al., 2020). Implementing a PDP network with the possibility to transfer or use cross-docking can achieve both the benefits of PDP and the benefits of cross-docking.

2.2 Pick-up and Delivery Problems with Transfer or Cross-dock Opportunity

Two types of routing models are studied that allow direct and indirect transport by planning vehicle routes. These two routing problems are defined as the PDPT and the PDP-CD, and are very similar. Both allow the possibility to transfer freight during the routes and ensure more routing possibilities, improve truck utilization, and reduce the number of driven kilometers (Shang & Cuff, 1996).

2.2.1 Pick-up and Delivery with Transfer

The PDPT was firstly introduced by Shang and Cuff (1996). Their research was a practical example of the Health Maintenance Organization. In the case, vehicles transported patients record, equipment and supplies between locations. Allowing transfers were considered to minimize the number of vehicles and reduce overall tardiness. According to Shang and Cuff (1996) could the problem be seen as a special type of the Dial-and-Ride problem (DARP). DARP routing problem is also taking into account transferring but is focused on passenger transportation, which are mostly focused on improving the service level.

After Shang and Cuff (1996), Mitrović-Minić and Laporte (2006) extended the research field of the PDPT. Mitrović-Minić and Laporte (2006) concludes that the PDPTW is the bases of the PDPT. The PDPTW research field is studied in detail and multiple ways have been found to solve major PDPTW route problems, including in practice.

The first model formulation of the PDPT is of Cortés et al. (2010). The formulation is an MILP. In the problem transfer points are known in advance. After the formulation of Cortés et al., 2010 more problems were formulated regarding PDPT. These researches added additional characteristics and constraints to the model of Cortés et al., 2010, this will be discussed further in Section 2.3.

2.2.2 Pick-up and Delivery with Cross-dock

A second formulation of the PDP with intermediate facility is the PDP-CD. Few papers were available for the PDPT formulation, this is even less so for the PDP-CD. The PDP-CD is firstly investigated by (Petersen & Ropke, 2011). In the research of Petersen & Ropke, a case was used from a Danish transporter of flowers, which is comparable with the case of VZT. In the case of the Danish transporter, flowers need to be picked up at gardeners' greenhouses and delivered to florists and supermarkets. In Denmark, the greenhouses are mostly located in the western part, while delivery is all over the country. Petersen and Ropke (2011) sees their problem the same as the formulations of (Rais et al., 2014) and (Cortés et al., 2010). Concerning multiple cross-docks and a single cross-dock.

Besides Petersen and Ropke (2011), two other publications are known regarding PDP-CD. Santos et al., 2013 formulates an integer programming formulation where two types of routes are considered: (1) Routes starting from a central depot, visiting a subset of suppliers, return to the central depot, changing load, and visiting customers to deliver freight. (2) Pick-up and delivery, also starting from the central depot but after visiting a subset of suppliers immediately visits customers to deliver and uses the central depot, not as a transfer point.

The next research found is of (Nikolopoulou et al., 2017). Their research aims to evaluate the differences between the direct and cross-dock distribution options and to conduct a comparative analysis about their cost-effectiveness. Requests with pick-up and delivery are used, but in the research, the requests can switch between routes for VRP-CD and PDP. After the research of Nikolopoulou et al. (2017) it is clear for each benchmark data-set the VRP-CD is preferred instead of the PDPTW and vice versa.

2.2.3 Differences PDPT and PDPCD

According to Sampaio et al. (2020) act, both problems PDPT and PDP-CD act similar in consolidating to improve truck utilization. In addition, also some differences are known. The main difference is that in PDP-CD problems, the central depot is the beginning and end of each route. Applying cross-docking, the central depot can also act as a cross-dock location. In PDPT problems, each location in the network is a possible location to transfer. Secondly in PDP-CD applications all vehicles need to be present at the cross-dock location, for PDPT this is not required as long as synchronization requirements are met (Sampaio et al., 2020).

2.3 Model Formulations for the PDPT and PDPCD

This section further zooms in on the different models known for the PDPT and PDP-CD. The mathematical formulations from previous studies are examined and compared to the case of VZT.

In section 2.2.1 is described that the first publication that applied transfers in routing problems were Shang and Cuff (1996) and Mitrović-Minić and Laporte (2006). These two publications do not provide a comprehensive mathematical formulation. The first publication that does include a mathematical formulation of the PDPT is of Cortés et al. (2010). They introduced the possibility to relax coupling constraints and allow transfers between vehicles in their MILP formulation. In the research of Cortés et al. (2010) passenger transportation was considered, passengers are allowed to move from one vehicle to another at a set of transfer nodes. In the research of Kerivin et al. (2008) a vehicle was allowed to use the transfer node multiple times. Unfortunately, does the model formulation of Kerivin et al. (2008) not include time windows, this is something that can be added. Other publications focusing on passenger transportation are the studies of Godart et al. (2018), Masson et al. (2014) and Ghilas et al. (2018). All based their models on earlier formulated PDPT and DARP. Godart et al. (2018) takes into account passengers and freight. Masson et al. (2014) applies shuttle routes. Their situation could be compared with the formulation of Ghilas et al. (2018) using shuttle routes. A more oriented formulation on the supply chain is the supply chain pick up and delivery problem with transfers. This problem was addressed by Dondo et al. (2009) and formulated a MILP based on seven different sets of constraints. The problem of Dondo et al. (2009) concerns distribution from suppliers to customers using distributions centers for transshipments. Dondo et al. (2009) mainly wanted suppliers and customers not to be visited twice by a vehicle. However, in the problem of Dondo et al. (2009) only two pick-up points occur.

The formulation of Rais et al. (2014) is also a well known PDPT formulation. In comparison with the model of Cortés et al. (2010), Rais et al. (2014) added an extra binary variable to counter subtours. After the basic model formulation, Rais et al. (2014) allows additional constraints regarding time windows, synchronization, one request per vehicle, the number and types of vehicles, vehicle depots and routes, vehicle stops, and the number of transfers a vehicle is allowed to make. Sampaio et al. (2020) and Voigt and Kuhn (2021) use the model of Rais et al. (2014) as basis in their researches. Both publications focus on delivery systems with crowd-sourced drivers. Finally, we discuss the formulations of Takoudjou et al., 2012 and Wolfinger, 2021. Both allow splitting requests, one of the additional constraints that also can be added in the model of Rais et al. (2014). By allowing request splitting, a higher full truckload can be generated. However, possibility ensures that the problem is harder to solve. All formulations discussed are shown in Table 2.1. The Table shows the constraints included per formulation. The bottom row shows the requirements of the problem of VZT. Looking at all the characteristics that are taken into account in the model formulations in literature in comparison with the requirements of VZT it can be concluded that the formulation of Rais et al. (2014) bests suits the problem description. In addition, the studies of Sampaio et al. (2020) and Voigt and Kuhn (2021) both took the formulation of Rais et al. (2014) as a starting point and applied changes to formulate their mathematical models. For this research, it is decided to use these three formulations by formulating the mathematical model of VZT, done in the following section.

Table 2.1: Model formulations found for the PDPT and PDPCD

Publication	Formulation	Demand Type	TW	Q	No. Vehicles	Fleet of Vehicles	Synchro-nization
Kerivin et al. (2008)	MILP	G	-	L	L	Homo	-
Cortés et al. (2010)	Arc-Based	G & P	H& S	L	L	Hetero	Yes
Godart et al. (2018)	MILP	G & P	S	L	L	Hetero	-
Masson et al. (2013)	MILP	P	H	L	L	Homo	-
Ghilas et al. (2018)	Set-Partitioning	P	H	L	L	Homo	-
Rais et al. (2014)	MILP	G	H	L	L	Hetero	Yes
Sampaio et al. (2020)	MILP	G	H	L	UL	Hetero	Yes
Voigt and Kuhn (2021)	MILP	G	H	L	UL	Hetero	Yes
Takoudjou et al. (2012)	MILP	G	H	L	L	Hetero	-
Wolfinger (2021)	Arc-Based	G	H	L	L	Hetero	-
VZT	-	G	H	L	L	Hetero	Yes

TW = Time Windows, Q = Vehicle Capacity, No.= Number, G = Goods, P = Passengers, H = Hard, S = Soft, L = Limited, UL = Unlimited, Homo = Homogeneous and Hetero = Heterogeneous

2.4 Solution Approaches for the PDPT and PDP-CD

In the previous Section 2.3 different model formulations are discussed regarding PDP's with the opportunity to use intermediate points. In literature different solution approaches are applied for solving PDPT and PDP-CD. These different solution approaches will be explained in this section. The approaches are split into two groups, exact and heuristic, both discussed in a separate subsection.

2.4.1 Exact approaches

Firstly, attention is given to the exact approaches for solving the PDPT and PDP-CD. In Table 2.2 are the publications given that used an exact approach. It is seen that three different solving algorithms, Column Generation, Branch & Cut, and Branch & Price, are used, and two different kinds of software, CPLEX and Gurobi are used for solving the problems.

Both Mues and Pickl (2005) and Santos et al. (2013) applied column generation in their solution approach. Column generation aims to reduce a given linear or MILP problem. Reducing the problem is done by leaving out surplus columns. Subsequently, new columns are generated if the solution of the reduced problem is not optimum. The problem is optimized again until a global optimum is found. Finally, CPLEX is used to solve the MILP. This approach is both applies for Mues and Pickl (2005) and Santos et al. (2013).

Santos et al. (2013) also refers to a Branch & Price approach. This approach combines Column Generation and the Branch and Bound approach. Branch and Bound algorithms are searching for an optimal solution between the lower and upper bounds of the search space. This approach is seen as a decomposition method. Branch and Cut is the other decomposition strategy applied in the found research. The set of constraints is decomposed to pure constraints, and then the branch & cut approach is applied to gain a pure integer problem. Due to the application of real variables and constraints as cut generators Cortés et al. (2010). This Branch & Cut approach is applied in 4 publication : Kerivin et al. (2008), Cortés et al. (2010), Rais et al. (2014) and Wolfinger (2021).

The solving algorithm used by Dondo et al. (2009) and Godart et al. (2018) is not found. However, it is known they used the solving software; CPLEX.

Table 2.2: Exact Solution Approaches

Publication	Solving Algorithm	Software	Instances Nodes	Request
Mues & Pickl, 2005	Column Generation	CPLEX		
Kerivin et al., 2008	Branch & Cut		10	15
Dondo et al., 2009		CPLEX	20	
Cortes et al., 2010	Branch & Cut	CPLEX	12	6
Santos et al., 2013	Column Generation	CPLEX	30	10
Rais et al., 2014	Branch & Cut	Gurobi	14	7
Godart et al., 2018		CPLEX		
Wolfinger and Salazar, 2021	Branch & Cut	CPLEX	10	13

In addition to the differences in solving algorithms and software usage, another issue that requires attention is the size of the problems solved with the exact method. These values are indicated for each research and given in Table 2.2, and only minor problems are solved.

The decision for using a transfer or cross-dock is made during solution generation. Transfer or cross-dock is chosen when it is cheaper. However, it is unclear what characteristics influence the decision to transfer or cross-dock.

2.4.2 Heuristic Approaches

After all the exact solution methods that are explained in the earlier section, are therefor in this section the different heuristic approaches explained. Starting with a overview of the found approaches given in Table 2.3. What is immediately apparent that larger problems can be solved with the heuristic approaches. In the coming subsection are the different solution strategies explained in more detail.

Table 2.3: Heuristic Solution Approaches

Publication	Heuristic solution approach	Requests	Nodes
Shang and Cuff (1996)	Specific	167	9
Mitrović-Minić and Laporte (2006)	Specific	100	200
Thangiah et al. (2007)	LS	167	9
Nikolopoulou et al. (2017)	LS	48	96
Wolfinger (2021)	LNS	25	50
Petersen and Ropke (2011)	ALNS	100	200
Qu and Bard (2012)	ALNS	25	50
Sampaio et al. (2020)	ALNS	100	200
Voigt and Kuhn (2021)	ALNS	250	500
Danloup et al. (2018)	GA	25	50
Takoudjou et al. (2012)	Hybrid	25	50
Godart et al. (2019)	Hybrid	-	-

Specific Heuristics
In Table 2.3 two studies are found that used problem specific heuristics. This first done by Shang and Cuff (1996) as earlier mentioned. They created a six level procedure. In the procedure mini-routes were constructed, and eventually the best-constructed mini-route was inserted to a vehicle. The second problem specific heuristic applied was of Mitrović-Minić and Laporte (2006). Their procedure was first constructie routes and subsequently improved them in the improvement phase. Transferring requests is decided during both phases and done by splitting of requests. In the approach of Mitrović-Minić and Laporte (2006) it is not clearly defined what is done in the improvement phase, therefore is the study non-reproducible.

Local Search
The second heuristic solution approach seen is local search. Local search is a heuristic method to solve NP-hard problems, such as routing problems. The method helps to minimize the problem by searching with iterative moves for better solutions in the neighborhood space. Local changes are applied to the current solutions. For routing problems, this is the exchange of nodes. The approach is applied till a solution deemed optimal is found or a set time is elapsed (Hoos & Stutzle, 2005). Before local search can be applied, an initial solution must be constructed (Petersen & Ropke, 2011). Local search has different applications. The two most well-known are Tabu search and Simulated Annealing (Qu & Bard, 2012). In Table 2.3 is seen that three different applications of local search are used in this research area.

- **Local Search**
  Thangiah et al. (2007) applied as first the local search method for the PDPT. Their research was a follow-up to the research of Shang and Cuff (1996). The applied insertion and removal approaches are used to change the routes. The use of local search on the problem instances of Shang and Cuff (1996) show a time reduction of 60% to solve the problem. A second study in this research area that used local search was used by Nikolopoulou et al. (2017). Their research was not focused on solving problems or the PDPT or PDP-CD but wanted to gain insights on the cost effective of the characteristics in routing problems. These characteristics are briefly explained in the next section 2.5.

- **Large Neighbourhood Search**
  An extension on the local search approaches as tabu search and simulated annealing is the Large Neighbourhood Search (LNS). In this expansion, a larger landscape of solutions is explored. Besides the nodes that could be exchanged, pieces of the routes are also destroyed and inserted again. Providing a broader search and more chances of finding the (near to) optimal solution. In the field of PDPT and PDP-CD only Wolfinger (2021) applied the LNS.

- **Adaptive Large Neighbourhood Search**
  A subsequently extension is the Adaptive Large Neighbourhood Search (ALNS). As for the LNS also for the ALNS parts of routes could be exhanged not only nodes as for the local search approach. In Table 2.3 seen that the ALNS solution approach is most used. Finding the optimal solution is very similar for the ALNS only the different destroy and repair methods are based on their performances (Petersen & Ropke, 2011). Petersen and Ropke (2011) is named before and focuses on a Danish transporter and used an ALNS, this is the same for Sampaio et al. (2020) and Voigt and Kuhn (2021). Qu and Bard (2012) also applied the ALNS for solving the problem om combinations with Greedy Randomized Adaptive Search Procedure (GRASP).

Evolutionary Approaches
The next approach that is found in literature is the use of a Genetic Algorithm (GA) to solve the PDPT. This is done by Danloup et al., 2018, they wanted to study if a GA algorithm could outperform the LNS. Danloup et al., 2018 found that in some cases, a better solution is gained in comparison with the LNS that is used. This is concluded after solution generation for both algorithms with known data in the literature.

Hybrid Approaches
The final heuristic approach discussed is the hybrid approach. A hybrid approach is applied in two publications, all with a different approach. A hybrid approach is defined as an approach using several techniques and methods in combination with each other Takoudjou et al., 2012.

The first publication found that applies a hybrid approach for the PDPT was published by Takoudjou et al., 2012. In their research, a diversification by re-starting local search based on variable neighborhood descent is applied. After an intensification procedure based on path re-linking was used from a new solution once a solution space had been explored. A parallel greedy heuristic introduces every request in a solution under construction. The decision to use a transfer point is the last step.This is opposite to the situation of VZT which first makes the transfer choice and then creates routes. This also applies for the hybrid approach of of Godart et al., 2019. Godart et al. (2018) sets that the problem exists of two subproblems, (1) the routing problem and (2) the assignment of transfer operations, are solved simultaneously. In the hybrid approach of Godart et al., 2019 a decomposition is applied to gain the possibility to solve larger instances. The steps that Godart et al., 2019 formulates are as follows; firstly, the demand is assigned to the vehicles with an evolutionary algorithm. Subsequently, the pick-up, delivery, and transfer operations are assigned to the vehicles with a greedy algorithm. Lastly, feasible routes are created by solving a MILP. Godart et al., 2019 conclude that the heuristic that assigns operations can be improved. Also, the evaluation function can be improved by using a faster function.

2.5 Influencing Characteristics for cross-docking

So far, we have discussed the set models and solution approaches for the routing problems with transfer or cross-docking opportunities. In addition, other publications focused on factors that influence the cross-dock decision. These factors are discussed in this section.

2.5.1 Time and Distance

Firstly, starting with the time and distance. As discussed in Section **??**, most heuristic solutions first construct an initial decision for cross-docking or transferring. This is mainly applied for the ALNS approaches and based on time and distance. The publications of Petersen and Ropke (2011), Sampaio et al. (2020) and Voigt and Kuhn (2021) all uses a similar strategy to determine this initial decision. The initial decision to cross-dock or not is made for every single shipping request. First is determining if the requests can be cross-docked in the given time window, with the set speed of the vehicles and the distance needed to be driven (Petersen & Ropke, 2011). If cross-docking is infeasible, the distribution strategy, direct shipping, is applied. If the time gap between pick-up and delivery is larger than some parameter λ_t, the request is cross-docked. If there is a long time between pick-up and delivery, it is unlikely that the request should be served with direct delivery and can be easily combined with other shipping requests. If the time is short between pick-up and delivery, it is assumed that not enough time is available to transport and transfer at the cross-dock in the given time. Both Petersen and Ropke (2011) and Sampaio et al. (2020) apply a second rule, based on the direct distance between pick-up and delivery and the distance using cross-docking. The ratio between these two distances is compared with an established threshold λ_d. If the ratio is higher than the threshold, the request is cross-docked.

Sampaio et al. (2020) appointed that transferring shipping requests with a long travel time might yield cost savings. The threshold of Sampaio et al. (2020) is based on the characteristics of the instances, the set the threshold on half of the longest possible travel time. The research of Nikolopoulou et al. (2017) also shows that time affects the objective values for problems subjected to cross-docking. They concluded that when increasing the maximum route duration, more benefit can be gained from using cross-docking instead of smaller route duration's. However, it may also be the case when increasing this time too much that multiple pick-up and delivery rounds can be performed at one vehicle making the use of a cross-dock not advantageous.

2.5.2 Shipping Quantity

A second characteristic influencing transfer or cross-dock decisions is the shipping quantity. Direct delivery is always the most cost-efficient with a full truckload. However, if the direct distances and indirect distances are roughly equal, it is likely to cross-dock transport requests. Gümüş and Bookbinder (2004) estimated a minimum target quantity to consider direct shipment.

S_k : Quantity ordered by customer k
$S_k < m$: The quantity ordered by customer k cannot exceed the truck capacity, m
d'' : The direct distance from Pick-up to Delivery
d : The indirect distance from Pick-up to Delivery using a cross-dock
F' : Trough put cost at the Cross-dock
P : Fixed cost of a truck
c : Cost per kilometer

$$\text{Cost Direct Distance} : P + cd''S_k$$
$$\text{Cost Indirect Distance} : \frac{PS_k}{m} + cdS_k + F'S_k$$

First of all, the quantity S_k order by a customer k, cannot be greater than the given truck capacity m, $S_k < m$. Subsequently, the direct distance is defined as d'' and d is the minimum indirect distance from supplier to customer k. The indirect distance is the distance from pick-up to the cross-dock location, plus the distance between cross-dock and delivery location. In addition three cost parameters were set by Gümüş and Bookbinder (2004). The parameter F' was set as the throughput cost per unit quantity at a cross-dock, P is the fixed cost of a truck, and lastly, c is the cost of transportation per unit quantity per mile.

After Gümüş and Bookbinder (2004) established these parameters, he give two formulations, one for calculating the direct costs:

$$P + cd''S_k$$

and a second for calculating the minimum indirect costs:

$$\frac{PS_k}{m} + cdS_k + F'S_k$$

Gümüş and Bookbinder (2004) concluded that for small quantity deliveries, indirect shipping is preferable. However, the more the quantities increase, the more rapidly the cost grows. The quantity S_* can be established such that direct shipping is less costly for $S_k > S*$; otherwise, cross-docking is preferred. To determine this quantity $S*$, the previous two formulas are used, and the following formulation is used:

$$S* = \frac{P}{P/m + c(d - d'') + F'}$$

Nikolopoulou et al. (2017) investigated not the influence of the shipping quantity but the influence of the vehicle capacity. Different capacity constraints were used by calculating the cost-efficient for cross-docking and direct shipping. Nikolopoulou et al. (2017) concluded that the vehicle capacity for both instances with a one-to-one network and with a many-to-many network could be used as a predictor between the direct-shipping and cross-docking strategy. Cross-docking became advantageous when the vehicle capacity was higher (Nikolopoulou et al., 2017).

2.5.3 Neighbor Index

Nikolopoulou et al. (2017) found that the outcomes between the direct shipping and cross-docking strategy are influenced on the geographic location. Nikolopoulou et al. (2017) defined the geographic distribution using indices one is the Nearest Neighbour Index (NNI). The NNI is a ratio between the observed distance d_{obs} and the random distance d_{ran}. Those distances are between all the nodes, pick-up nodes P and delivery nodes D and is referred to as the distance for node $i \in P \cup D$ to node $j \in P \cup D$ as d_{ij}. The observed distance presents the average of distances between each node and its nearest neighbour. The random distance is the expected average distance that would occur, if the distribution is random. The area A is, the area of the grid of the nodes. The NNI is mathematically formulated as follows:

$$NNI = d_{obs}/d_{ran}$$

$$d_{obs} = \sum_{i \in P \cup D} nd_i/(2 * n)$$

$$nd_i = min_{j \in P \cup D, i \neq j} \quad d_{ij}$$

$$d_{ran} = 0.5 * \sqrt{A/(2 * n)}$$

In the research of Nikolopoulou et al. (2017) is described that the NNI values less than one, indicating some form of clustering. Subsequently, the results found in the research indicate that cross-docking is more profitable than direct shipping when the pick-up and delivery points are clustered.

2.5.4 Pairing Index factor

A second index determined by Nikolopoulou et al. (2017) is the Paring Index Factor (PI). The index quantifies the geographical distribution based on the distance between supplier and customer pairs. Nikolopoulou et al. (2017) defines three classes based on this index, large, mixed, and small supplier-customer pairs. Also, this index is a ratio, whereby the pick-up and delivery nodes $P \cup D$ and the arcs $(i, j) \in A$ are used. This formulation is dp_i the distance between pick-up and its designated delivery node. The variable d_{avg} is the average distance overall arcs. The mathematical formulation of the Pairing Index (PI) is formulated as follows:

$$PI = d_{pair}/d_{avg}$$

$$d_{pair} = \sum_{i \in P} dp_i/n$$

$$d_{avg} = \sum_{(i,j) \in A} d_{ij}/|A|$$

For this measure, the higher the index, the large the distance between supplier and customer. However, only for one-to-one network structures Nikolopoulou et al. (2017) found that this index was influencing the distribution strategy. This was not the case for the data-set with the many-to-many structure.

2.5.5 Depot Locations

A final variable that has been named in the literature as influencing whether cross-docking is cost effective is the placement of the depot. In the study of Nikolopoulou et al. (2017) different depot locations had been used. The results showed that more benefit could be obtained from the placement of a central depot as opposed to depot locations that were placed more towards the pick-up locations.

2.6 Summary and Conclusion Literature Review

In literature firstly three different network designs were found using intermediate facilities. The network designs hub-and spoke and cross-docking do not apply to the situation of VZT. The hub-and-spoke network is mostly oriented on the location of the facilities and in cross-docking strategies are focused on transporting all freight via a intermediate facility. The PDP most fits the problem description of VZT, and the PDPT and PDP-CD in specific. The difference in the problem definitions is that in PDPT is assumed that each location can be used to exchange freight, where in a PDP-CD only shipping requests are exchanged at a depot location. For the case of VZT only the depot is used for transferring and not the other locations in the network.

Subsequently, different model formulations were analyzed and it is concluded that the model of Rais et al. (2014) is most closely aligned with the problem of VZT. However, Rais et al. (2014) does assume that each location can be used as a transfer point which is not true for the business case. Another aspect explored in the literature are the different solution approaches used to find solutions. Exact solutions have only been found for small problems with a maximum size of 20 nodes. For the heuristic solutions this number is much higher, Petersen and Ropke (2011) solved problems of 100-200 requests with their ALNS. What was also striking in the literature is that the Local Search heuristic was the most used and then in particular the ALNS approach.

Lastly, characteristics that affect the cost effectiveness of cross-docking are found. Nikolopoulou et al. (2017) concluded that the following characteristics influence the cost-effectiveness of cross-docking: time and distance influence , vehicle capacity, the geographical location of the locations, the distance between the pick-up and delivery pairs and the depot locations. In addition, Gümüş and Bookbinder (2004) states that also the shipping quantity can have an influence on the cost. All of these insights found have been kept in mind when further researching the case study at VZT.

The research gap found is that the PDP-CD and PDPT problems are addressed briefly in the literature and that several solution approaches have been provided but that no software exist for solving those problems in practice. The PDPTW problem which is the predecessor of these problems has already been explored in more depth and has many solution methods also for large problems. Useful solving software for the PDPTW are also known. however, it has never been explored in the literature whether a PDPTW model can be used for solving PDPT problems where the decision of whether to do a transfer is determined.

Chapter 3

Business Analysis

In this chapter, the current situation of VZT is described in more detail. Firstly, the scope is defined in more detail. Deeper analysis followed. Firstly the Demand and Number of Shipments are analyzed. Insights are gained from historical to indicate how many shipping requests daily must be scheduled in routes. Next, the geographical distribution is further studied. First, the structure of unique locations is examined. After which, two indices found from the literature are analyzed. Other variables relevant to cross-docking include vehicle capacity, time limitations, and the cost of VZT. These insights serve as inputs to the subsequent model formation in Chapter 4 and determine whether cross-docking can be cost-effective for VZT. Eventually, this information needs to answer the following research question:

2. What is the current situation of VZT in terms of the promising cross-dock characteristics?

To give answer to the second research question historical data of VZT is used of the year 2020. The historical data is filtered according to the scope described in section 3.1. In addition, the steps to clean up the data are given in Appendix B.

3.1 Description of the context

The current operations of VZT are explained in Chapter 1. In order to gain insight into the operations, a few discussions with employees of VZT were held. The discussion and an analysis of the business data define the scope in more detail. As mentioned in Section 1.1, is VZT operating in the Netherlands and parts of Belgium and Germany. Figure 3.1 shows the various customer locations. The nodes visualized in the figure are pick-up and delivery nodes. In addition, the darker the color, the more customers at the same or nearly the same location.

The scope of the study has already been briefly stated in Chapter 1. In this section a more detailed explanation is given. Firstly this study is only focused on the pick-up locations in region 'Limburg', shown in Figure 3.2(a). The reason for this is to make the problem manageable. Besides, the distance between the pick-up locations in the 'Limburg' region and the delivery points is larger than the other regions. In addition, in literature is seen that the larger the distances the more appropriate it is to apply cross-docking (Hosseini et al., 2014).

The last argument for scoping to the 'Limburg' region is that the depot in Venlo has high costs. Depot Venlo is the cross-docking depot for the' Limburg' region. While investigating when cross-docking is preferable, it is also interesting to analyze if the Venlo depot is profitable. If it turns

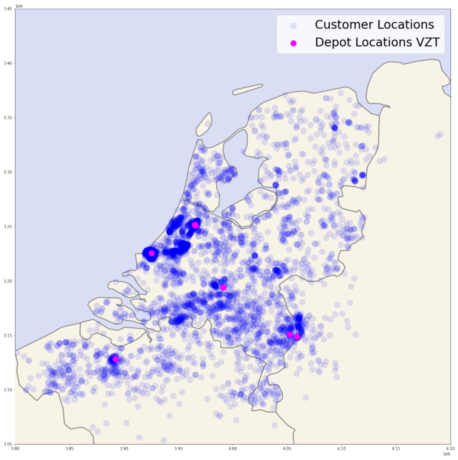
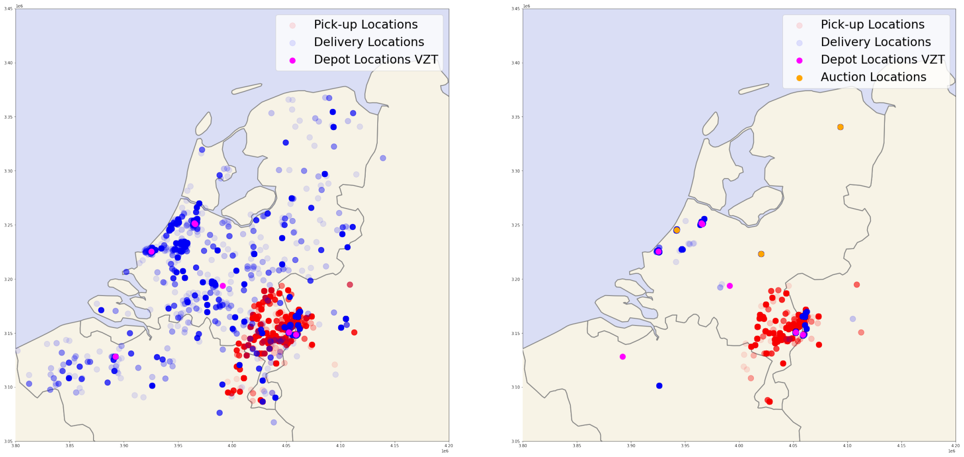


Figure 3.1: Customer Locations VZT



(a) Pick-up and Delivery Locations, Scope Pick-up region Limburg

(b) Pick-up and Delivery Loactions, Scope Pick-up region Limburg and BBT & KLOK

Figure 3.2: Geographical visualizations region Limburg

out that cross-docking saves only a small amount of costs and the depot has a high cost, it needs to be considered whether this depot should be retained.

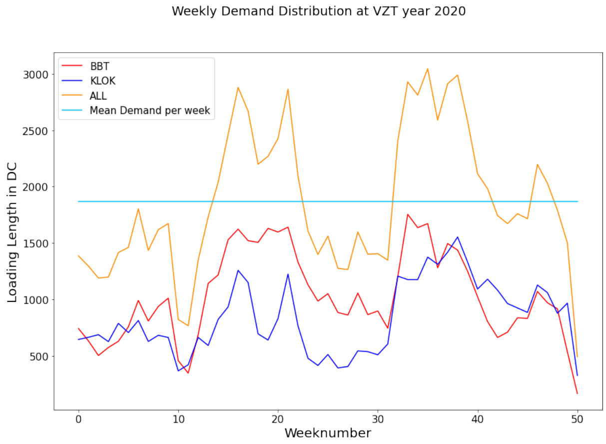
The second delineation executed to scope the research is based on the operational flows. As explained in Section 1.1 VZT has five different operational flows operated during day and night. At VZT, a distinction is made between day and night transport. Day transports are more of a stochastic nature. Shipping requests are added to already existing routes for the day planning. There is a point in the process for night transport where most shipping requests are known. This allows all shipping requests can be scheduled in larger quantities at one time.

The type of operation flows that belong to night transportation are: KLOK, a part of the BBT and the collection flow of the National Distribution. For this research is decided to scope to the order flows Box Deliveries applicable for night transportation and KLOK and to omit National Distribution. National Distribution is not included because in this flow, the shipping requests are collected at the growers and transported to depot De Kwakel. As mentioned earlier, De Kwakel is the main location of VZT. From here almost all deliveries are planned for national distribution. Because it is all transported to De Kwakel, it is a many-to-one flow that differs from the other two operation flows and where cross-docking is known to be unprofitable (Buijs et al., 2014). The various pick-up and delivery nodes that remain after this delineation are visible in Figure 3.2(b). Again, for the pickup and delivery points, the darker the color of the red and blue dots the more often these points appear in the data from VZT. The figure also shows the auction locations where VZT does not have a depot but where often need to be delivered.

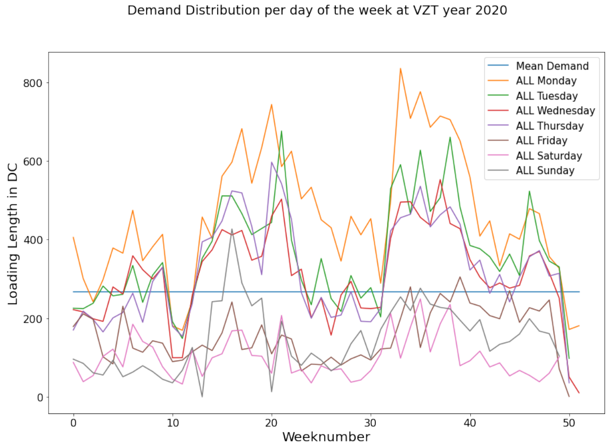
3.2 Demand

As earlier mentioned in Chapter 1 the shipping quantity of VZT is expressed in DC because of the special equipment that is used in the flori-culture industry.

Figure 3.3(a) is the distribution of demand visualized for the BBT and KLOK and the sum of the two expressed in DC. In the graph, two peaks are seen. Every year increases the sales of flori-culture products around the spring period. During the vacations, sales and shipments decline. Once these are over, sales grow, and so do the shipments requests. VZT mainly transports plants, so the increase in transport starts around March/April. For transporters transporting flowers, this period starts in February because of Valentine's Day. The same fluctuations can be seen for the number of shipments, visualized in Figure 3.4(a).



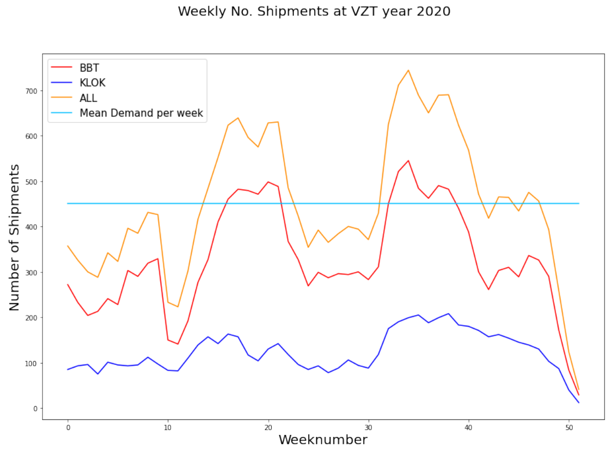
(a) Distribution of BBT, KLOK and Together



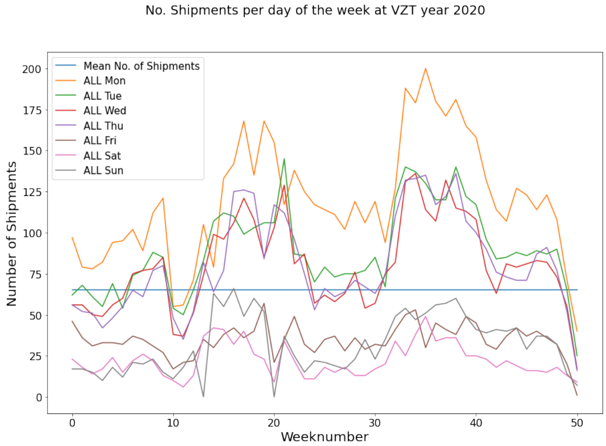
(b) Demand of all orders per day of the week & KLOK

Figure 3.3: Demand Distribution VZT 2020

In addition to the weekly figures, a plot is given for both demand Figure 3.3(b) and the number of shipments Figure 3.4(b) for the day of the week. This shows very clearly that Monday is mostly the busiest day. The Tuesday, Wednesday, and Thursday often overlap in both figures but are often smaller than the quantities of the Monday. Finally, it can be concluded that Friday, Saturday and Sunday are the days when the least transport is needed. The quantities on Monday are higher because more clock sales at the auctions occur, and export of flori-culture products mostly takes place at the beginning of the week.


Weekly No. Shipments at VZT year 2020

(a) Distribution of BBT, KLOK and Together


No. Shipments per day of the week at VZT year 2020

(b) All number of orders per day of the week & KLOK

Figure 3.4: Number of Shipment Distribution per week

A line is visualized for the mean of demand and shipments in all four figures. The mean loading length is weekly 1866 DC and daily 267 DC. The number of shipping requests is 451 transport requests per week and 65 requests per day on average. A final point that might be interesting regarding the demand and number of shipments is the average loading length overall shipment requests. The data shows that the range of the demand of a shipping requests is [1,69] and that the average demand value of a shipment request is 4.46 DC.

3.3 Geographical Distribution

In Section 3.1 already a small insight is given of the geographical distribution of VZT. In this section, the geographical distribution is analyzed in more detail. Section 3.1 has explained the decision of the scope. Looking at Figure 3.2(b), some form of clustering can be seen. All pick-up points are located in the south of the country, and the delivery points are mainly in the west of the country, with a few exceptions in Belgium, Groningen, and Ede.

Nikolopoulou et al., 2017's research mentioned earlier in Chapter 2 distinguish three distribution classes Random, clustered, and a combination random-clustered. The clustered distribution is created in clusters of four. Half of the number of nodes is distributed in the four clusters for the random-clustered class the other half is randomly distributed. To quantify these distributions Nikolopoulou et al., 2017 uses two indices. They do this using a Nearest Neighbour Index and a Pairing Index. It was statistically tested if these indices affect the best distribution strategy: (1) Direct delivery or (2) Cross-docking. The decision between the best distribution strategy is something that VZT would like to know. Therefore these indices will be calculated for the VZT data. Firstly an explanation of the calculation of the two indices is given.

3.3.1 Unique Locations

This section is investigated as if VZT has a many-to-many structure. In Section 3.2 it has already been found that VZT transports on average 65 orders per day. In a one-to-one network, this would mean that the network has 2×65 number of unique nodes. However, this is at VZT, not the case. Analyzing the data shows that a day on average has 41 unique locations, including 21 pick-up points on average and 20 delivery points on average.

To elaborate on this, a unique pick-up point serves on average 2.32 delivery points, with an average loading length of 12.63 DC. In the other direction, unique delivery points are served by 2.30 unique pick-up points on average, with an average demand of 27.31 DC. Lastly, the distances between the nodes are something to highlight. The mean average between all nodes is 52.47 kilometers, the mean distance between the pick-up locations is 13.31 kilometers, and the delivery locations 12.38 kilometers. As seen earlier in Figure 3.2, can the differences be clarified because both the pick-up points and the delivery points are clustered. Moreover, those clusters are far apart, showing a higher average distance between all unique nodes.

3.3.2 NNI & PI

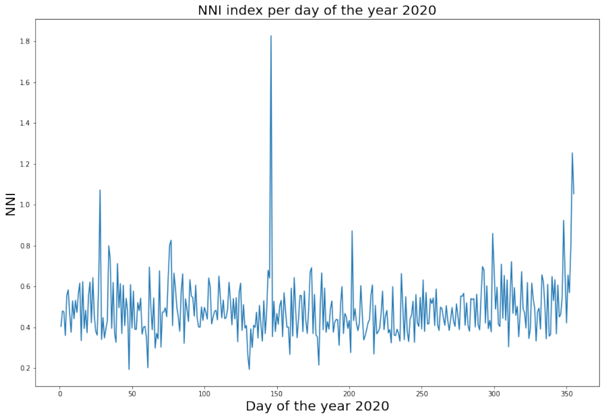
As explained in Section 2.5.3 and 2.5.4 introduced Nikolopoulou et al. (2017) two different indices indicating if cross-docking was efficient to apply. In order to gain insights into the situation of VZT and to see if cross-docking is cost-efficient, the indices are calculated per day of the year 2020.

The first index NNI introduced by Nikolopoulou et al., 2017 is set to gain information of the nearest neighborhood locations. Values less than 1 for the NNI, indicate a degree of clustering. For the benchmark data of Nikolopoulou et al., 2017, this was the case for the Clustered class. The value was above 1 for most of the Random and Random-Clustered problems, with a range of [1.00, 1.04] and [0.98, 1.15]. Nikolopoulou et al., 2017 investigated problems of different sizes with different parameters. Concluded was that all Clustered and Random-Clustered problems with a central depot were better solved using cross-docking than applying direct shipping.

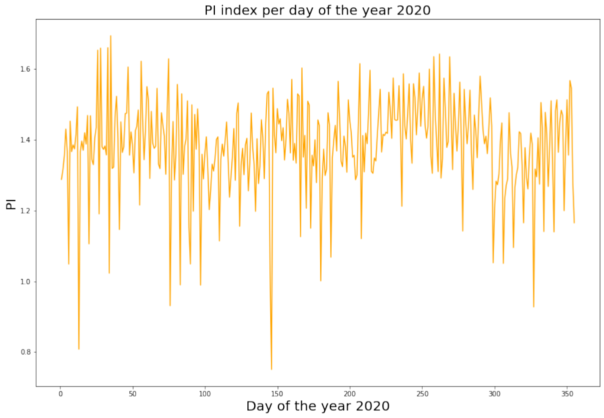
The Figures3.2(a) & (b) indicate that the data of VZT is clustered. Like the research of Nikolopoulou et al. (2017), the NNI is calculated for the business case of VZT. Figure 3.5 shows the distribution of the NNI per day of the year 2020. In the Figure is seen that most of the values are below 1, thus are suggesting that clustering is seen. A few outliers are seen, this occurs when only a few shipping requests require transportation.

Subsequently the PI index is set by Nikolopoulou et al. (2017). As explained in section 2.5.4, this index is set to measure the average distance between pick-up and delivery pairs. This means that when the distances between pick-up en delivery are large that the index is higher. If the pairs are closely located then the PI is lower. Most of the measurements are around the value of 1.4, saying that the mean distance between location pairs are far apart from each other. As for the NNI are also outliers seen for the PI the same reasoning.

On the basis of the NNI and PI values and the conclusions of Nikolopoulou et al. (2017), we can assume that cross-docking appears to be advantageous for VZT. However, this remains to be proven further in the research



(a) Distribution NNI 2020



(b) Distribution PI 2020

Figure 3.5: NNI and PI based on Nikolopoulou et al. (2017)

3.4 Vehicle Fleet

The next characteristic that is discussed for the VZT case is the vehicle fleet. VZT uses three different kinds of vehicles in their operations. The vehicles that they use are “Bakwagens”, Trailers and “Lange Zware Vrachtvoortuigen (LZV)”. These vehicles each have their vehicle capacities. The vehicle capacities are expressed in the number of DC’s that fit the vehicles. The vehicle capacity for the three types of vehicles are 28 DC for the “Bakwagens”, 43 DC for the Trailers & 70 DC for “LZV”. The vehicle types are used for different purposes. For example, ”Bakwagens” are mostly used to collect shipments at pick-up points. Larger vehicles have difficulties driving along country roads where the pick-up points are often located. LZV’s are mainly used for longer distances between depots and auction areas. The trailers are used for both pick-up and delivery. In Figure 3.6 are the three different type of vehicles visualized.

(a) Bakwagen (b) Trailer (c) LZV

Figure 3.6: Different Vehicle Types at VZT

Besides the type of vehicles, it is vital to find out the average speed of the vehicles. In most literature, the distance and time are set 1:1, which means that the average speed of vehicles is assumed to be 60 km/h.

For this study, it is tried to find the average speed of the vehicles at VZT. The average speed was attempted to be ascertained with the historical data of VZT of the year 2020. The data consist of times and distances monitored for the vehicles on the duration and distances they traveled. However, analyzing the data shows that it appears that many outliers exist. It often happens that a speed below 1 is driven and that vehicles drive faster than 100 km/h, much higher than the allowed speed of 80 km/h.

The outliers are caused by a delay in information transfer between the systems of VZT. The operations of the drivers are monitored with Transics, the board computer system used at VZT. The information in the board computers is transferred to ORD, the plannings software of VZT. Because of the delay between those two systems, it could occur that the saved times are not realistic and that the calculated speeds with the data are not realistic.

To gain the average speed of the vehicles, the duration and distances from depot Venlo to the five most frequent pick-up addresses and from depot Venlo to the five most frequent delivery addresses were examined, the data is shown in Appendix C. The distances, times and speeds are given in Table 3.1 and 3.2.

Table 3.1: Distances, Time and Speed for the five most visited growers

Transport pair	Distance	Average Time	Average Speed
Grower 1	33.9 km	43 min	47.3 km/h
Grower 2	27.4 km	33 min	49.8 km/h
Grower 3	14.2 km	25 min	34.1 km/h
Grower 4	12.9 km	19 min	40.7 km/h
Grower 5	32.9 km	43 min	45.9 km/h
Mean	24.6 km	33 min	43.6 km/h

Table 3.2: Distances, Time and Speed for the five most visited auctions

Transport pair	Distance	Average Time	Average Speed
Aalsmeer	168.2 km	2h 41 min	62.7 km/h
Ede	94.4 km	1h 37 min	58.4 km/h
De Kwakel	170.1 km	2h 39 min	64.2 km/h
Naaldwijk	187.3 km	2h 56 min	63.9 km/h
Rijnsburg	185.7 km	3h 5 min	60.2 km/h
Mean	161.1 km	2h 35 min	61.9 km/h

3.5 Time Constraints

The next topic to discuss is the time constraints that the problem of VZT knows. In these sections, these different time constraints will be discussed. For example, the constraints on shipments will be discussed. Next, the time constraints of the depots are discussed. Finally, the driving and working hours of the drivers are explained.

3.5.1 Time restrictions of the orders

In Section 1.1 the different operations of VZT were explained. It has been briefly mentioned that the time windows differ per operation. This subsection gives a more detailed explanation regarding the time restrictions on the shipment requests.

The shipping requests classified as KLOK requests need transportation from growers to auction locations. Sales at the auctions start early in the morning, and the floriculture products need to be at the auction locations at 3:30 AM. The time of collection at the growers depends on the grower's preferred time. However, it rarely occurs that the preferred time of the growers is before 5:00 PM. This is because VZT has the rule that growers can order transportation until 5:00 PM and that the shipping request must be ready for transportation within an hour. The second class of shipping requests that is taken into account is the BBT class. The time restrictions for pick-up are the same as the KLOK shipments. However, the delivery restrictions differ. The time of delivery is later for the BBT requests, 08:00 AM. In some cases the time windows for picking up and delivery differ because of customer requests.

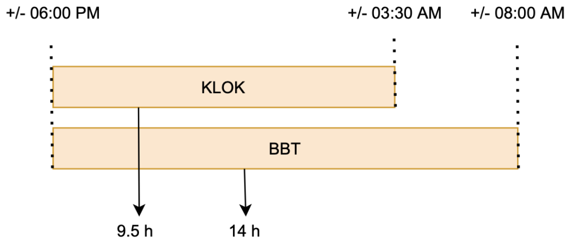


Figure 3.7: Time restrictions for pick-up and delivery locations for the shipping request KLOK and BBT

In addition to the time restrictions on collection and delivery of requests. Shipping also has loading and unloading times. In conversation with the owner of VZT, the loading and unloading times of the shipping requests were determined and shown in Table 3.3.

Table 3.3: Loading and Unloading times at Pick-up, Cross-dock and Delivery location

Location	Set-up time	Load/Unload time
Pick-up	15 min	1.5 min * DC
Crossdock	15 min	0.4 min * DC
Delivery	15 min	0.4 min * DC

3.5.2 Cross-dock restrictions

A second variable regarding time is the time of cross-docking at the depot. In this research depot Venlo and Ammerzoden are used in the analysis. Both depots are open all day. In addition, both depots are used as cross-dock locations. For cross-docking the orders, the planners assume maximum times that the shipping requests must be at the depots. In reality, there may be some fluctuation with these times but for this study they are fixed because a deterministic model is assumed. For depot Venlo, is assumed that everything will be received at the depot before 11:00 PM and that one can leave from 00:00 AM to deliver the shipping requests.

3.5.3 Drivers limitations

A final restriction regarding time is the maximum driving time and service time of the drivers. The law states that drivers can only drive for a maximum number of hours in the day to prevent accidents. This of course also applies for VZT. The maximum driving time in a day is 9 hours and the maximum duty time is 15 hours.

3.6 Costs at VZT

In literature is seen that a lot of different variables are costly related. To calculate the cost, the cost factors of VZT must be determined. Only then can a comparison be made to whether the new approach is more cost-effective than the current situation.

First of all, we start with the cost of employees. The employees that occur in the transporting process are drivers and box employees. The work of the drivers is clear, they transport the goods. In addition, they are also responsible for loading and unloading the goods. A box employee assists the driver at the cross-dock location and monitors the cross-dock locations. The hourly wage for both types of employees is as follows. The hourly wage for drivers averages €27.00 and for box employees it is €28.50.

Another transportation cost to consider is the cost per kilometer driven. This cost per kilometer is calculated based on the cost of 2020, and the number of kilometers driven in that year. A summary of the cost are shown in Table 3.4. In addition, it is known that the number of kilometers driven in 2020 is set at 5,834,520. By dividing the costs and kilometers, the cost per kilometer can be determined at 0.58 euro per kilometer.

Table 3.4: Cost items for calculating kilometer price

Variable	Cost 2020
Fuel	€1,638,293
Maintenance costs	€391,200
Tires	€123,908
Insurance and taxation	€84,902
Eurovignettes	€66,594
Other tangible assets	€1,068,787
Total	€3,373,684

Another cost that is set is the cost for starting a vehicle. This cost is used in the planning system to avoid using unlimited cars. The cost is determined at €220 per vehicle.

Lastly, we have the cost of cross-docking. There are several costs associated with this like rent, electricity and internet. These costs are shown in table 3.5.

Table 3.5: Cross-dock costs

Variable	Weekly cost	Yearly Cost
Rent	€ 1,312	€68,224
Internet	€ 213	€ 11,076
Inter transport material	€ 175	€ 9,100
Total	€1,700	€88,400

Chapter 4

Mathematical Formulations

This chapter formulates the model appropriate to the problem of VZT. In Chapter 2, all appropriate literature was analyzed, and models were compared along with VZT's situation. In addition, in Chapter 3, a business analysis was performed on the current situation of VZT. The gathered information of Chapter 2 and Chapter 3 serve as input for the model formulations in this Chapter and its assumptions. In addition, the following sub-question was formulated and is answered in this Chapter:

3. How to formulate the model of the routing problem of VZT?

Two model formulations are given. The first model to be formulated, therefore, is a PDP-CD model, which takes into account the opportunity to use a cross-dock in the routing problem. Secondly, the literature showed that such models are challenging to solve, especially for large numbers in a significant amount of time. Therefore, a second model is formulated the PDPTW. This problem is examined whether this model can be used for pick-up and delivery with cross-docking. Explanations of using this model will be explained in more detail later. The Chapter is divided into two parts the first part for the PDP-CD and the second part for the PDPTW.

4.1 Part I : PDP-CD model for VZT case

In this first part we are formulating the PDP-CD model for VZT. The mathematical model is based on the earlier named MILP models in Section 2.3. The models of Rais et al. (2014), Sampaio et al. (2020) and Voigt and Kuhn (2021) are combined to ensure that the newly created model fits is accurate. Rais et al., 2014 formulation is on itself consistent with the VZT case. However, because of the introduction of new formulations by Voigt and Kuhn (2021) and Sampaio et al. (2020), it is expected that some modifications are an improvement of the model of Rais et al. (2014) and are therefor taken into account. In addition, the model of Rais et al. (2014) is built as a pick-up and delivery problem with transfer capability. For VZT, it involves cross-docking at a central depot and is not considered to consolidate at other locations as well.

4.1.1 Model Assumptions PDP-CD

Several assumptions are made for the PDP-CD model. In order to understand the model the assumptions are listed below.

- In the model is assumed that locations can be visited more then once. This is because the model approach uses requests from VZT data. Pick-up and delivery locations are created for all requests. As seen in the business analysis in Chapter 3, it happens that multiple requests leave from a unique pick-up point, and multiple requests need to be delivered to a unique delivery point. Because of this, duplicates will occur in the model. As a result, the same location can be visited more than once.

- As earlier explained uses the flori culture special equipment to transport their product. For the model is ensured that all requests are quantified in DC, namely VZT transport sometimes other kind of units as well.

- The depot Venlo is the start, end and cross-dock location of the vehicles. In reality it can occur that the vehicles are also requested in other regions an not immediately return to the depot.

- In Chapter 3 is explained that the shifts of the vehicles are starting at 06:00 PM. It may happen that some shipping requests are picked up before this time by a vehicle of the day shift.

- Lastly is assumed that all shipping requests are known at the time of planning. In reality, some shipping requests may be added later on. However, this is not taken into account in this model.

4.1.2 Sets, Parameters & Decision variables for the PDPT

This subsection describes the required sets, parameters and decision variables. First of all we define a few notations from graph theory, as Rais et al. (2014) has done. We have a directed graph $G = (N, A)$ with node-set N and arc-set A. For $i, j \in N$, we denote a arc from i to j as $(i, j) \in A$. The set of nodes consist of pick-up and delivery nodes $i \in N, i\{1, ..., n+2\}$, start depot node $i \in N, i = \{0\}$, end depot node $i \in N, i = \{n+1\}$ and a transshipment node $i \in N, i = \{n+2\}$. For the VZT case, depot and transfer node are one and the same node. However, for the MILP separate nodes and sets are formulated for start depot, end depot and transshipment node. This was done so that it is evident when the route started and ended and if a cross-dock was done when analyzing the results.

Subsequently we set K as set of vehicles indexed by $k \in \{1, ..., |K|\}$. Each vehicle k, has a maximum capacity defined as u_k. The start and end depot of the vehicles are $i \in N, i = \{0\}$, and $i \in N, i = \{n+2\}$. The vehicles are transporting shipping requests. Set R is set to index the pick-up and delivery requests, by $r \in \{1, ..., |R|\}$. The quantities are denoted by q_r of the request r. Every request r is a pair $(p(r), d(r))$, with $p(r) \in N$ the pick-up node and $d(r) \in N$ the corresponding delivery node. For each request $r \in R$ load with quantity q_r needs to be transported from $p(r)$ to $d(r)$.

Next we set the parameters, the travel costs c_{ijk} and travel time t_{ijk} are given for each vehicle $k \in K$ traveling along arc $(i, j) \in A$. Additionally each request has a demand value q_r. Vehicles have a capacity of u_k and each pick-up and delivery node has a time window which is indicated as $[a_{p(r)}, b_{p(r)}]$ and $[a_{d(r)}, b_{d(r)}]$. The last parameter that is taken into account is a sufficient large number $M = 1000$.

Finally, the decision variables are discussed. The model has three binary variables and two continuous variables. Let $x_{ijk} = 1$, indicating that vehicle k uses the arc (i, j) and $x_{ijk} = 0$, otherwise $\forall (i, j,) \in A$ and $k \in K$. Secondly let $y_{ijkr} = 1$ if request r is transported with vehicle k using the arc (i, j) and $y_{ijkr} = 0$ otherwise $\forall r \in R, \forall (i, j) \in A$ and $\forall k \in K$. For the indication of the transfer of requests at the transfer point the binary variable s_{jrkl} is set. Let $s_{jrkl} = 1$ indicating that request r is transferred from vehicle k to vehicle l at node j, $s_{jrkl} = 0$ otherwise $\forall j \in N, \forall r \in R$ and $\forall k, l \in K$. The two continuous variables t_{jk}^{ARR} and t_{jk}^{DEP} are time variables. These ensure that time windows are not exceeded and that pick-up takes place before delivery.

Sets

N : The set of all locations in the network; $N = \{0, 1, ...n+1, n+2\}$
A : The set of arcs (i,j) , $i \in N, j \in N, i \neq j$
K : The set of vehicles with start depot $i = \{0\}$ and end depot $i = \{n+2\}$; $K = \{1, ..., |K|\}$
R : The set of shipping requests, with paired pick-up and delivery $(p(r), d(r))$; $R = \{1, ..., |R|\}$

Parameters

c_{ijk} : Cost to traverse demand on arc (i,j) with vehicle k
t_{ijk} : Time to traverse demand on arc (i,j) with vehicle k
q_r : Request quantity
u_k : Vehicle capacity; $u_k = 43$
M : Sufficiently large number; $M = 1000$
$[a_{p(r)}, b_{p(r)}]$: Time Window for pick-up
$[a_{d(r)}, b_{d(r)}]$: Time Window for delivery

Decision variables

s_{jrkl} : Decision variable, 1 if request $r \in R$ is transferred from vehicle k to vehicle l at node $j \in N, j = \{n+1\}, k, l \in K$; 0 Otherwise
t_{jk}^{ARR} : Time of arrival of vehicle $k \in K$ at node $j \in N$
$t^{\text{DEP}_{jk}}$: Time of departure of vehicle $k \in K$ at node $j \in N$
x_{ijk} : Binary decision variable, 1 if arc $(i,j) \in A$ is traversed with $k \in K$, 0 Otherwise
y_{ijkr} : Binary decision variable, 1 if request $r \in R$ is traversed on arc $(i,j) \in A$ with $k \in K$, 0 Otherwise

4.1.3 The MILP for the PDP-CD

In this section the MILP for the PDP-CD is formulated for the described VZT case. First the set model is given after which the objective and constraints are described.

$$\text{Min} \sum_{k \in K} \sum_{(i,j) \in A, i=0} f_k x_{ijk} + \sum_{k \in K} \sum_{(i,j) \in A} c_{ijk} x_{ijk} \tag{4.1}$$

$$\text{s.t.} \sum_{j:(0,j) \in A} x_{0jk} \leq 1 \qquad \forall k \in K \tag{4.2}$$

$$\sum_{j:(0,j) \in A} x_{0jk} = \sum_{j:(j,n+2) \in A} x_{j(n+2)k} \qquad \forall k \in K \tag{4.3}$$

$$\sum_{j:(i,j) \in A} x_{ijk} = \sum_{j:(j,i) \in A} x_{jik} \qquad \forall k \in K, \quad \forall i \in N \setminus \{0, n+2\} \tag{4.4}$$

$$y_{ijkr} \leq x_{ijk} \qquad \forall (i,j) \in A, \quad \forall k \in K, \quad \forall r \in R \tag{4.5}$$

$$\sum_{k \in K} \sum_{j:(p(r),j) \in A} y_{p(r)jkr} = 1 \qquad \forall r \in R \tag{4.6}$$

$$\sum_{k \in K} \sum_{j:(d(r),j) \in A} y_{d(r)jkr} = 1 \qquad \forall r \in R \tag{4.7}$$

$$\sum_{k \in K} \sum_{j:(n+1,j) \in A} y_{(n+1)jkr} = \sum_{k \in K} \sum_{j:(j,n+1) \in A} y_{j(n+1)kr} \qquad \forall r \in R \tag{4.8}$$

$$\sum_{j:(i,j) \in A} y_{ijkr} = \sum_{j:(j,i) \in A} y_{jikr} \qquad \forall i \in N(\{n+1\} \cup \{p(r), d(r)\}) \quad \forall k \in K, \quad \forall r \in R \tag{4.9}$$

$$t^{\text{DEP}}_{ik} + t_{ijk} - t^{\text{ARR}}_{jk} \leq M(1 - x_{ijk}) \qquad \forall (i,j) \in A, \quad \forall k \in K \tag{4.10}$$

$$t^{\text{ARR}}_{jk} \leq t^{\text{DEP}}_{jk} \qquad \forall j \in N, \quad \forall k \in K \tag{4.11}$$

$$\sum_{r \in R} q_r y_{ijkr} \leq u_k x_{ijk} \qquad \forall (i,j) \in A, \quad \forall k \in K \tag{4.12}$$

$$\sum_{j(j,n+1) \in A} y_{j(n+1)kr} + \sum_{j(n+1,j) \in A} y_{(n+1)jlr} \leq s_{(n+1)rkl} + 1 \qquad \forall k, l \in K, \quad \forall r \in R \quad k \neq l \tag{4.13}$$

$$t^{\text{ARR}}_{n+1k} - t^{\text{DEP}}_{n+1l} \leq M(1 - s_{(n+1)rkl}) \qquad \forall k, l \in K, \quad \forall r \in R, \quad k \neq l \tag{4.14}$$

$$a_{p(r)} \leq t^{\text{ARR}}_{p(r)k} \qquad \forall k \in K, \quad \forall r \in R \tag{4.15}$$

$$a_{d(r)} \leq t^{\text{ARR}}_{d(r)k} \qquad \forall k \in K, \quad \forall r \in R \tag{4.16}$$

$$t^{\text{DEP}}_{p(r)k} \leq b_{p(r)} \qquad \forall k \in K, \quad \forall r \in R \tag{4.17}$$

$$t^{\text{DEP}}_{d(r)k} \leq b_{d(r)} \qquad \forall k \in K, \quad \forall r \in R \tag{4.18}$$

$$x_{ijk} \in \{0,1\} \qquad \forall (i,j) \in A, \quad \forall k \in K \tag{4.19}$$

$$y_{ijkr} \in \{0,1\} \qquad \forall (i,j) \in A, \quad \forall k \in K, \quad \forall r \in R \tag{4.20}$$

$$t^{\text{ARR}}_{jk} \in R^+_0 \qquad \forall j \in N, \quad \forall k \in K \tag{4.21}$$

$$t^{\text{DEP}}_{jk} \in R^+_0 \qquad \forall j \in N, \quad \forall k \in K \tag{4.22}$$

$$s_{jrkl} \in \{0,1\} \qquad \forall j \in N, \quad \forall r \in R, \quad \forall k, l \in K \tag{4.23}$$

The objective function (4.1), is chosen to minimize the transportation cost. The cost are based on the cost per kilometer. For each arc the euclidean distance is calculated and multiplied with a cost factor, that is determined in Chapter 3. The costs are calculated in the objective by summing the costs of the arcs that are used. The objective is used both by Sampaio et al. (2020) and Rais et al. (2014). Rais et al. (2014) gives the extension by adding the cost for each vehicle used in order to solve the problem with as few vehicles as possible.

All formulated constraints ensure that the problem is solved according to the problem specifications of VZT. The constraints regarding the vehicle flow are set in equations 4.2 - 4.4, 4.10 and 4.11. Equation 4.2 enforces that at least one rout is initiated beginning at the vehicle depot. However, multiple vehicles can start from the depot but this constraint ensures that at least 1 vehicle is used. Equation 4.3 is associated with 4.2, namely constraint 4.3 enforces that every vehicle that departs from the vehicle depot must also return to the depot. Constraint 4.4 ensure the flow conservation of the vehicles trough the network. Equations 4.10 and 4.11 ensure that the vehicles arrive at the locations between the given time windows, together with equations 4.15 and 4.16. Besides ensure the equations 4.10 and 4.11 that sub tours are countered. Similar to the application of Voigt and Kuhn (2021) and Sampaio et al. (2020).

In addition to the constraints focused on the vehicle flow, constraints were also formulated focused on the request flow. Constraints 4.6 and 4.7 are set to guarantee that every pick-up and every delivery point are visited. Equations 4.8 and 4.9 are responsible for the flow conservation of the requests at the transfer node and the non-transfer nodes. Constraint 4.9 is formulated as done by Sampaio et al. (2020).

Finally, constraint 4.5 is set to enforce a vehicle flow on an arc if there is a request flow in the same vehicle on the same arc Rais et al., 2014. Vehicle capacity is restricted by 4.12. Constraints 4.15 - 4.18 ensure that none of the time windows are exceeded. The constraints are a lower and upper bound for both pick-up and delivery. Finally, constraints 4.19- 4.23, which indicate whether the decision variables are binary or continuous. As explained in Section 4.1.2 are the variables x_{ijk}, y_{ijkr} and s_{rjkl} binary variables. Besides, are the variables $t\text{ARR}$ and $t\text{DEP}$ defined as continuous variables.

The PDPT model described for the case at VZT is programmed in Python and is solved to optimality by using the Gurobi solver. The output of the model is the objective value along with the optimal route. The formulated model is tested in the next chapter. The next chapter also provides further explanation of the model testing set up.

4.2 Part II: PDPTW model for VZT case

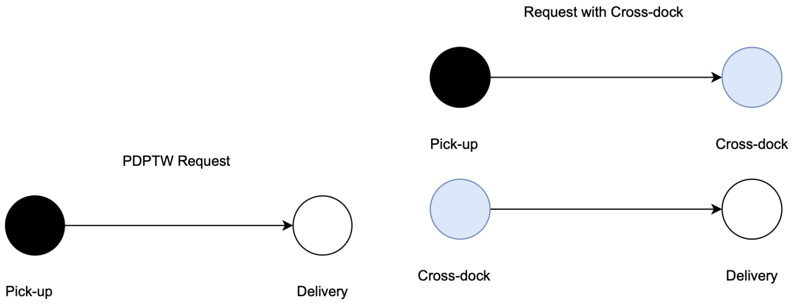
A second model application is provided in this second section of this chapter. This model fits more with the current situation of VZT, of deciding its cross-docks and establishing the routes.

This model assumes that the decision regarding the cross-docking of shipping requests is made first, after which the routes are calculated with a PDPTW model. The following subsections will elaborate on using the model in this study. Followed by a description of the sets, parameters, and decision variables. Lastly, the MILP formulation for the PDPTW model is given and explained.

4.2.1 Splitting Requests to use the PDPTW Model

This section explains how the PDPTW can be applied for the VZT case, followed by the formulation of the PDPTW. The PDPTW is an extension of the Vehicle Routing Problem with time windows. In a PDPTW problem, goods must be collected at a pick-up location before being delivered to a specified delivery location (Li & Lim, 2003). To apply cross-docking in a PDPTW model, are shipping requests manually split into two shipping requests, similar to the current plannings process at VZT. For cross-docking orders, shipments must be split in two to schedule them in ORD. The two shipping requests created are (1) one from a pick-up node to the cross-dock location. (2) The second one is created from the cross-dock location to the delivery nodes. The splitting of the shipping requests is given in Figure 4.1(b).

In addition, the time windows are set so that the collection operation at the pick-up node and delivery at the cross-dock location must be performed first, and only then can delivery take place. The explanation of setting these time windows is explained later in Chapter 6. The decision for choosing the shipping requests that are transported via cross-dock is further explained in Chapter 7. This chapter looks only at the possible use of a PDPTW model.



(a) Normal PDPTW request (b) PDPTW request split for cross-docking

Figure 4.1: PDPTW request and a PDPTW request split

For using the PDPTW model for cross-docking it is important to test if PDPTW problems can be solved with the model. The problems regarding cross-docking are called VRP-CD. In such problems all requests are cross-docked. The model need to be able to solve a normal PDPTW model and needs to be able to solve problems with cross-docking such as VRP-CD, this is tested in Chapter 6.

4.2.2 Model Assumptions PDPTW

The earlier mentioned assumptions for the PDP-CD in Section 4.1.1 also apply for the PDPTW. Only one additional assumption is made for the PDPTW use.

- Time windows are fixed for pick-up to cross-dock and from cross-dock to delivery. This is set for depot Venlo at the latest arrival at 11:00 PM and earliest departure at 00:00 AM. This constraint is different from the previously mentioned constraints. This has to do with the fact that the time of cross-docking in the model of the PDP-CD is not fixed, but the model considers that pick up and delivery at the cross-dock must take place earlier than the pick up at the cross-dock and delivery at the end location. This cannot be done for the PDPTW model for which time windows are established.

4.2.3 Sets, Parameters & Decision Variables for the PDPTW

The sets, parameters and decision variables for the PDPTW model are formulated and described in this section. The PDPTW that is used is introduced by Parragh et al. (2008).

In comparison with the PDPTW formulation is also the PDPTW formulation based on the graph theory. A direct graph $G = (N, A)$ with node-set N and arc-set A are set. For $i, j \in N$, we denote a arc from i to j as $(i, j) \in A$. The node-set consists of all pick-up nodes P and all delivery nodes D, plus the start and end depot $\{0\}$ and $\{n + \tilde{n} + 1\}$. In reality this is the same location but for the formulation two separate nodes are given. In the lists of sets the number n and $\acute{n}$ are defined, these give the number of pick-up and delivery nodes, we assume that our pickup and delivery nodes are paired such that $n = \acute{n}$. For each shipping request, a pick-up and delivery node is created. This means that it can happen that nodes are created for the same locations.

Subsequently we set K as set of vehicles indexed by $k \in \{1,\ ...,\ |K|\}$. Each vehicle k, has a maximum capacity defined as u_k. The start and end depot of the vehicles are $i \in N, \{i = 0\}$, and $i \in N, i = \{n + 2\}$. The vehicles the transport demands from pick-up nodes to delivery nodes. The demands requiring transportation are defined as q_i. Each value q_i is associated with a node, a positive value indicates that these goods should be collected at the node and a negative value indicates that the goods need to be delivered. The vehicles all have a maximum route duration. As mentioned in Chapter 3, drivers are allowed to be work for 15 hours in a row. The maximum route duration is therefore set as parameter $T_k = 15$ hours. This means that shipping requests must be transported and cross-docked within this time. This maximum duration is generous, and it is expected that all orders can be picked up and delivered within this time.

All nodes in the network have time windows ensuring the vehicles arrive between these times. The earliest visit time is set as e_i and the latest arrival at l_i. In addition, there is a service time set for every node this value is set as d_i. The parameters M, f_k and c_{ijk} and t_{ijk} are set as well. These parameters are already mentioned earlier in Section 4.1.3.

Finally, we have the decision variables. The model has one binary variable and two continuous variables. Let $x_{ijk} = 1$, indicating that vehicle k uses arc (i, j) and $x_{ijk} = 0$ other wise $\forall k \in K$ and $\forall (i, j) \in A$. The continuous variable Q_i^k keeps track of the load of the vehicles. This means that with this decision variable is tracked whether the maximum capacity is not exceeded. Lastly the decision variable B_i^k is set to ensure that the time windows are not exceeded and that pick-up takes place before delivery.

Sets

n : Number of Pick-up nodes
$\acute{n}$: Number of Delivery nodes
P : Set of Pick-up nodes $P = \{1, ..., n\}$
D : Set of Delivery nodes $D = \{n + 1, ..., n + \tilde{n}\}$
N : The set of nodes in the underlying network, $P \cup D; N = \{0, ..., n + \acute{n} + 1\}$
A : The set of arcs from i to j , $i \in N, j \in N, i \neq j$
K : The set of vehicles with start depot$i = \{0\}$ and end depot $i = \{n + 2\}; K = \{1, ..., |K|\}$

Parameters

c_{ijk} : Cost to traverse demand on arc $(i{,}j)$ with vehicle k
t_{ijk} : Time to traverse demand on arc $(i{,}j)$ with vehicle k
q_i : Demand/supply at node i, for pick-up a positive value, for delivery a negative value
e_i : Earliest time to begin service at node i
l_i : Latest time to begin service at node i
d_i : Service duration at node i
T_k : Maximum ride time of vehicle k
u_k : Vehicle capacity

f_k : Vehicle cost
M : Sufficiently large number

Decision Variables

x_{ijk} : Binary decision variable, 1 if arc $(i,j) \in A$ is traversed with $k \in K$, 0 Otherwise
Q_i^k : Load of vehicle k when leaving node i
B_i^k : Start of service of vehicle k at node i

4.2.4 The MILP for the PDPTW

In this section the derived PDPTW mathematical model for the VZT case is described. First the set model is given after which the objective and constraints are described.

$$\text{Min} \sum_{k\in K} \sum_{(i,j)\in A, i\in o(k)} f_k x_{ijk} + \sum_{k\in K} \sum_{(i,j)\in A} c_{ijk} x_{ijk} \tag{4.24}$$

$$\text{s.t.} \sum_{k\in K} \sum_{j:(i,j)\in A} x_{ijk} = 1 \qquad \forall i \in P \cup D \tag{4.25}$$

$$\sum_{j:(0,j)\in A} x_{0jk} = 1 \qquad \forall k \in K \tag{4.26}$$

$$\sum_{i:(i,n+\acute{n}+1)\in A} x_{i,i,n+\acute{n}+1k} = 1 \qquad \forall k \in K \tag{4.27}$$

$$\sum_{i:(i,j)\in A} x_{ijk} = \sum_{i:(j,i)\in A} x_{jik} \qquad \forall j \in P \cup D, \quad \forall k \in K \tag{4.28}$$

$$B_j^k + M(1 - x_{ijk}) \geq B_i^k + d_i + t_{ijk} \qquad \forall (i,j) \in A, \quad \forall k \in K \tag{4.29}$$

$$Q_j^k + M(1 - x_{ijk}) \geq Q_i^k + q_j \qquad \forall i,j \in N, \quad \forall k \in K \tag{4.30}$$

$$Q_i^k \geq a_i \qquad \forall i \in N, \quad \forall k \in K \tag{4.31}$$

$$Q_i^k \leq b_i \qquad \forall i \in N, \quad \forall k \in K \tag{4.32}$$

$$\sum_{j:(i,j)\in A} x_{ijk} - \sum_{j:(n+i,j)\in A} x_{ijk} = 0 \qquad \forall i \in P, \quad \forall k \in K \tag{4.33}$$

$$B_i^k \leq B_{n+i}^k \qquad \forall i \in P, \quad \forall k \in K \tag{4.34}$$

$$e_i \leq B_i^k \leq l_i \qquad \forall i \in N, \quad \forall k \in K \tag{4.35}$$

$$B_{n+\acute{n}+1}^k - B_0^k \leq T^k \qquad \forall k \in K \tag{4.36}$$

The objective function (4.24), is exactly the same as for the PDPT, minimizing the transportation cost and the number of vehicles used. Again the cost are based on the cost per kilometer plus the costs of the time required from node i to node j. For each arc the euclidean distance is calculated and multiplied with a cost factor, that is determined in Chapter 3.

Subsequently various constraints are formulated for the PDPTW. Starting with equation 4.25, set to ensure that every node is serviced once, with exception of the depot location. Next are the equations 4.26 & 4.27, which are very similar to the constraints set for the PDP-CD, constraints 4.2 & 4.3. Both ensuring that the vehicles need to leave the depot and also return to the depot. Constraint 4.28 ensures the flow conservation. Equation 4.33 is set to ensure that pick-up and delivery of the same requests are transported with the same vehicle.

The equations 4.29, 4.34 - 4.36 are established to meet the time constraints. As side benefit they prevent sub-tours. Constraint 4.36 is the last with respect to time, ensuring that routes do not exceed the maximum set time. Constraint 4.30 ensure that the vehicle capacity is not exceeded during a route together with 4.31 and 4.32. Constraints 4.31 and 4.32 indicate the lower and upper bound between which the vehicle capacity should be.

The formulated PDPTW model is programmed in two ways. First, the PDPTW was used to solve the model to optimality with Gurobi. This will be used to test the model correctness of the PDP-CD model compared to the solution of a PDPTW model.

Lastly, the PDPTW also will be solved heuristically. This is because it combines with heuristically splitting up the orders so you can use it to address the PDP-CD with the PDPTW model. The PDPTW is programmed in Python with Google OR tools. An existing script was used for this and has been modified. The heuristic procedure is a Guided Local Search and explained in more detail in the next Chapter 5

Chapter 5

Guided Local Search

This chapter explains the solution approach for the PDPTW. The heuristic approach used, is a GLS. It is programmed in Python and is solved with help of Google OR tools. At the end of this chapter, it is clear how the GLS heuristic is constructed in Google OR tools; furthermore, how a solution for the PDPTW is established.

5.1 Introduction to Guided Local Search

In this first section, an introduction is given for the GLS. As mentioned in Chapter 2 are routing problems NP-hard problems, meaning that finding an optimal solution is difficult. Practical problems cannot be solved optimally. In Chapter 2 is seen that a local search approach is often used for the PDPT & PDP-CD problems.

Local search is a heuristic approach that helps to minimize the problem by searching with iterative moves for better solutions in the neighborhood space. As mentioned, this is for a routing problem the exchange of nodes (Hoos & Stutzle, 2005). The search stops when all neighbors are investigated or if a certain time is elapsed (Voudouris et al., 2010). In a short time, Local Search can find reasonable solutions. However, it can be stuck in local optima. This means that in the near neighborhood space, a better solution is not found but may be there (Voudouris et al., 2010). To improve this, the GLS has been proposed and prevents the Local Search from getting stuck in local optima.

According to Alsheddy et al. (2018) can the GLS be described as follows. The GLS sits on top of Local Search algorithms. For using a GLS, we need to define features for candidate solutions in the neighborhood spaces. When a Local Search is used and is trapped in local optima, the defined features are selected and penalized. Besides the Local Search, searches through the solution space using an augmented objective function by the accumulated penalties (Alsheddy et al., 2018). These terms are further explained in the following section.

5.2 The GLS algorithm

A brief introduction was given for the GLS in the previous section. In this section, we will take a closer look at the algorithm of the GLS. Features need to be defined for using the GLS. As explained, those features can be penalized during the search to avoid getting stuck in a local optimum. The chosen feature is the arc (i, j) is used or not in the solution. Google-OR tools set these features (Google, n.d.). The GLS associates costs and a penalty with each feature (Alsheddy et al., 2018). The costs are defined by taking the cost coefficients from the objective function, g. For our problem, this involves the costs c_{ijk} set in the objective function in the previous Chapter 4.

Subsequently, the penalties are set to 0 and increase when the local search reaches a local optimum. According to Voudouris et al. (2010) the following applies "The objective function g is set and maps every candidate solution x to a numerical values". The GLS defines the augmented objective function h and is used in the Local Search to get not trapped in local minima by using penalties. The augmented function used for this research and determined by Google-OR tools looks as follows:

$$h(x) = \sum_{(ijk)} c_{ijk}(x) + \lambda \sum_{(ijk)} (I_{ijk}(x) \times p_{ijk} \times c_{ijk}(x))$$

$x =$ A candidate solution
$ijk =$ Feature ijk
$c_{ijk} =$ Cost of traversing on arc (i, j) by vehicle k
$I_{ijk} =$ Indication of solution x exhibits feature ijk
$p_{ijk} =$ Penalty for feature ijk
$\lambda =$ Penalty factor used for finding similar solutions, in Google OR-tools set to 0.1

The indication factor used for the GLS is set as follows according to Voudouris et al. (2010):

$$I_{ijk}(x) = \begin{cases} 1, & \text{if solution } x \text{ has feature } ijk \\ 0, & \text{otherwise} \end{cases}$$

Next, the penalties and their modifications are set. Penalties start with a value of 0 and increase by the time to value 1 for each local optimum. The feature is only penalized if the utility is large enough (Voudouris et al., 2010). The utility function used for a feature ijk in a solution x and is defined as follows by Google OR tools:

$$u_{ijk}(x) = I_{ijk}(x) \frac{c_{ijk}(x)}{(1 + p_{ijk})}$$

If a feature ijk is not present in a solution x, the utility function is 0. Otherwise, the utility is proportional to the costs. The thought behind this is that a feature that shows up often in optimal it might be part of a good solution (Google, n.d.). The GLS focused on finding promising areas by taking the costs and penalties into consideration by selecting features to penalize. Candidate solutions that have good features have lower costs. Lastly, as mentioned earlier, the penalties need to help prevent the search from getting stuck in local optima.

5.3 Implementation of the GLS

In this section the pseudo-code of the GLS is given. First the variables and methods used in the pseudo-code are explained. The variables x, ijk, c_{ijk}, I_{ijk}, p_{ijk} and λ are already explained in the previous section 5.2.

$P =$ Problem
$g =$ Objective function
$h =$ Augmented objective function
$M =$ The number of features
$ConstructionMethod(P) =$ Method for constructing initial solution
$ImprovementMethod(x_k, h) =$ Method for improving solution x_k according function h

Algorithm 1 Guided Local Search algorithm

```
Guided Local Search $(P, g, \lambda, [I_1, ..., I_M], [c_1, ..., c_m], M)$

  $k \leftarrow 0$
  $x_0 \leftarrow ConstructionMethod(P)$
  {set all penalties to 0}
  for $ijk \leftarrow 1$ until $M$ do
      $p_{ijk} \leftarrow 0;$
  end for
  {define augmented objective function}
  $h \leftarrow g + \lambda * \sum p_i * I_{ijk};$
  while $StoppingCriterion$ do
      $x_{k+1} \leftarrow ImprovementMethod(s_k, h);$
      {compute utility features}
      for $i \leftarrow 1$ until $M$ do
          $u_{ijk} \leftarrow I_{ijk}(x_{k+1}) * c_{ijk}/(1 + p_{ijk});$
      end for
      {penalize features with maximum utility}
      for all $i$ such that $u_{ijk}$ is maximum do
          $p_{ijk} \leftarrow p_{ijk+1};$
      end for
      $k \leftarrow k + 1;$
  end while
  $x^* \leftarrow$ best solution found with respect to objective function $g$
  return $x^*$
```

The algorithm is an initial solution set with the $ConstructionMethod(P)$ for problem P. As seen in Chapter 2, is an initial solution computed followed by improving this solution with Local Search. This also applies for the GLS approach. The initial solution used is the parallel best insertion strategy. A solution is built by iteratively inserting the cheapest node at its cheapest position. The cost of the insertion is based on the set cost function (Voudouris et al., 2010).

As long as the stopping criteria are not achieved, better solutions are sought. The stopping criteria set for this research are based on time. For the model validation in the next chapter, one hour is set. It will be examined whether the problems can be solved in a shorter time to reduce the time in the case study.

Lastly the $ImprovementMethod(x_k, h)$ is seen. The improvement methods are different heuristics used where nodes are exchanged within the route. The literature review in Chapter 2 has already given some examples of these. The improvement methods are established at google or tools.

Chapter 6

Model Validation

In Chapter 4, two model formulations were given for the problem of VZT. Firstly a model was formulated for the PDP-CD, wherein cross-dock decisions are made mathematically. Secondly, a PDPTW formulation was given where for the use resembles the current situation of VZT where decisions for cross-docking shipping requests are made first, and then the routes are made. The two model formulations of Chapter 4 are validated in this chapter, and answer is given to the fourth sub-question:

> *4. How validate the model and approaches formulated in research question 3?*

Both model formulations of Chapter 4 are programmed in Python and solved with Gurobi. In addition, the PDPTW model is also heuristically solved with a GLS programmed in Python and is solved using Google OR tools.

This Chapter is split into two parts. First the PDP-CD is tested. The benchmark data used is first explained, and the results are presented next. Secondly, the PDPTW model is tested. The PDPTW is tested with PDPTW instances but also for routing problems with cross-docking. Again, the benchmark data is first explained, after which the results are presented.

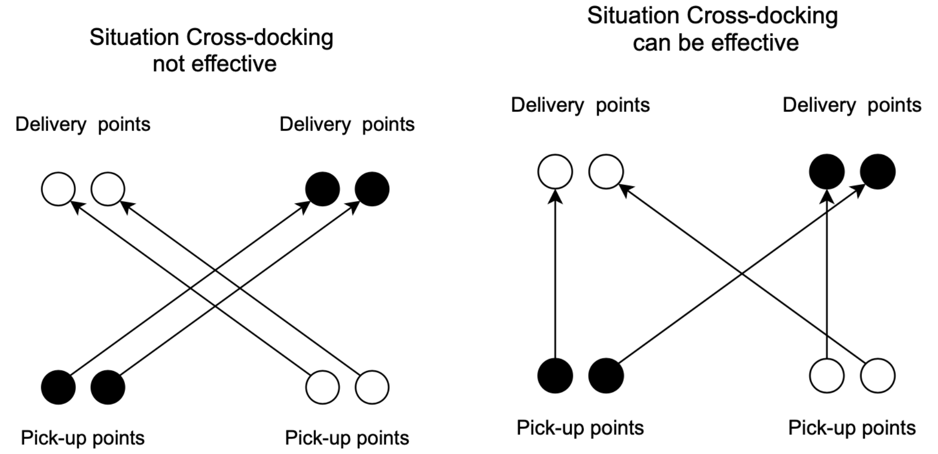
6.1 Part I: PDP-CD Validation

6.1.1 Benchmark Data PDP-CD

In the literature benchmark data for PDPT problem is rare. The benchmark data used by Sampaio et al. (2020), Voigt and Kuhn (2021) are larger instances and can not be solved to optimality with the programmed model in a considerable time. The data sets of Rais et al. (2014) are not directly usable; these need to be self-generated from the benchmark data of Li and Lim (2003). Because previously used benchmark data is not applicable, it is chosen to adapt the benchmark data of Nikolopoulou et al. (2017) and test the model. Adjusting the data of Nikolopoulou et al. (2017) was done using three steps.

1. First, the smallest data set of Nikolopoulou et al. (2017) was taken as a basis for creating test data. This data set consists of twelve shipping requests, all with unique pickup and delivery nodes, placed in [100, 100]. The amount of requests is too much to solve with the formulated MILP for the PDPT. Therefore, we created three data sets with 3, 4, and 5 requests consisting of 6, 8 & 10 nodes plus the depot node. The nodes selected from the

data set of Nikolopoulou et al. (2017) was done such that cross-docking could potentially be advantageous. Two situations are shown in Figure 6.1. The first situation (Figure 6.1(a)) indicates a situation wherefore cross-docking is not cost-effective and the second situation (Figure 6.1(b)) where cross-docking may be cost-effective. The location of the depot is placed in the middle of the graph.



(a) Situation Cross-docking is not effective (b) Situation Cross-docking can be effective

Figure 6.1: Situations when Cross-docking can be effective or not

2. After the nodes are selected, time windows are added to the problem. This is because the data set of Nikolopoulou et al. (2017) is a PDP problem meaning that the instances do not contain time windows. The time windows that are created are from 0 to the maximum route duration, mathematical expressed in Equations 6.1, 6.1 & 6.3.

$$\text{Pick-up node} : 0 - T \tag{6.1}$$

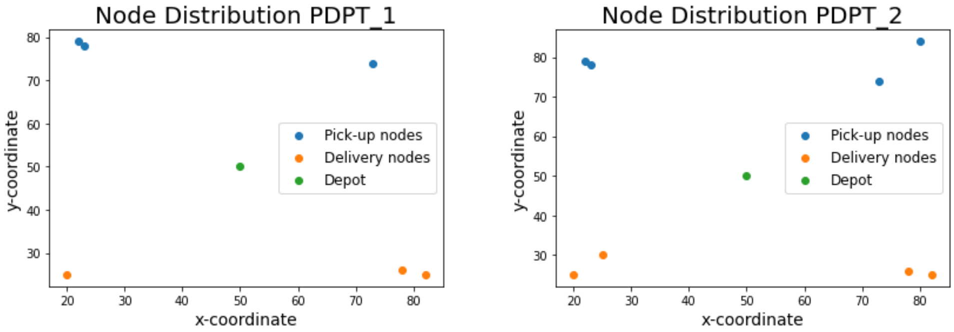
$$\text{Delivery node} : 0 - T \tag{6.2}$$

$$T : \text{Maximum Route Duration} \tag{6.3}$$

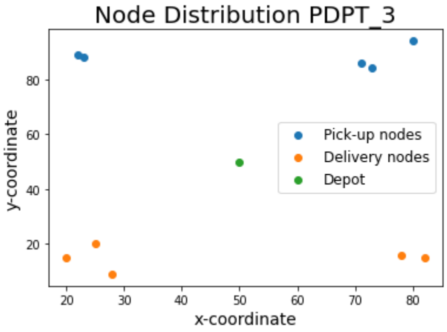
3. The third and last step that is taken to create data for testing the PDPT is changing the demands of the shipping requests. For setting the requests, demands must be ensured that the sum of the demands must be higher than the vehicle capacity. This is important because cross-docking cannot be applied when all the requests fit into one vehicle, and that is precisely what we want to test with our model. Table 6.1 shows the determined demands per request. In addition to the demand, the further specifications of the data sets are also shown.

The specifics of the created data sets are summarized in Table 6.1. The complete data sets are given in Appendix D. The service time at the nodes is set to 2 time units and at the cross-dock at 5 time units. Besides, the speed of the vehicles is set to 1 kilometer per minute. Lastly, the distance is calculated with euclidean distances and used as a cost factor.

The data sets are now known for testing the PDP-CD and shown in Figure 6.2. Since the data is created and has not been used before, is decided to evaluate the results gained with the PDP-CD, with the results gained with the PDPTW. If cross-docking is not advantageous then both models PDP-CD and PDPTW should given the same objective values. If cross-docking is beneficial, then the objective value for PDP-CD must be lower than the one from the PDPTW.



(a) Node Distribution PDPT_1 (b) Node Distribution PDPT_2



(c) Node Distribution PDPT_3

Figure 6.2: Node Distribution of the PDPCD data sets

Table 6.1: Data-sets used testing PDPCD

Instance	Nb. Requests	Nb. Nodes	Nb. Vehicles	Mean Distance PD pair	Mean Distance to Depot	TW	qi	Q
PDPT_1	3	7	3	60	38	[0,250]	[50, 50, 50]	100
PDPT_2	4	9	3	64	38	[0,250]	[50, 50, 50, 50]	100
PDPT_3	5	11	3	83	45	[0,250]	[35, 35, 35, 35, 35]	100

6.1.2 Results PDP-CD

The results for the PDP-CD are shown in Table 6.2 and for the PDPTW in Table 6.3. A few things ares seen. Firstly, the results shown in Table 6.2 & 6.3. It is seen that the computational time of the PDP-CD is higher compared with the PDPTW, especially for instance with five shipping requests is much more time required. However, because the model is only tested for a few instances, further research is needed to draw hard conclusions. However, in the study of Rais et al. (2014) it is shown that solving an PDPT or PDP-CD problems is computationally extensive.

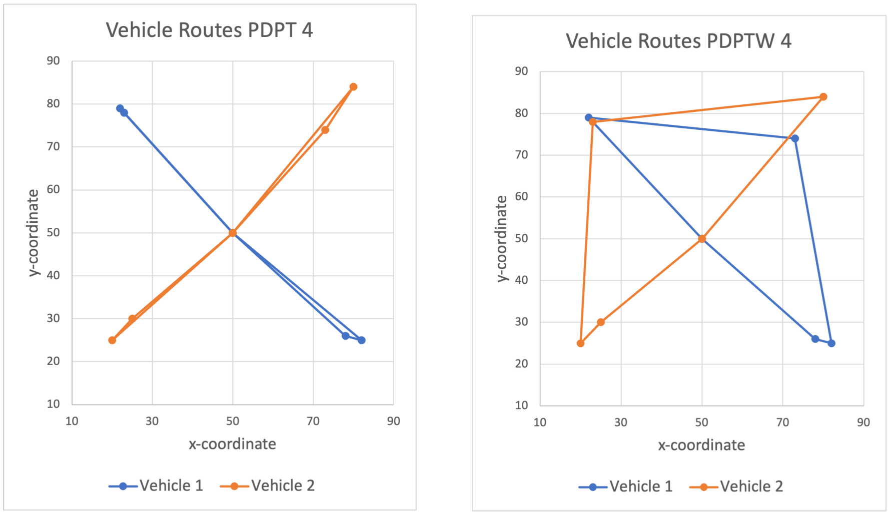
Table 6.2: Solutions PDP-CD

Instance	Nb. Vehicles used	Distance (km)	Time	Transfer used
PDPT_1	1	257	0.31	No
PDPT_2	2	327	21	Yes
PDPT_3	3	428	3427	No

Table 6.3: Solutions PDPTW

Instance	Nb. Vehicles used	Distance (km)	Time
PDPT_1	1	257	0.08
PDPT_2	2	376	0.81
PDPT_3	3	428	10.5

Secondly, for two of the three instances, a transfer was used. Using no transfer means that direct shipping was the best distribution strategy. This was concluded because the outcomes were the same for the PDPTW. Fortunately, cross-docking was used in the routing for one of the instances. In addition, the use of the cross-dock ensures that a lower objective value is achieved compared to the outcome of PDPTW. To indicate the differences in route solutions using a cross-dock, this is visualized in Figure 6.3.



(a) Routes create with the PDP-CD (b) Routes created with the PDPTW

Figure 6.3:
Obtained Solutions for the PDPT_2 and PDPTW
solving to optimality with Gurobi

With testing the three instances, it was seen that the model could adequately solve these problems. However, because only a few instances were used, no firm conclusions can be drawn. However, there is a suspicion that the computational time grows by adding additional requests to the problem. Translating the model into a heuristic could solve the problem of VZT. However, there is not enough knowledge available at VZT to adapt a heuristic according to changes in the business.

6.2 Part II: GLS Validation

The second part of this Chapter is described in this section. The PDPTW model formulated in Chapter 4 is programmed in Python and heuristically solved with Google OR-tools using a GLS.

This section consists of two subsections. First is the used benchmark data explained, followed by generated results. In addition, the GLS is tested for two reasons. Firstly to see if it can properly solve a PDPTW and secondly, if the model can solve problems using cross-docking; these problems are abbreviated to VRPCD. Section 4.2.1 explained that the cross-dock is implemented by splitting requests into two.

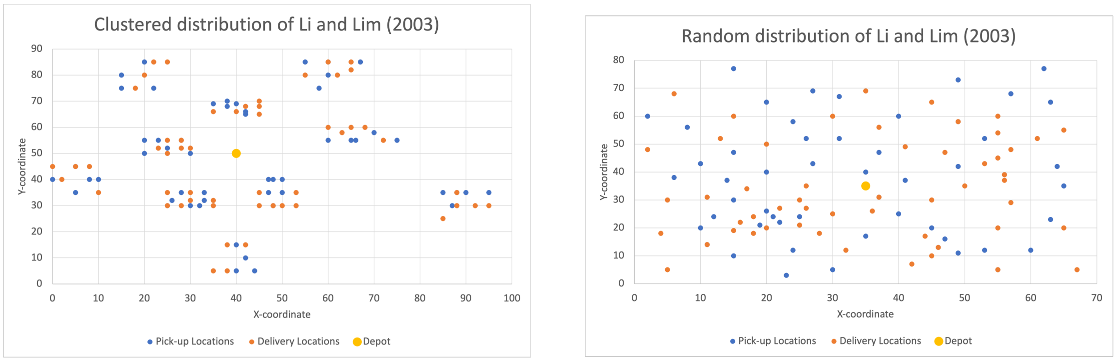
6.2.1 Benchmark Data for GLS Validation

Three different kinds of data sets are used for testing the PDPTW model and testing the applicability of problems with cross-docking. The three data sets are explained in more detail in the following subsections.

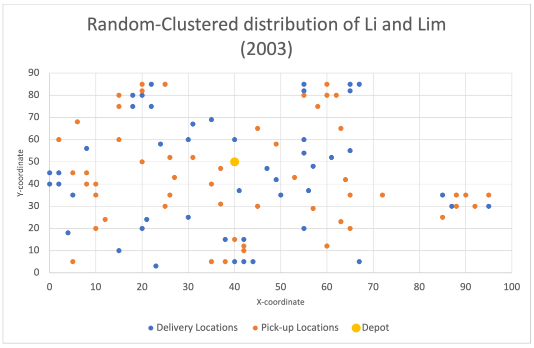
Benchmark data 1: Li and Lim

The GLS explained in Chapter 5 is firstly subjected to the data-sets of Li and Lim (2003). This first benchmark data is used to test if the programmed model is sufficient and can solve properly PDPTW problems. Li and Lim (2003) created three different data sets and were the first to solve the PDPTW for large instances with various distribution properties. These distribution properties are classified into three different classes Clustered, Random, and Random-Clustered, shown in Figure 6.4.

Figure 6.4: Node Distribution for distribution classes Clustered, Random and Random-Clustered



(a) Clustered Distribution Li and Lim (b) Random Distribution Li and Lim



(c) Random - Clustered Distribution Li and Lim

The study of Li and Lim (2003) solved a PDPTW problem for the following objective function:

$$Cost(S) = \alpha NV + \beta TC(S) + \gamma SD(S) + \lambda WT(S)$$

The cost factors used in the objective function were Number of Vehicles (NV), Scheduled Duration (SD), Travel Cost (TC) & Waiting Time (WT). The weight for the cost factors was set by Li and

Lim (2003) as follows $\alpha > \beta > \gamma > \lambda$. Unfortunately, their study does not describe the weights they used for these variables.

In addition, the GLS does not optimize waiting times and scheduling duration but takes into account the cost of vehicles and distance. In addition, the GLS is solved for five data sets per different distribution class. The parameters used are set by Li and Lim (2003).

Benchmark data 2: Nikolopoulou I

The second benchmark data used for model testing is the first type of data-set created by Nikolopoulou et al. (2017) and called in this study NI. The purpose of testing with the NI benchmark data differs from testing with the data of Li and Lim (2003). NI data is used to test if a problem with cross-docking can be appropriately solved with a PDPTW model, using the GLS.

For the NI data set Nikolopoulou et al. (2017) created different problem sizes with a one-to-one network with a number of nodes of {24,56,72,96}, these different problem sizes are tested. Figure 6.5 is the node distribution of the 96 node problem visualized. The parameters used to solve the problem are a Vehicle Capacity (Q) of 100, a maximum route time (T1, T2, T3) of 250, 265, and 280, and a service time (s) at the cross-dock of 5 time units and service time of 2 time units at every node. These parameters were established by Nikolopoulou et al. (2017). Three different maximum route duration's are set to gain insights into the solutions, allowing a longer amount of time.

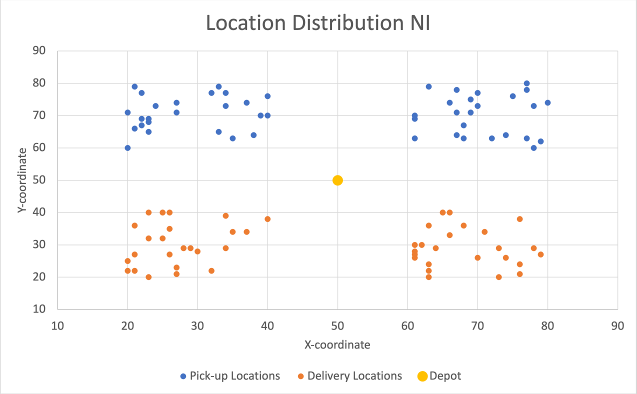


Figure 6.5: Location Distribution NI

In addition, Nikolopoulou et al. (2017) created data sets for a PDP problem and not for a PDPTW. Meaning that the instances have no time windows for the shipping requests. To solve the problem, time windows are created. We created time windows by using the maximum schedule duration. It is assumed that half of the time is available for picking-up shipping requests, and the other half of the time is used for delivering the shipping requests. This assumption is based on the fact that the depot is in the center of the locations, seen in Figure 6.5. The time windows for solving the PDPTW are set as described in 6.1, 6.2 & 6.3. For the shipping requests that are cross-docked the time windows are given in Equations 6.4, 6.5, 6.6 & 6.7.

$$\text{Pick-up node} : 0 - (0.5 * T - \text{service time at cross-dock}) \tag{6.4}$$

$$\text{Cross-dock after Pick-up} : \ 0 - (0.5 * T - \text{service time at cross-dock}) \tag{6.5}$$

$$\text{Cross-dock before Delivery} : (0.5 * T) - T \tag{6.6}$$

$$\text{Delivery} : (0.5 * T) - T \tag{6.7}$$

Benchmark data 3: Nikolopoulou II

The second data-set of Nikolopoulou et al. (2017) that is used for testing the PDPTW model programmed with Google OR-tools is a many-to-many network. As explained, we test the model with the NI data set because we want to test if the PDPTW model properly solves problems with cross-docked shipping requests. The GLS is tested for this second date set of Nikolopoulou et al. (2017) because it contains a many-to-many network instead of one-to-one. This second type of data set of Nikolopoulou et al. (2017) is called NII.

The instances of Nikolopoulou et al. (2017) contain 10, 12, or 14 nodes; all these nodes can require transportation between them, the node distribution of the 14 node problem is given in Figure 6.6. The requests for data set type NII instances are all translated to one-to-one requests.

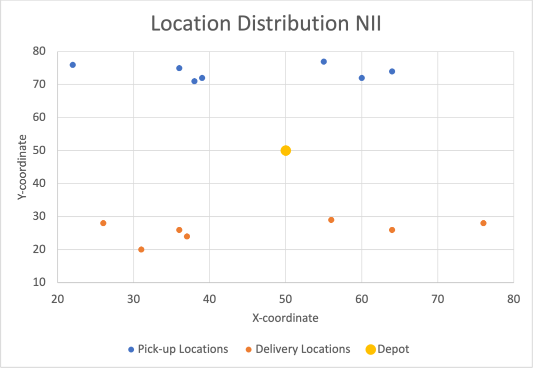


Figure 6.6: Location Distribution NII

Nikolopoulou et al. (2017) created three different demand distributions schemes for the data set NII. The demand distribution of the classes has a change of 25%, 50%, and 75% of being non-zero. This means that in class DM1 and DM2, requests have a demand of zero. In class DM3, all pick-up nodes serve all delivery points.

The parameters used in testing data set NII is the given vehicle capacities by Nikolopoulou et al. (2017); these differ per instance. The same applies to the maximum scheduling duration. The service time incurred is a service time (s) of 2 time units for all nodes and 5 seconds for cross-docking. No advantage is included when multiple orders are collected or delivered at the same node. Also, the service time is incurred for the request with a demand of 0. As mentioned in section 6.2.1 time windows were set for the NI data set. The same strategy is applied to the NII data. As for the NI data set, results are also acquired for the NII data set with different maximum route durations (T1, T2, T3). In addition, for these data sets, different demands classes are tested (DM1, DM2 & DM3).

6.2.2 Results GLS Validation

In this sub-section, the results are presented for the three benchmark data sets used to test the GLS approach. Besides, the results need to be present if it is possible to solve routing problems with cross-docking shipping requests.

Results Benchmark data 1: Li and Lim

As explained in section 6.2.1 created Li and Lim (2003) data sets with three different node distributions. These different distributions have been tested and the results and are presented in Table 6.4

for the Clustered instances, Table 6.5 for the Random instances & 6.6 for the Random-Clustered instances.

Table 6.4: Results of the LC instances

	Obtained solution by Li and Lim 2003				Obtained solution with GLS				GAP TC %
Instance	NV	SD	TC	CT	NV	SD	TC	CT	
LC101	10	9,829	829	33	10	9,829	829	8	0.00%
LC102	10	9,829	829	71	10	9,829	829	3	0.00%
LC103	10	10,058	828	191	10	9,898	828	4	0.00%
LC104	9	10,038	862	1,254	9	10,072	863	4,858	0.12%
LC105	10	9,829	829	47	10	9,829	829	4	0.00%

CT = Computational Time

Table 6.5: Results of the LR instances

	Obtained solution by Li and Lim 2003				Obtained solution with GLS				GAP TC %
Instance	NV	SD	TC	CT	NV	SD	TC	CT	
LR101	19	3,599	1,659	87	19	3,599	1,659	1,686	0.00%
LR102	17	3,202	1,487	1,168	17	3,202	1,487	1,626	0.00%
LR103	13	2,729	1,293	169	13	2,721	1,336	1,748	0.29%
LR104	9	2,050	1,012	459	9	2,216	1,065	1,721	5.23%
LR105	14	2,632	1,377	69	14	2,638	1,387	1,725	0.73%

CT = Computational Time

Table 6.6: Results of the LRC instances

	Obtained solution by Li and Lim 2003				Obtained solution with GLS				GAP TC %
Instance	NV	SD	TC	CT	NV	SD	TC	CT	
LRC101	14	2,956	1,709	119	14	2,956	1,709	1,223	0.00%
LRC102	13	2,764	1,564	152	13	2,845	1,578	1,002	0.90%
LRC103	11	2,444	1,259	175	11	2,444	1,259	1,154	0.00%
LRC104	10	2,238	1,128	202	10	2,238	1,128	220	0.00%
LRC105	13	2,830	1,638	13	179	2,930	1,653	47	0.92%

CT = Computational Time

Evaluating the gained results presented in Tables 6.4, 6.5 & 6.6. Firstly can be concluded that the gained solutions are almost equal to the obtained solutions by Li and Lim (2003). For the Clustered and Random-Clustered instances, only deviations occur less than 1%. For the Random instances, two instances also differ less than 1% with the obtained solution of Li and Lim (2003). Only one instance with a Random distribution deviates with 5.23%. The deviation can occur because the model needs more time to gain the optimal solution. However, we decided not to let the model calculate longer than 3600 seconds (1 hour). Something else that stands out is that the clustered problems are solved quickly. This does not apply for the Random and Random-clustered instances, which needed on average 1,701 seconds and 729 seconds.

Results Benchmark data 2: Nikolopoulou 1 (NI)

As mentioned in the previous section, created Nikolopoulou et al. (2017) two types of data sets. The results for the NI data-set are presented in this section.

The goal of testing with the NI instances was to see if the GLS approach for solving a PDPTW model can solve routing problems with cross-docking by fixing the time windows. In Table 6.7 the results are shown of the instances tested. This first table shows the results of the solutions obtained with a maximum route duration of T = 250. The results show that not for all PDPTW problems, the optimal solution is also not always found, but the difference is a maximum of 3.59%. This occurs, for instance, with 96 nodes. The problem with a deviation of 3.59% consists the most nodes. A difference is visible for problems 56 and 72, but this is below 1%. In addition, the results presented for solving the cross-dock problems, called VRPCD, are also not solved to optimality in non of the cases. Therefore, the problem instances are also subjected to larger time frames (T2 = 265 & T3 = 280) to see if this affects the calculation of the optimal solution. The results of this are shown in Table 6.8.

Table 6.7: Solutions NI tested with T1

	Obtained Solution by Nikolopoulou		Obtained Solution GLS		GAP TC %	
Instance	PDP	VRPCD	PDP	VRPCD	PDP	VRPCD
Niko 24	364	348	364	391	0.00%	12.35%
Niko 56	709	689	711	738	0.28%	7.11%
Niko 72	941	887	945	906	0.43%	2.14%
Niko 96	1,170	1,153	1,212	1,185	3.59%	2.78%

The results in Table 6.8 show that when enlarging the duration where-in transport needs to be executed; better results could be achieved for cross-docking the instances. The different deviations for the time duration show that for T1, this is 6.10% on average for T2 2.05% and T3 0.84%.

Table 6.8: Solutions for different maximum
time duration's T1, T2 & T3 for data set NI

	T1			T2			T3		
Instance	Niko	GLS	GAP %	Niko	GLS	GAP %	Niko	GLS	GAP %
Niko 24	348	391	12.36%	348	348	0.00%	348	348	0.00%
Niko 56	689	738	7.11%	689	715	3.77%	689	698	1.31%
Niko 72	887	906	2.14%	887	904	1.92%	887	892	0.56%
Niko 96	1,153	1,185	2.78%	1,153	1,182	2.52%	1,153	1,170	1.47%

The reason that the cross-docking problems cannot be solved properly and do not give the same results as Nikolopoulou et al. (2017) is most likely due to the time windows that are fixed. Nikolopoulou et al. (2017) has solved the cross-docking instances with a VRP-CD model. During the model calculation, the time that the shipping requests should be present at the cross-dock facility will be decided.

Results Benchmark data 3: Nikolopoulou 2 (NII)

The NII data is the last data set used to test the GLS approach and applying to split requests. As mentioned, these instances consist of 10, 12, and 14 nodes and where instances are defined with different demand distributions (DM1, DM2 & DM3). Results were obtained for different maximum time durations (T1, T2 & T3). The results are divided by demand class and shown in Tables 6.9 6.10 & 6.11.

The results for the first demand class DM1, presented in Table 6.9, show that for almost non of the instances is achieved to obtain the optimal solution. Only the smallest instance size is achieved to find the optimal solution for T2 & T3. Besides, by enlarging the time durations, the GAP is decreased between the solutions of Nikolopoulou et al. (2017) and the obtained solutions with the

Table 6.9: DM1 cross-docking NII

NII - DM1									
	T1			T2			T3		
Instance	Niko	GLS	GAP %	Niko	GLS	GAP %	Niko	GLS	GAP %
NII_10	475	476	0.21%	475	475	0.00%	475	475	0.00%
NII_12	584	786	34.59%	584	672	15.97%	584	584	13.87%
NII_14	930	978	5.16%	930	975	4.84%	930	936	0.65%

GLS. For DM2 (Table 6.10) and DM3 (Table 6.11) the same conclusions can be drawn. However, for DM2 and DM3, requests could not be planned for the tight maximum route duration.

Table 6.10: DM2 cross-docking NII

NII - DM2									
	T1			T2			T3		
Instance	Niko	GLS	GAP %	Niko	GLS	GAP %	Niko	GLS	GAP %
NII_10	800	Infeasible	-	770	1,040	35.06%	770	817	6.10%
NII_12	816	Infeasible	-	816	1,249	53.06%	816	907	11.15%
NII_14	857	1,346	57.06%	841	1,067	26.87%	841	895	6.42%

Table 6.11: DM3 cross-docking NII

NII - DM3									
	T1			T2			T3		
Instance	Niko	GLS	GAP %	Niko	GLS	GAP %	Niko	GLS	GAP %
NII_10	813	Infeasible	-	813	1,220	50.06%	813	877	7.87%
NII_12	970	Infeasible	-	848	Infeasible	-	830	1,047	26.14%
NII_14	907	1,856	105.73%	811	1,165	43.65%	808	901	11.51%

The reason that not the same solutions are found as by Nikolopoulou et al. (2017) is because of the time windows that are fixed; this limits the problems. Using a VRP-CD model, applied by Nikolopoulou et al. (2017), picking-up requests or delivering requests could take longer than half the maximum route duration. This is a limitation of using a PDPTW with shipping requests that are cross-docked.

Chapter 7

Case Study at VZT

This chapter aims at answering the last two research questions:

5.How to set up the case study for VZT?

6. What results have been achieved for the case study at VZT?

To answer those questions, the data sets used in the case study are explained at first. These data sets are subjected to different cross-docking and direct shipping strategies. The applied strategies are set according to the literature and explained the subsequent sections. The data sets are modified to suit the above mentioned strategies and solved with the validated GLS approach. The results are compared, recommendations and conclusions are drawn at the end of the chapter.

7.1 Data Preparation

The first section of this chapter explains the data sets used in the case study. We decided to create five sets of 30 shipping requests. These five data sets reflect the actual problems that occur at VZT. The decision to create five data sets was made because smaller data sets guarantee the nearby optimal solution is found in a reasonable time frame. Several steps were taken to ensure that the data from VZT could be solved with the GLS. These are explained below. The data sets created by following these steps are shown in Appendix E.

1. First, the data from VZT was filtered by the busiest day, 07-09-2020. Five random selections of 30 requests were made from this day. These are the requests used in the case studies. The busiest day was chosen because it allows selection from a larger set of requests, and therefore the created data sets have less overlap in requests.

2. Secondly, the data had to be modified to load into the programmed GLS in python. All requests were split into a separate pick-up and delivery requests. These are then connected by a Pick-up Index and a Delivery Index. The Pick-up Index and Delivery Index are created by assigning a number to each pick-up and delivery location of all requests.

3. Next, the time windows were adjusted. The data from VZT consists of time indications in hours where the routes start at 06:00 PM. But the start time is set to 0 in the model. Therefore, all time units in the data sets were calculated in seconds and reduced by 18 hours to synchronize the start time.

4. Fourthly, the service time was added. This is done using the periods for loading and unloading defined in Chapter 3.

5. Lastly, for the case study, shipping requests are cross-docked according to the cross-dock strategies explained in Section 7.2. The cross-docked shipping requests are modified by splitting the requests. In addition, the time windows are modified and set as explained below.

Table 7.1: Characteristics five created data sets

	Mean Distance PD pair (km)	Mean available time PD pair (hr)	Range Demand	Total Demand	Unique Locations	Unique Pick-up	Unique Delivery
VZT_1	135	12.93	[1,34]	167	38	24	14
VZT_2	162	12.90	[1,43]	204	34	21	13
VZT_3	149	12.18	[1,31]	143	33	21	12
VZT_4	137	12.50	[1,34]	196	35	22	13
VZT_5	150	12.72	[1,31]	245	29	17	12

PD = Pick-up Delivery, km= kilometer, hr= hour

It is essential to know if the created data sets reflect reality. The characteristics of the five data sets are therefore analyzed and presented in Table 7.1. Various characteristics of the data sets are given and compared with the business analysis in Chapter 3. Besides, the geographical locations of the five instances are visualized and shown in Appendix F. All five instances are pretty similar concerning the location of the pick-up and delivery points which reflects real life situation of VZT.

Next, the parameters used in the case study are defined. They are determined based on the business analysis performed in Chapter 3. The set parameters are as follows.

Vehicle Capacity = 43 DC
Depot Locations = Venlo
Vehicle Speed = 1 kilometer per minute
Maximum Route Duration = 15 hours
Time Windows at Cross-dock = Latest arrival at Cross-dock 11:00 PM
Earliest departure of Cross-dock 00:00 AM

7.2 Cross-docking & Direct Shipping Strategies

As described in Chapter 2, several insight have been gained about the influence of characteristics on the effectiveness of cross-docking shipping requests. These insights are the basis for determining the strategies to be applied to the data sets. The different strategies applied in the case study are defined in the following subsections. In addition, different direct shipping strategies are described.

7.2.1 All cross-docking

The first strategy used in the case study is the All cross-docking strategy. All shipping requests are cross-docked and transported via Depot Venlo for this strategy. As explained in Chapter 1, all shipping requests are currently cross-docked at VZT to save costs and to minimize the use of vehicles. Therefore, this strategy is defined as the baseline which is used to compare the performance of the other strategies.

7.2.2 Time, speed & distance

The following strategy applied in the case study is cross-docking based on time, speed & distance. The strategy is based on the way Petersen and Ropke (2011) decided to cross-dock orders in their construction phase to gain an initial solution before applying a ALNS. As explained in Chapter 2 they based the decision to cross-dock on time and distance. We have established our strategy by adding a third criterion namely speed. Firstly, the decision not to cross-dock a shipping request is based on the available time. The available time is when an order must be picked up and then delivered. It was calculated from the set-up time, loading and unloading time, and travel time. If not enough time is available to transport via a cross-dock depot, the shipping request is transported by direct shipping.

Next, we calculated the required speed of the vehicles to deliver the shipping requests on time when using cross-docking. If this speed is higher than the determined 1 km/min, these requests are transported with the direct shipping strategy. This strategy is called the TIME strategy.

7.2.3 Shipping Quantity

The third strategy for cross-docking shipping requests is based on the shipping quantity. The strategy is based on the calculation of Gümüş and Bookbinder (2004) described in Chapter 2. The calculation of Gümüş and Bookbinder (2004) was used to determine the shipping quantity for which direct transport is more advantageous than cross-docking. The calculation of Gümüş and Bookbinder (2004) is applied on two scenarios (SHIP 1 & SHIP 2). One where only the fixed cost of the vehicle was included and a second where the driver's hourly rate was also included. Using vehicles is cheaper for scenario one, and more shipments will be selected for direct shipment. The case study examines whether these fixed costs impact transportation costs.

7.2.4 Network

The fourth and final strategy applied for the instances is based on the locations' network distribution. The assumption is made that when a request has a unique pick-up point and needs to go to a unique delivery point, it is better to transport it directly. This strategy is referred to as ONE. A second assumption is that when a delivery point is unique, it is better to transport it directly. Requests can be combined in pick-up routes and not be consolidated at the depot. This strategy is referred to as MANY. Both strategies, ONE & MANY, are based on previously found literature described in Chapter 2

7.2.5 Direct Shipping

In addition to the cross-dock strategies, different shipping strategies are examined. The results can be used to evaluate the cost difference between cross-dock and direct shipping strategies. Direct transport does not use the depot for cross-docking. Hence it is of interest for VZT to see whether the costs saved with direct shipping outweigh the depot costs.

The direct shipping strategy was calculated in three ways. First,the data sets are taken as is without imposing additional criterion, this first Direct Shipping strategy is named DS1. Next, the time windows of the data set are adjusted (DS2). This is done by not allowing retrieval and delivery all day but allowing this to be the same as for cross-docked requests. The time windows are defined as follows.

$$\begin{aligned} \text{Pick-up}: &\quad 18:00\ \text{PM} - 23:00\ \text{PM} \\ \text{Delivery}: &\quad 00:00\ \text{AM} - \text{maximum delivery time} \end{aligned}$$

As a result, the pick-up and delivery operations must also be performed in a smaller time window for the direct shipping strategy.

Finally, the direct shipping strategy is calculated with a higher set-up time (DS3). This is the third direct shipping strategy applied because all requests are translated to separate pick-up and delivery nodes. Meaning that multiple nodes are created that could have the same coordinates. A location can be served by multiple vehicles, which is not customer-friendly. The set-up time is increased to 30 minutes to see if serving same locations multiple times is reduced.

7.2.6 Overview Strategies applied in the Case Study

All strategies are explained, the results of the strategies applied to the data instances are presented in Section 7.3. Below in Table 7.2, all different strategies listed wherefore solutions are obtained with the GLS approach for the PDPTW problem. The defined strategies are used separately but also in combination with each other. However, the strategies SHIP 1, SHIP 2, ONE & MANY are always combined with TIME. This is because we wanted to avoid that requests can not be scheduled. Table 7.2 shows all strategies and their combinations analyzed. The number of runs performed are the 13 different strategies executed for five different data sets.

Table 7.2: Strategies applied in Case study

Single	Double	Triple
All	TIME + SHIP 1 = TS1	TIME + SHIP 1 + ONE = TS1O
TIME	TIME + SHIP 2 = TS2	TIME + SHIP 1 + MANY = TS1M
DS1	TIME + ONE = TO	TIME + SHIP 2 + ONE = TS2O
DS2	TIME + MANY = TM	TIME + SHIP 2+ MANY = TS2M
DS3		

7.3 Current Scenario

As earlier mentioned is VZT cross-docking all the shipping requests to a cross-dock facility to consolidate the freight and to minimize the number of vehicles. A baseline is set, so the obtained results can be compared to the current situation. The baseline for this research is the strategy whereby all shipping requests are split and transported via the cross-docking facility. The results of the five data sets used to cross-dock all shipping requests are shown in Table 7.3. The columns indicate: the number of vehicles used (NV), scheduling duration (SD), travel cost (TC), dropped requests (DR), the found objective with penalties for dropped requests & objective without the penalties.

Table 7.3: Solutions ALL Cross-Docking strategy

Current Scenario						
Instance	NV	SD	TC	DR	Objective with penalties	Objective
VZT_1	4	3,207	1,893	0	6,283	6,283
VZT_2	4	3,424	2,058	2	4,006,551	6,551
VZT_3	4	3,330	1,908	2	4,006,239	6,239
VZT_4	5	4,094	2,454	0	7,919	7,919
VZT_5	5	4,245	2,369	2	4,007,837	7,837

Table 7.4: Solutions TIME cross-docking strategy

Time Scenario					
Instance	NV	SD	TC	OS	Objective
VZT_1	4	3,302	1,902	1	6,279
VZT_2	5	4,015	2,325	3	7,810
VZT_3	4	2,986	1,661	3	6,012
VZT_4	5	4,003	2,440	1	7,902
VZT_5	6	4,890	2,962	2	9,483

In Table 7.3 it is seen that three high objective values occur in the obtained solutions. These high objective values are associated with the dropped requests. The solution contains dropped requests due to the fixed time windows associated with the nodes and the available time that the shipping requests need to be transported and cross-docked.

For this study, the time windows of cross-docking have been defined as explained in Chapter 3. However, these shipping requests could be cross-docked because time windows are less strict in reality. To still get a baseline, without solutions with dropped requests, the data sets were subjected to the time, speed, distance cross-docking strategy, explained in Chapter 7. Several requests are selected for direct shipping, by applying the time, speed & distance strategy on the five data sets.

In Appendix G maps of the Netherlands are visualized for each data set showing the nodes selected for Cross-docking and Direct Shipping, the map of VZT_2 is shown in Figure 7.1. It is notable that for each of the five data sets, the node placed in Naaldwijk is selected for direct transport. This means that for this research it is hard to cross-dock shipping requests with this delivery location for requests with the set time windows.

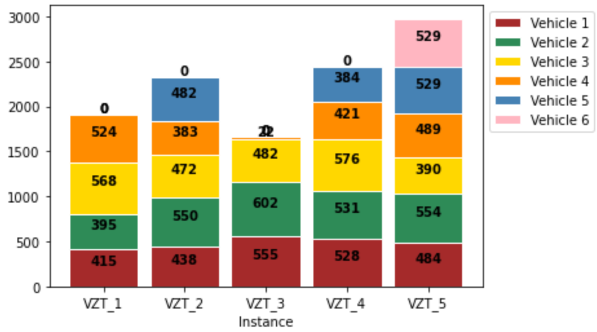
(a) Dropped Nodes VZT2

(b) TIME Solutions VZT2 2

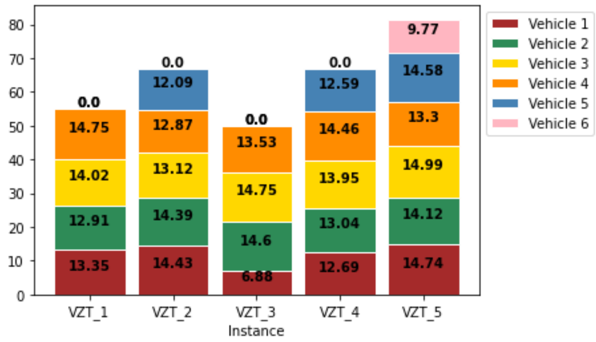
Figure 7.1: Solution VZT2

The number of requests selected for Direct Shipping, and therefore out selected for cross-docking are given in Table 7.4 per instance in the column OS (= out selected). In addition, after using the rule time, speed & distance, no dropped requests occur in the obtained solutions. It is logical that this rule should always be applied. Namely, if not enough time is available to cover the distance, shipping requests can never be transported through a cross-dock location. This is in line with the reasoning of Petersen and Ropke (2011).

Lastly, the number of used vehicles and the number of kilometers they traveled in a period are analyzed. Figure 7.2(a) shows the amount kilometers per vehicle, and Figure 7.2(b) shows the number of hours that the vehicles were operating. What stands out is that for one vehicle, for instance, VZT_3, only 22 kilometers is driven. This is much lower than the other vehicles for the obtained solution of VZT_3. The rest of the vehicles drive between 384 - 602 kilometers in a route. The time ranges are between 12.87 - 14.99 hours. An exception is seen for a vehicle for VZT_3 that took 6.88 hours and for VZT_5, a vehicle that took 9.77 hours. The outliers for the distance and time in service could indicate that if a different distribution strategy is applied, the number of vehicles can be reduced. This is in line with the goal of VZT, reducing the number of vehicles.



(a) Distance per vehicle TIME solution



(b) Time per vehicle TIME solution

Figure 7.2: Vehicles time and distances by applying TIME strategy

7.4 Results - Combinations of strategies

7.4.1 TS1, TS2, TO & TM

In this second section, we compare the results of the TIME strategy with the results of combined strategies namely shipping quantity + TIME (TS1 TS2) and network + TIME (TM TO), as explained in Section 7.2. The number of shipping requests not selected for cross-docking but for direct shipping are shown in Table 7.5.

Table 7.5: No. Shipping requests selected for Direct Shipping per Cross-Docking strategy TS1, TS2, TO & TM

Instance	TS1	TS2	TO	TM
VZT_1	6	3	3	5
VZT_2	8	5	4	7
VZT_3	3	3	6	6
VZT_4	5	3	2	5
VZT_5	7	4	3	6

Subsequently, the solutions for the data sets are calculated and presented in Table 7.6. For none of the data sets, cross-docking based on one of the two mapping strategies, TO or TM, was cost-efficient. For two of the five data sets, it was best to apply TS1; this is also the case for the TS2 strategy. For data set VZT_3, cross-docking based on the time, speed & distance would be best.

The results of the case study show value in including shipping quantity when deciding cross-dock. This is important for VZT to consider. The case study shows that cost savings can be achieved when this is included in the decision making.Although the differences are minor in the case study but a significant cost savings can be expected in real life considering larger data pool. On a larger scale, it may be more significant cost savings. More requests need to be transported daily at VZT than the number taken for the instances in this case study.

Figure 7.3 shows the number of vehicles used for establishing the routing solutions. Promising is that the minimal objective for data set VZT_2 shows a decrease in the number of vehicles used by applying strategy TS1 compared to the other objective values obtained with the other strategies. Besides, for the data set VZT_4 there is also a difference in the number of vehicles used. The decrease in the number of vehicles needed to set routes by not cross-docking everything is an important understanding. This suggests that the use of vehicles can be reduced by not cross-docking everything. This is in contrast to what VZT is doing now, which is cross-docking all shipping requests.

Table 7.6: Objective Values Cross-docking for TS1, TS2, TO & TM

Instance	TIME	TS1	TS2	TO	TM
VZT_1	6,279	6,375	**6,212**	6,279	6,246
VZT_2	7,810	**6,712**	7,673	8,027	7,879
VZT_3	**6,012**	6,178	6,178	6,293	6,293
VZT_4	7,902	6,500	**6,480**	7,934	6,532
VZT_5	9,483	**9,227**	9,404	9,446	9,445

In addition to the objective values, obtained distances and times for different cross-docking strategies are presented in Table 7.7. The strategies were compared based on distance and time. The lowest value for both distance and time is indicated in bold for each instance. For three of the five cases, the distance and time were the lowest value for the best-fitted strategy. However,

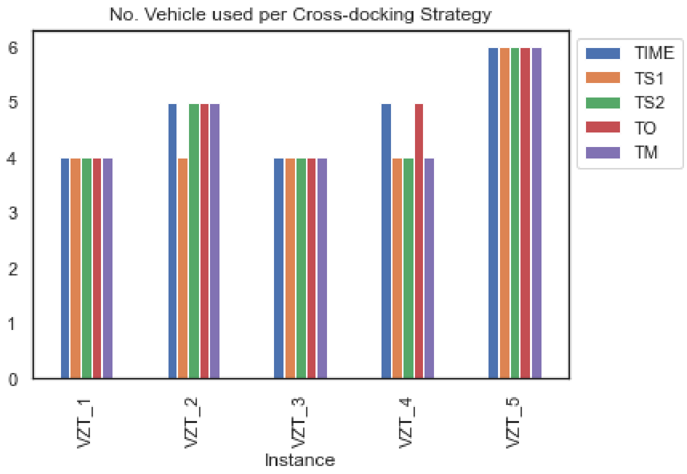


Figure 7.3: Number of Vehicles used applying
the different cross-docking strategies TS1, TS2, TO & TM

for two of the cases, this differs. The minimum time or distance for two instances was not found for the lowest objective value. This has to do with the fact that when kilometers are reduced by using a cross-dock, the service time is increased because the shipping requests must be loaded and unloaded multiple times. If the objective function is changed, other route solutions can be found by minimizing only kilometers or time.

Table 7.7: Distance and Time
per Cross-Docking strategy TIME, TS1, TS2, TO & TM

	TIME		TS1		TS2		TO		TM	
Instance	Distance	Time	Distance	Time	Distance	Time	Distance	Time	Distance	Time
VZT_1	1,902	3,302	1,995	3,381	**1,849**	3,317	1,902	3,301	1,883	**3,152**
VZT_2	2,325	4,015	2,259	**3,459**	2,233	3,800	**2,230**	4,210	2,401	4,202
VZT_3	**1,661**	**2,986**	1,823	3,152	1,823	3,152	1,934	3,270	1,934	3,271
VZT_4	2,440	4,003	2,073	3,398	**2,056**	**3,373**	2,457	4,124	2,070	3,376
VZT_5	2,962	4,890	**2,768**	**4,605**	2,905	4,887	2,942	4,920	2,930	4,891

7.4.2 TS1O + TS1M + TS2O + TS2M

This second subsection combines the strategies with each other. In Table 7.8, all possible combinations are given. Also, the number of shipping requests selected for direct shipping are shown in Table 7.8. The solutions obtained for these combinations are presented in table 7.9. Moreover, the best strategy resulted for the data sets in the previous subsection 7.2 is also presented with their objective value in Table 7.9.

Looking at the results presented in Table 7.9 it is seen that for three of the five data sets, the lowest objective value was found already in the previous sub-section. Only for VZT_2 and VZT_5 a better solution is found. For both, strategy TS1 performs better. For VZT_2 TS1M is better, and for VZT_5 this is the TS1O. When applying the TS1M strategy, it is seen that compared to TS1O, TS2O & TS2M a reduction takes place in the cost. This has to do with reducing the number of vehicles needed in the solution.

Also, more attention is given to the distances and time for the obtained solutions, presented in Table 7.10. We can conclude that time and distance again do not have the lowest value for the best strategy for these applications.

Table 7.8: No. Shipping requests selected for Direct Shipping per Cross-docking strategy TS1O, TS1M, TS2O & TS2M

Instance	TS1O	TS1M	TS2O	TS2M
VZT_1	6	8	4	6
VZT_2	9	11	6	8
VZT_3	6	6	6	6
VZT_4	6	8	4	6
VZT_5	8	11	5	8

Table 7.9: Objective Values for the Cross-docking TS1O, TS1M, TS2O & TS2M

Instance	Best Strategy	Best Objective	TS1O	TS1M	TS2O	TS2M
VZT_1	TS2	**6,212**	6,375	6,288	6,269	6,301
VZT_2	TS1	6,712	7,638	**6,348**	7,674	7,683
VZT_3	TIME	**6,012**	6,293	6,293	6,293	6,293
VZT_4	TS2	**6,480**	6,514	7,773	6,571	6,484
VZT_5	TS1	9,227	**9,205**	9,283	9,342	9,331

Table 7.10: Distances and Time per Cross-Docking strategy TS1O, TS1M, TS2O & TS2M

Instance	TS1O		TS1M		TS2O		TS2M	
	Distance (km)	Time (min)	Distance (km)	Time (min)	Distance (km)	Time (min)	Distance (km)	Time (min)
VZT_1	1,905	3,381	1,917	3,378	**1,900**	**3,211**	1,938	3,246
VZT_2	2,207	3,812	**1,913**	**3,207**	2,235	3,793	2,242	3,855
VZT_3	**1,934**	**3,270**	**1,934**	**3,270**	**1,934**	**3,270**	**1,934**	**3,270**
VZT_4	2,075	**3,183**	2,360	4,023	2,132	3,394	**2,046**	3,400
VZT_5	**2,748**	**4,223**	2,823	5,002	2,868	4,578	2,865	4,559

7.5 Direct Shipping (DS1, DS2 & DS3)

Lastly, three different Direct Shipping strategies are applied to the gain solutions for the data sets. As earlier mentioned, locations can be visited multiple times. To counteract this, the setup time is set to 30 minutes instead of 15 minutes (DS3). Besides, the time windows are changed for a second strategy (DS2). The obtained objective values for the three different direct shipping scenarios are given in Table 7.11, and the number of vehicles is given in Table 7.12.

Table 7.11: Objective Values different Direct Shipping strategies

Instance	DS1	DS2	DS3
VZT_1	6,110	6,198	6,295
VZT_2	6,240	8,336	6,464
VZT_3	4,875	5,929	6,135
VZT_4	6,252	7,343	6,516
VZT_5	8,195	9,112	9,295

Table 7.12: No.Vehicle Used Direct Shipping

Instance	DS1	DS2	DS3
VZT_1	4	4	4
VZT_2	4	6	4
VZT_3	3	4	4
VZT_4	4	5	4
VZT_5	5	6	6

Evaluating the results of the direct shipping scenarios, it is first concluded that the direct shipping strategy with no additional restrictions is most cost-effective for all five data sets. Next is seen that for the other two scenarios, a higher objective value is found and that also more vehicles are used. Between DS2 and DS3, it depends on which has the lowest objective. The obtained solutions for the direct shipping scenarios are graphically shown in Appendix H. DS2 shows that more vehicles must be used than DS1 & DS3. This is seen in the route visualization in Appendix H, and in Table 7.13. By setting the time windows in DS2, a vehicle has to wait between pick-up and delivery, thus requiring more vehicles in the time available.

The mean distances and times of the vehicles for the direct shipping scenarios are also analyzed. The mean distances and meantime traveled are the lowest values seen for the DS2 scenario in four cases. This has to do with the fact that a vehicle can serve fewer locations because of the tighter time windows; therefore, more vehicles are used, and the operations are spread over the vehicles. Besides, more vehicles are used for this scenario. The locations are more spread over the vehicles, leading to a lower average distance and time per vehicle.

Table 7.13: Kilometer and Time per vehicle Direct Shipping

Instance	Variable	DS1		DS2		DS3	
		Mean	Range	Mean	Range	Mean	Range
VZT_1	Distance (km)	**441**	[364, 568]	458	[394, 511]	446	[394, 511]
	Time (hrs)	11.60	[8.85, 13.93]	11.83	[10.09, 13.31]	**11.40**	[10.09, 13.31]
VZT_2	Distance (km)	461	[408, 507]	**317**	[100, 505]	466	[408, 507]
	Time (hrs)	12.00	[11.33, 13.33]	**8.92**	[6.46, 13.32]	13.59	[11.33, 13.33]
VZT_3	Distance (km)	512	[406, 617]	**393**	[144, 523]	395	[241, 520]
	Time (hrs)	13.62	[12.93, 14.98]	**11.10**	[6.53, 13.65]	11.97	[8.61, 14.24]
VZT_4	Distance (km)	460	[406, 547]	**294**	[106, 528]	470	[395, 542]
	Time (hrs)	12.43	[10.69, 14.01]	**10.26**	[6.43, 12.83]	13.38	[11.06, 14.86]
VZT_5	Distance (km)	544	[436, 721]	443	[378, 493]	**440**	[376, 493]
	Time (hrs)	12.75	[10.15, 14.95]	**10.82**	[9.46, 12.95]	12.52	[10.28, 14.86]

Table 7.14: Kilometers and times for the best Cross-Docking strategy and for the direct shipping strategies

Instance	Best CD Strategy	Values for Best CD Strategy		DS1		DS2		DS3	
		Distance (km)	Time (min)	Distance (km)	Time (min)	Distance (km)	Time (min)	Distance (km)	Time (min)
VZT_1	TS2	1,849	3,317	**1,765**	**2,785**	1,832	2,840	1,782	3,005
VZT_2	TS1M	1,913	3,207	**1,843**	**2,880**	1,924	3,573	1,863	3,211
VZT_3	TIME	1,661	2,986	**1,536**	**2,451**	1,572	2,665	1,578	2,873
VZT_4	TS2	2,056	3,373	**1,838**	**2,982**	1,926	3,079	1,877	3,260
VZT_5	TS1O	2,748	4,223	2,723	**3,827**	2,655	3,895	**2,637**	4,105

Lastly, the direct shipping strategy results are compared with the best found cross-dock strategy per data set. The direct shipping strategy without additional requirements (DS1) was seen as the strategy with the least cost. Also, compared to the best objective values after using the cross-dock strategies, the DS1 strategy is best overall for all five instances. Direct shipping is probably the most advantageous due to several reasons. First of all, it can be because cross-docking takes too much time, so the reduction of cost by the fewer kilometers that need to be driven is not in proportion with the extra costs for the time involved by cross-docking. Table 7.14 confirms this suspicion. However, the table also shows that no kilometers are saved with cross-docking compared to direct transportation strategies. This may be due to the placement of the depot, which is not centrally located, as would be best according to Nikolopoulou et al. (2017). For VZT, this could mean that cross-docking cost savings increase by moving operations to another depot.

7.6 Concluding the Results

This subsection concludes which transportation strategy fits best according to the case study. As described, different cross-dock as well as direct shipping strategies were applied to the data sets. Table 7.15 shows the results (objective values) of the best strategy found per data sets as well as the values for TIME, DS1, DS2 and DS3 strategies.

Table 7.15: Comparison objective values

Instance	Best strategy	Best Objective value	TIME	DS1	DS2	DS3
VZT_1	TS2	6,212	6,279	6,110	6,198	6,295
VZT_2	TS1M	6,348	7,810	6,240	8,336	6,464
VZT_3	TIME	6,012	6,012	4,875	5,929	6,135
VZT_4	TS2	6,480	7,902	6,252	7,343	6,516
VZT_5	TS1O	9,205	9,483	8,195	9,112	9,295

First, it can be concluded that cross-docking all shipping requests is impossible for the five data sets of the case study due to the fixed time windows set for cross-docking. Unfortunately, this is a limitation of the study. In reality, VZT sometimes shifts these time windows slightly so that it does become possible to cross-dock all requests. Next, the instances were subjected to the TIME strategy. No shipping requests were dropped for these solutions, and feasible solutions were obtained.

Thirdly, the data instances were subjected to the strategies TS1, TS2, TO & TM explained in Section 7.2. Using the strategies the objective values were decreased for four of the five instance. For instances VZT_1 and VZT_4 it was best to apply the TS2 strategy. This strategy included time, distance and speed and the shipping quantity calculation for the higher cost per vehicle. In addition, for instance VZT_4 applying this strategy led to a lower number of vehicles used. For VZT_2 and VZT_5 it was best to apply the TS1 strategy. Again the time, distance and speed were included in the strategy, only this time the shipping quantity calculation for the lower cost per vehicle was taken into account. Also, for VZT_2, it is seen that there was a reduction in the use of the number of vehicles. Next, the cross-dock strategies were combined and the instance were subjected to the TS1O, TS1M, TS2O & TS2M scenario's. For three of the five instances no advantages was seen. However, for VZT_2 and VZT_5 better solutions were found. Both for strategy TS2 in combination with one of the two network strategies.

Based on the results, it can be concluded that in the applied cross-docking strategies for the case study, shipping quantity impacted costs in four out of five cases. Moreover, fewer vehicles had to be used for direct shipping compared to cross-docking all shipping requests. Based on the outcome of the case study, VZT should set up its cross-docking strategy based on the shipping quantity. An approach can be to ship larger quantities directly, thus minimizing number of vehicles used instead of cross-docking all their shipping requests.

The case study results show that most costs and vehicles can be saved by using direct shipment. For VZT, this means that direct shipment would lead to the least number of vehicles required. In reality, the operations and costs at the depot Venlo can also be reduced.

Chapter 8

Conclusion and Recommendations

The results have been briefly discussed in the previous Chapter. In this Chapter, the research questions are repeated after an answer is given to the main research question. Second, recommendations and further research are discussed.

8.1 Conclusions

The research questions are repeated followed by a brief answer:

1. What studies are found in literature that provide insights for the problem definition of VZT?

In the literature, two types of insights were gathered. Firstly model formulations were found for routing problems with cross-docking or transfer opportunities. These routing problems are in line with the problem of VZT. However, no existing software exists in practice to solve such problems. Another approach needs to be investigated to solve such routing problems. The gap found for this research is how a PDPTW can be used to solve problems PDP-CD. It is found that multiple software and solution approaches exist for solving the PDPTW.

Secondly, different characteristics were found that influence the cost-effectiveness of cross-docking. Characteristics that had influence were Time and distance (Petersen & Ropke, 2011), Shipping Quantity (Gümüş & Bookbinder, 2004), Vehicle capacity(Nikolopoulou et al., 2017), Neighbor locations (Nikolopoulou et al., 2017) and Depot location (Nikolopoulou et al., 2017).

2.What is the current situation of VZT in terms of the promising cross-dock characteristics?

After the insights gathered in answering research question 1, the current situation at VZT is examined. Firstly the scope of VZT was more defined. Next, attention was given to the promising cross-dock variables in the business analysis. In addition, cost factors are identified. The business analysis shows that cross-docking seems effective for VZT. Especially looking at the NNI and PI formulated by Nikolopoulou et al. (2017). However, the depot location in Venlo is not entirely central, and the costs are high. Due to the non-centralized location, cross-docking can be less advantageous.

3. How to formulate the model of the routing problem of VZT?

The next step was to define a model that fits the case of VZT. From the literature was concluded which model best fits VZT. Two model formulations were made as an answer to the third research question. The reason for the two formulations is because, in theory, the formulation of PDP-CD best fits towards VZT. However, in practice, a PDPTW model is used. For applying the PDPTW model, first, the cross-docking decision is performed, and then the routes are calculated. The routing model for this second approach is a PDPTW model formulated by Parragh et al. (2008). For this model, a heuristic was created the GLS, and explained in more detail in Chapter 5.2.

4. How validate the model and approaches formulated in research question 3?

In this section, the models formulated in question 3 were tested using benchmark data. The first formulated model the PDP-CD based on the models of Rais et al., 2014, Voigt and Kuhn (2021) and Sampaio et al. (2020) was solved using self-created data, attached in the Appendix D. The results were evaluated using the PDPTW model formulated. Both solutions were calculated to optimality with Gurobi and programmed in Python. It is concluded that the PDP-CD model seems correct but that this needs to be ensured by running more tests.

Secondly, the GLS approach was validated. The GLS was tested using three benchmark data sets. First, the GLS was tested to see if a PDPTW problem properly can be solved. Validating the approach was done with benchmark data of Li and Lim (2003). Results of the benchmark data show that the PDPTW can solve the problem properly. Minor differences are seen because the programmed model needs more time to solve.

Next, it was tested if the GLS can be used for problems with cross-docked requests and by fixing the cross-docking time windows. This was done by two benchmark data sets of Nikolopoulou et al. (2017). During the validation, it appears that using the GLS for solving problems with cross-docking translated to a PDPTW is hard. Only solutions can be found for larger time frames. Unfortunately, with the larger time frames still, a difference is seen from the results obtained with the GLS and the results from the literature.

5.How to set up the case study for VZT?

6. What results have been achieved for the case study at VZT

For these two research questions, five data sets have been created that represent the reality at VZT. In addition, several cross-docking strategies were defined, which were tested in the case study. These cross-docking strategies are determined according to the found literature in Chapter 2. Strategies that are set were for time and distance (Petersen & Ropke, 2011), two scenarios are determined for the shipping quantity (Gümüş & Bookbinder, 2004), and finally, two strategies were created based on the network (Nikolopoulou et al., 2017).

Evaluating the results in the last Chapter 7 it was first seen that cross-docking based on the shipping quantity was best in four cases. Larger shipping requests take more time to load and unload, so the cost savings on kilometers do not outweigh the extra costs calculated in time. Subsequently, the datasets were subjected to different direct shipping strategies. The lowest objective values have been found for the direct shipping strategy. In addition, the values of distance and time are also the lowest for these solutions. This is in line with the research of Nikolopoulou et al. (2017) which suggests that when the depot is not centrally located, cross-docking is not advantageous.

The case study results show that most costs and vehicles can be saved by using direct shipment. For VZT, this means that direct shipment would lead to the least number of vehicles required. In reality, the operations and costs at the depot Venlo can also be reduced.

How can VZT standardize its cross-dock decision in such a way that they optimize their operations?

It has been concluded that cross-docking can be of value in reducing the cost of transportation (Nikolopoulou et al., 2017). Therefore, in this study, several strategies were applied to VZT's situation to find out which strategies fit their situation best. However, the case study of VZT shows that cross-docking is not advantageous compared to the outcomes for direct transport. On several aspects, the outcomes do not correlate with previous findings in the literature. Based on the NNI and PI, and the large time windows at VZT it was assumed that cross-docking would be advantageous. However, the depot Venlo was not centrally located. Moreover, in literature, instances with multiple clusters for pickup and delivery cross-docking were advantageous. However, VZT has only one cluster for pickup and one cluster for delivery. Lastly, it can be questioned if this implementing the direct shipping strategy is realistic in practice. In the case study, it is assumed that locations can be visited more than once. In reality, this could lead to a higher probability of damage on the customer's side. Besides, it is not customer-friendly to visit them multiple times when this is unnecessary.

8.2 Recommendations & Limitations & Future Research

The concluded strategy that is most cost-effective is the direct shipping strategy. The case study showed that fewer vehicles are used when implementing the direct strategy, the number of kilometers is reduced, and the least amount of time is required. However, the question is whether it is realistic to apply this strategy in practice for VZT. Indeed, a reduction in vehicles, kilometers, and time can be achieved. In addition, if VZT chooses to apply only direct shipment, costs can be reduced by eliminating the Venlo Depot, or giving the depot other purposes. However, it must be kept in mind that the vehicles depart from this depot, and other operations occur.

In addition, in this study, we chose to investigate whether existing software from VZT can be used to solve cross-docking problems with fixed time windows. As concluded, this is possible for problems with a larger time frame but still challenging and not solved to optimality. As a result, it is not known for the case study if cross-docking is not advantageous. What is known is that the way it is solved now was not advantageous. Therefore, it is not recommended that VZT apply the direct strategy, mainly because this study tolerated multiple visits for locations is less customer-friendly.

What is recommended for VZT is not to cross-dock all shipping requests but instead focus more on the shipping quantity by deciding to cross-dock requests. In the case-study was seen that the shipping quantity was influencing the costs for the different cross-dock strategies. When including this variable in the decision for cross-docking, better solutions were found than cross-docking all requests. The case study shows that small costs can be saved on this. However, translated yearly, this may involve larger amounts for VZT

In addition other recommendation are defined and listed below:

- One limitation of this research is fixing the time windows for cross-docking. The results for method validation already show that it is difficult to get the optimal results. A recommendation flowing from this is that VZT should investigate for multiple fixed time windows if the strategies would obtain better solutions.

- Secondly is assumed that only vehicles with a capacity of 43 DC were used. By enlarging the vehicle capacity it is concluded by Nikolopoulou et al. (2017) that more advantageous is seen in cross-docking compared with direct shipping. A recommendation for future research is to see if by using larger vehicles for the transport from cross-dock to delivery points impacts the solution whether or not cross-docking is advantageous.
- Thirdly, in this case study, the Venlo depot is seen as a cross-dock depot. The depot acts as the starting point of the cars and as a cross-dock location. Because the depot is not centrally located, which is seen as a requirement for cost-effectiveness for cross-docking. Therefore the third recommendation given to VZT is to investigate whether its cross-dock operations could be moved from the Venlo depot to the Ammerzoden depot. Firstly, this would enable us to determine whether cross-docking would be advantageous for this more centralized depot. In addition, as a next step, it could be examined whether it would be profitable to keep the Venlo depot.
- A final recommendation for VZT is to look further into the decision-making for cross-docking based on the shipping quantity. Only two scenarios were considered in this study. In addition, only the cost of the vehicle, kilometers, and cross-docking were considered. However, it is expected that time is also of influence and deserves more attention.

Further research should be done for using PDPTW software for PDP-CD problems. This study tried to apply a PDPTW solution approach by fixing the time windows. We can look at other ways to determine these time windows in the future. Besides, it could be investigated if other constraints can be set that enforces operations to take place one after the other so that no time windows need to be determined.

Finally, further research can be done to expand the shipping quantity formula of Gümüş and Bookbinder (2004). At the moment, it does not include costs for the time in the calculation. This research has shown that this cost item is also essential to include. In addition, it may be relevant that in the formulation of Gümüş and Bookbinder (2004), something can be included about locations that are close by, which may also influence the cross-docking decision.

Bibliography

Alsheddy, A., Voudouris, C., Tsang, E. P. & Alhindi, A. (2018). Guided local search.

Buijs, P., Vis, I. F. & Carlo, H. J. (2014). Synchronization in cross-docking networks: A research classification and framework. *European Journal of Operational Research*, *239*(3), 593–608.

Cortés, C. E., Matamala, M. & Contardo, C. (2010). The pickup and delivery problem with transfers: Formulation and a branch-and-cut solution method. *European Journal of Operational Research*, *200*(3), 711–724.

Danloup, N., Allaoui, H. & Goncalves, G. (2018). A comparison of two meta-heuristics for the pickup and delivery problem with transshipment. *Computers & Operations Research*, *100*, 155–171.

de Keizer, M. (2015). *Logistics network design & control: Managing product quality in a blooming sector* (Doctoral dissertation). Wageningen University.

Dondo, R., Méndez, C. A. & Cerdá, J. (2009). The supply-chain pick-up and delivery problem with transshipments. *Computer aided chemical engineering* (pp. 1009–1014). Elsevier.

Esmizadeh, Y. & Mellat Parast, M. (2021). Logistics and supply chain network designs: Incorporating competitive priorities and disruption risk management perspectives. *International Journal of Logistics Research and Applications*, *24*(2), 174–197.

Ghilas, V., Cordeau, J.-F., Demir, E. & Woensel, T. V. (2018). Branch-and-price for the pickup and delivery problem with time windows and scheduled lines. *Transportation Science*, *52*(5), 1191–1210.

Godart, A., Manier, H., Bloch, C. & Manier, M.-A. (2018). Milp for a variant of pickup & delivery problem for both passengers and goods transportation. *2018 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 2692–2698.

Godart, A., Manier, H., Bloch, C. & Manier, M.-A. (2019). Hybrid metaheuristic for the pickup and delivery problem designed for passengers and goods transportation. *IFAC-PapersOnLine*, *52*(13), 2584–2589.

Google. (n.d.). 7.6. guided local search (gls). https://acrogenesis.com/or-tools/documentation/user_manual/manual/metaheuristics/GLS.html#rl-real-conventions

Guastaroba, G., Speranza, M. G. & Vigo, D. (2016). Intermediate facilities in freight transportation planning: A survey. *Transportation Science*, *50*(3), 763–789.

Gümüş, M. & Bookbinder, J. H. (2004). Cross-docking and its implications in location-distribution systems. *Journal of business Logistics*, *25*(2), 199–228.

Hoos, H. & Stutzle, T. (2005). Stochastic local search: Foundations and applications morgan kaufmann. *San Francisco.*

Hosseini, S. D., Shirazi, M. A. & Karimi, B. (2014). Cross-docking and milk run logistics in a consolidation network: A hybrid of harmony search and simulated annealing approach. *Journal of Manufacturing Systems*, *33*(4), 567–577.

Kerivin, H., Lacroix, M., Mahjoub, A. R. & Quilliot, A. (2008). The splittable pickup and delivery problem with reloads. *European Journal of Industrial Engineering*, *2*(2), 112–133.

Li, H. & Lim, A. (2003). A metaheuristic for the pickup and delivery problem with time windows. *International Journal on Artificial Intelligence Tools*, *12*(02), 173–186.

Masson, R., Lehuédé, F. & Péton, O. (2013). Efficient feasibility testing for request insertion in the pickup and delivery problem with transfers. *Operations Research Letters*, *41*(3), 211–215.

Masson, R., Ropke, S., Lehuédé, F. & Péton, O. (2014). A branch-and-cut-and-price approach for the pickup and delivery problem with shuttle routes. *European Journal of Operational Research*, *236*(3), 849–862.

Mitrović-Minić, S. & Laporte, G. (2006). The pickup and delivery problem with time windows and transshipment. *INFOR: Information Systems and Operational Research*, *44*(3), 217–227.

Mues, C. & Pickl, S. (2005). Transshipment and time windows in vehicle routing. *8th International Symposium on Parallel Architectures, Algorithms and Networks (ISPAN'05)*, 6–pp.

Nikolopoulou, A. I., Repoussis, P. P., Tarantilis, C. D. & Zachariadis, E. E. (2017). Moving products between location pairs: Cross-docking versus direct-shipping. *European Journal of Operational Research*, *256*(3), 803–819.

O'Kelly, M. E. & Miller, H. J. (1994). The hub network design problem: A review and synthesis. *Journal of Transport Geography*, *2*(1), 31–40.

Parragh, S. N., Doerner, K. F. & Hartl, R. F. (2008). A survey on pickup and delivery models part ii: Transportation between pickup and delivery locations. *Journal für Betriebswirtschaft*, *58*(2), 81–117.

Petersen, H. L. & Ropke, S. (2011). The pickup and delivery problem with cross-docking opportunity. *International Conference on Computational Logistics*, 101–113.

Porter, M. E., Ramirez-Vallejo, J. & Van Eenennaam, F. (2011). The dutch flower cluster. *Harvard Business School Strategy Unit Case*, (711-507).

Qu, Y. & Bard, J. F. (2012). A grasp with adaptive large neighborhood search for pickup and delivery problems with transshipment. *Computers & Operations Research*, *39*(10), 2439–2456.

Rais, A., Alvelos, F. & Carvalho, M. S. (2014). New mixed integer-programming model for the pickup-and-delivery problem with transshipment. *European Journal of Operational Research*, *235*(3), 530–539.

Royo, B., Fraile, A., Larrodé, E. & Muerza, V. (2016). Route planning for a mixed delivery system in long distance transportation and comparison with pure delivery systems. *Journal of computational and applied mathematics*, *291*, 488–496.

Sampaio, A., Savelsbergh, M., Veelenturf, L. P. & Van Woensel, T. (2020). Delivery systems with crowd-sourced drivers: A pickup and delivery problem with transfers. *Networks*, *76*(2), 232–255.

Santos, F. A., Mateus, G. R. & Da Cunha, A. S. (2013). The pickup and delivery problem with cross-docking. *Computers & Operations Research*, *40*(4), 1085–1093.

Savelsbergh, M. W. & Sol, M. (1995). The general pickup and delivery problem. *Transportation science*, *29*(1), 17–29.

Shang, J. S. & Cuff, C. K. (1996). Multicriteria pickup and delivery problem with transfer opportunity. *Computers & Industrial Engineering*, *30*(4), 631–645.

Steen, M. et al. (2010). A world of flowers: Dutch flower auctions and the market for cut flowers. *Journal of Applied Horticulture*, *12*(2), 113–121.

Takoudjou, R. T., Deschamps, J.-C. & Dupas, R. (2012). A mip formulation for the pickup and delivery problem with time window and transshipment. *IFAC Proceedings Volumes*, *45*(6), 333–338.

Thangiah, S. R., Fergany, A. & Awan, S. (2007). Real-time split-delivery pickup and delivery time window problems with transfers. *Central European Journal of Operations Research*, *15*(4), 329–349.

Voigt, S. & Kuhn, H. (2021). Crowdsourced logistics: The pickup and delivery problem with transshipments and occasional drivers. *Networks*.

Voudouris, C., Tsang, E. P. & Alsheddy, A. (2010). Guided local search. *Handbook of metaheuristics* (pp. 321–361). Springer.

Wolfinger, D. (2021). A large neighborhood search for the pickup and delivery problem with time windows, split loads and transshipments. *Computers & Operations Research*, *126*, 105110.

Appendix A

Logistic Equipment Flori-Culture Industry

Figure A.1: Deense Kar

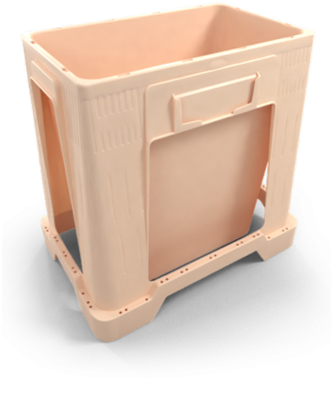


Figure A.2: Fust

Appendix B

Shipping Requests Data

This appendix explains the historical data from VZT used in this study. The historical data collected are the shipping request of VZT of the year 2020. The data consists of all shipping requests of VZT plus some side service requests that VZT also is offering. Section 3.1 indicates the scope of the study. The historical data gained for the research need to be cleaned and specified to the scope. Therefor is below a description given, step by step, for cleaning the data.

1. Dropping Requests for Day Transportation
As explained are only shipping requests taken into account that need to be performed during the evening/ night.

2. Dropping Requests that are NOT KLOK or BBT
In section 3.1 is defined that this research scopes to the KLOK and BBT operations. The shipping requests for the other operations are therefor dropped.

3. Add coordinates to locations
For not all the locations in the data are coordinates known. Therefor the coordinates are gathered via unicode.

4. Dropping Requests that do no belong to 'Limburg' region
For all shipping requests we checked whether their pick-up location belongs to the 'Limburg' region. If this was not the case, these shipping requests were dropped.

5. Merging orders with the same start and end location, same time windows
Requests with the same begin and end point are merged, this is in reality also the case.

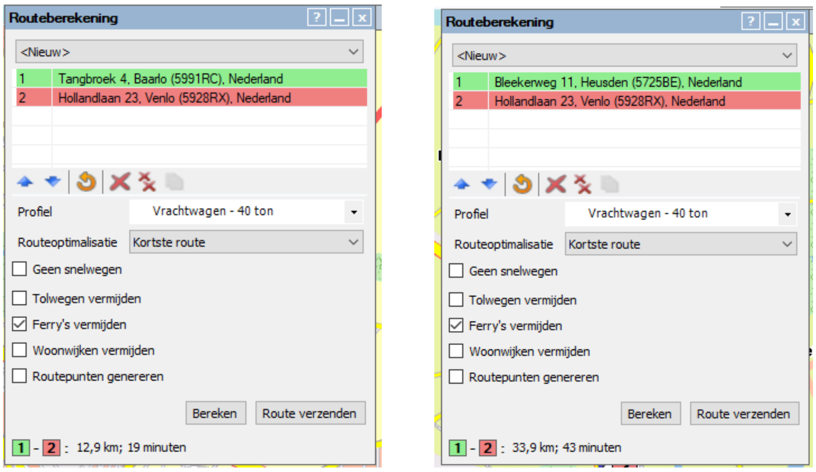
6. Add to the orders whether there end locations is at one of the auctions In this way, it becomes visible how many customers are in the auction area.

7. Add per request the number of request in total that need transportation from the same node
It this way it is can be seen how many requests departure from the same pick-up node at that day.

8. Add per request the number of request in total that need transportation to the same node
It this way it is can be seen how many requests departure from the same delivery node at that day.

Appendix C

Vehicle Speed



<Nieuw>

1	Tangbroek 4, Baarlo (5991RC), Nederland
2	Hollandlaan 23, Venlo (5928RX), Nederland

Profiel: Vrachtwagen - 40 ton

Routeoptimalisatie: Kortste route

☐ Geen snelwegen
☐ Tolwegen vermijden
☑ Ferry's vermijden
☐ Woonwijken vermijden
☐ Routepunten genereren

1 - 2 : 12,9 km; 19 minuten

(a) Baarlo to Venlo Depot

<Nieuw>

1	Bleekerweg 11, Heusden (5725BE), Nederland
2	Hollandlaan 23, Venlo (5928RX), Nederland

Profiel: Vrachtwagen - 40 ton

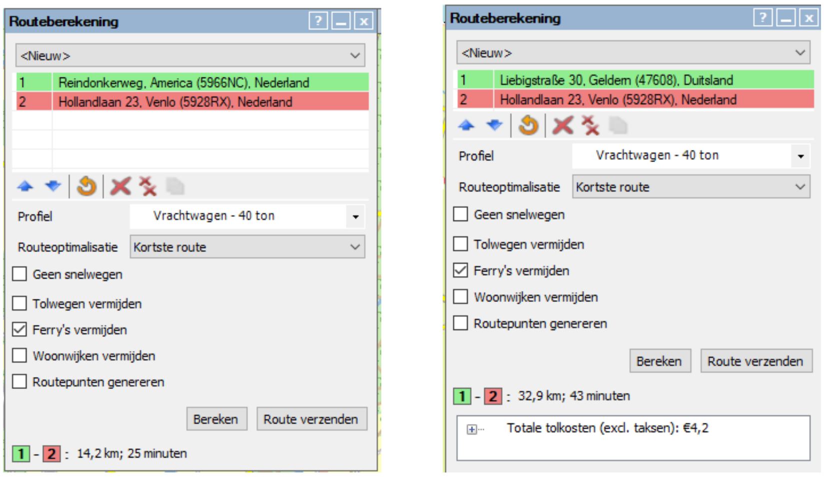
Routeoptimalisatie: Kortste route

☐ Geen snelwegen
☐ Tolwegen vermijden
☑ Ferry's vermijden
☐ Woonwijken vermijden
☐ Routepunten genereren

1 - 2 : 33,9 km; 43 minuten

(b) Heusden to Venlo Depot & KLOK

Figure C.1: Distance and Time Grower to Venlo



Routeberekening

<Nieuw>

1 Reindonkerweg, America (5966NC), Nederland

2 Hollandlaan 23, Venlo (5928RX), Nederland

Profiel Vrachtwagen - 40 ton

Routeoptimalisatie Kortste route

☐ Geen snelwegen

☐ Tolwegen vermijden

☑ Ferry's vermijden

☐ Woonwijken vermijden

☐ Routepunten genereren

1 - 2 : 14,2 km; 25 minuten

Routeberekening

<Nieuw>

1 Liebigstraße 30, Geldern (47608), Duitsland

2 Hollandlaan 23, Venlo (5928RX), Nederland

Profiel Vrachtwagen - 40 ton

Routeoptimalisatie Kortste route

☐ Geen snelwegen

☐ Tolwegen vermijden

☑ Ferry's vermijden

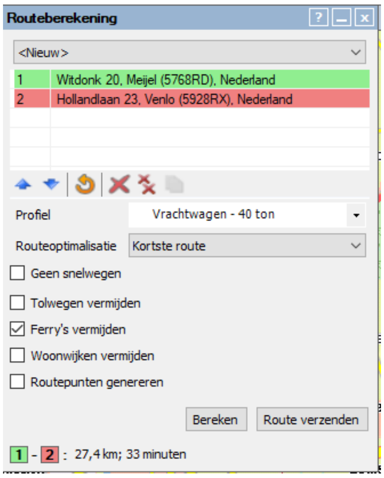
☐ Woonwijken vermijden

☐ Routepunten genereren

1 - 2 : 32,9 km; 43 minuten

Totale tolkosten (excl. taksen): €4,2

(c) America to Venlo Depot & KLOK (d) Geldern to Venlo Depot & KLOK



Routeberekening

<Nieuw>

1 Witdonk 20, Meijel (5768RD), Nederland

2 Hollandlaan 23, Venlo (5928RX), Nederland

Profiel Vrachtwagen - 40 ton

Routeoptimalisatie Kortste route

☐ Geen snelwegen

☐ Tolwegen vermijden

☑ Ferry's vermijden

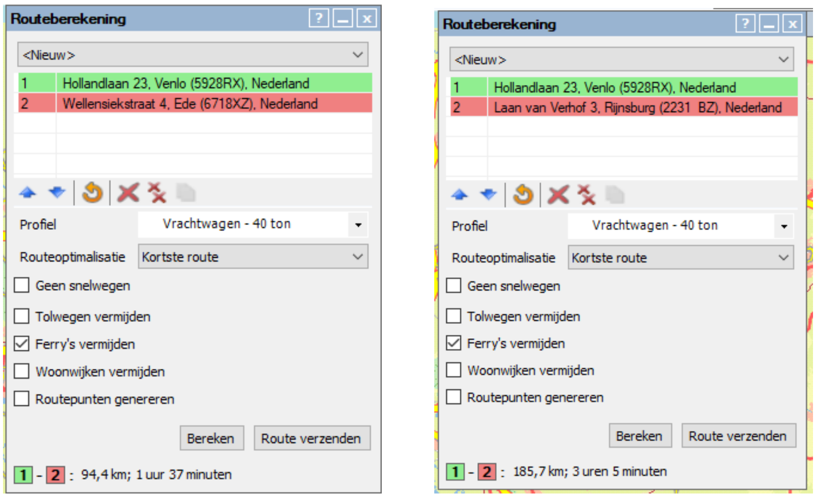
☐ Woonwijken vermijden

☐ Routepunten genereren

1 - 2 : 27,4 km; 33 minuten

(e) Meijel to Venlo Depot& KLOK

Figure C.1: Distance and Time Grower to Venlo



Routeberekening

<Nieuw>

1 Hollandlaan 23, Venlo (5928RX), Nederland
2 Wellensiekstraat 4, Ede (6718XZ), Nederland

Profiel: Vrachtwagen - 40 ton
Routeoptimalisatie: Kortste route

☐ Geen snelwegen
☐ Tolwegen vermijden
☑ Ferry's vermijden
☐ Woonwijken vermijden
☐ Routepunten genereren

1 - 2 : 94,4 km; 1 uur 37 minuten

(a) Venlo Depot to Plantion Ede

Routeberekening

<Nieuw>

1 Hollandlaan 23, Venlo (5928RX), Nederland
2 Laan van Verhof 3, Rijnsburg (2231 BZ), Nederland

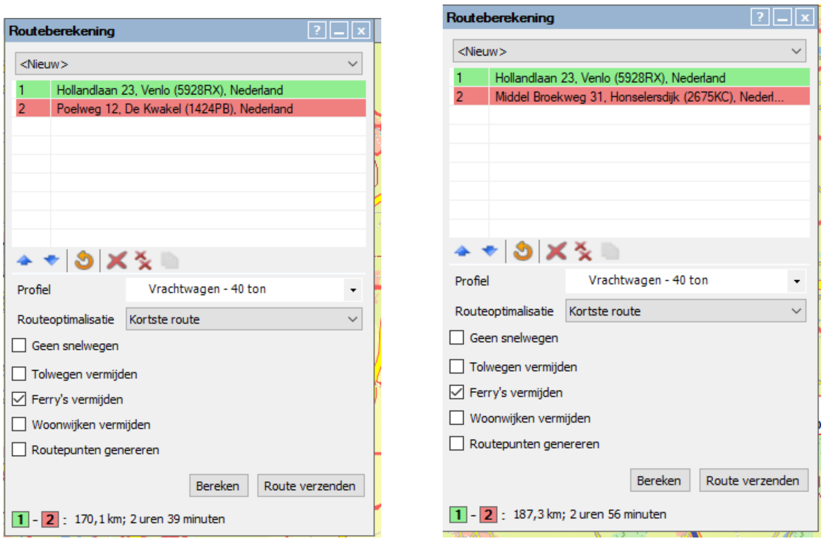
Profiel: Vrachtwagen - 40 ton
Routeoptimalisatie: Kortste route

☐ Geen snelwegen
☐ Tolwegen vermijden
☑ Ferry's vermijden
☐ Woonwijken vermijden
☐ Routepunten genereren

1 - 2 : 185,7 km; 3 uren 5 minuten

(b) Venlo Depot to RFH Rijnsburg & KLOK

Figure C.2: Distance and Time Grower to Venlo



Routeberekening

<Nieuw>

1 Hollandlaan 23, Venlo (5928RX), Nederland
2 Poelweg 12, De Kwakel (1424PB), Nederland

Profiel: Vrachtwagen - 40 ton
Routeoptimalisatie: Kortste route

☐ Geen snelwegen
☐ Tolwegen vermijden
☑ Ferry's vermijden
☐ Woonwijken vermijden
☐ Routepunten genereren

1 - 2 : 170,1 km; 2 uren 39 minuten

Routeberekening

<Nieuw>

1 Hollandlaan 23, Venlo (5928RX), Nederland
2 Middel Broekweg 31, Honselersdijk (2675KC), Nederl...

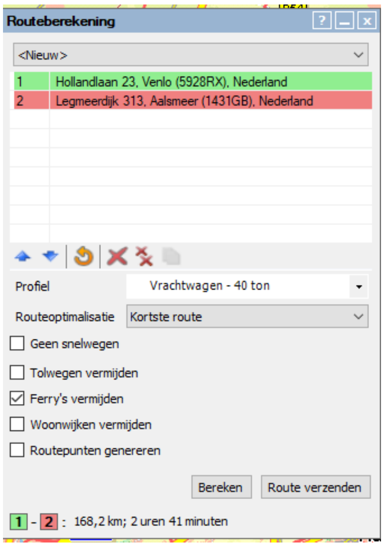
Profiel: Vrachtwagen - 40 ton
Routeoptimalisatie: Kortste route

☐ Geen snelwegen
☐ Tolwegen vermijden
☑ Ferry's vermijden
☐ Woonwijken vermijden
☐ Routepunten genereren

1 - 2 : 187,3 km; 2 uren 56 minuten

(c) Venlo Depot to De Kwakel Depot& KLOK

(d) Venlo Depot to RFH Naaldwijk & KLOK



Routeberekening

<Nieuw>

1 Hollandlaan 23, Venlo (5928RX), Nederland
2 Legmeerdijk 313, Aalsmeer (1431GB), Nederland

Profiel: Vrachtwagen - 40 ton
Routeoptimalisatie: Kortste route

☐ Geen snelwegen
☐ Tolwegen vermijden
☑ Ferry's vermijden
☐ Woonwijken vermijden
☐ Routepunten genereren

1 - 2 : 168,2 km; 2 uren 41 minuten

(e) Venlo Depot to RFH Aalsmeer & KLOK

Figure C.2: Distance and Time Grower to Venlo

Appendix D

Benchmark Data Created for PDPT Testing

Table D.1: Dataset PDPT_1

Location ID	X	Y	Demand	Paired PI or DI	LB-TW	UB-TW	Service Time
0	50	50	0	0	0	0	0
1	22	79	50	4	0	250	2
2	23	78	50	6	0	250	2
3	73	74	50	5	0	250	2
4	78	26	-50	1	0	250	2
5	82	25	-50	3	0	250	2
6	20	25	-50	2	0	250	2
7	50	50	0	0	0	0	0
8	50	50	0	0	0	0	0

Table D.2: Dataset PDPT_2

Location ID	X	Y	Demand	Paired PI or DI	LB-TW	UB-TW	Service Time
0	50	50	0	0	0	0	0
1	22	79	50	6	0	250	2
2	23	78	50	8	0	250	2
3	73	74	50	7	0	250	2
4	80	84	50	5	0	250	2
5	25	30	-50	4	0	250	2
6	78	26	-50	1	0	250	2
7	82	25	-50	3	0	250	2
8	20	25	-50	2	0	250	2
9	50	50	0	0	0	0	0
10	50	50	0	0	0	0	0

Table D.3: Dataset PDPT_3

Location ID	X	Y	Demand	Paired PI or DI	LB-TW	UB-TW	Service Time
0	50	50	0	0	0	0	0
1	22	89	35	8	0	250	2
2	23	88	35	10	0	250	2
3	73	84	35	9	0	250	2
4	80	94	35	7	0	250	2
5	71	86	35	6	0	250	2
6	28	9	-35	5	0	250	2
7	25	20	-35	4	0	250	2
8	78	16	-35	1	0	250	2
9	82	15	-35	3	0	250	2
10	20	15	-35	2	0	250	2
11	50	50	0	0	0	0	0
12	50	50	0	0	0	0	0

Appendix E

Five Data set for the Case Study of VZT

Table E.1: VZT_1

Location ID	Latitude	Longitude	Demand	Paired PI or DI	LB TW	UB TW	Service time
0	51,40	6,14	0	0	0	0	0
1	51,44	6,01	2	31	0	46800	180
2	51,33	6,03	1	32	0	46800	90
3	51,21	5,76	3	33	0	36000	270
4	51,26	5,55	4	34	0	36000	360
5	51,36	5,93	12	35	14400	46800	1080
6	51,38	6,24	1	36	0	46800	90
7	51,38	6,24	4	37	0	46800	360
8	51,38	6,24	11	38	1800	36000	990
9	51,39	6,25	3	39	0	86400	270
10	51,54	6,43	1	40	0	46800	90
11	51,34	6,02	1	41	7200	46800	90
12	51,37	5,96	1	42	0	50400	90
13	51,38	6,24	1	43	1800	46800	90
14	51,44	6,01	13	44	0	46800	1170
15	51,55	6,16	10	45	3600	46800	900
16	51,57	6,26	34	46	7200	57600	3060
17	51,34	6,02	1	47	7200	46800	90
18	51,55	6,22	1	48	3600	50400	90
19	51,44	6,01	1	49	3600	46800	90
20	51,38	6,24	16	50	3600	50400	1440
21	51,46	6,12	3	51	3600	46800	270
22	51,14	5,99	3	52	0	86400	270
23	51,39	5,93	4	53	0	36000	360
24	51,44	6,11	2	54	0	50400	180
25	51,39	6,24	2	55	3600	46800	180
26	...	...	...	...	...	...	...

Table E.2: VZT_2

Location ID	Latitude	Longitude	Demand	Paired PI or DI	LB TW	UB TW	Service time
0	51,4039	6,1356	0	0	0	0	0
1	51,33	6,03	1	31	0	46800	90
2	51,38	5,78	42	32	0	54000	3780
3	51,34	6,02	3	33	7200	54000	270
4	51,36	5,93	12	34	14400	46800	1080
5	51,60	6,25	2	35	0	46800	180
6	51,48	6,25	12	36	0	82800	1080
7	51,34	5,88	6	37	0	46800	540
8	51,47	6,10	1	38	0	46800	90
9	51,44	6,01	3	39	0	46800	270
10	51,44	6,01	43	40	3600	54000	3870
11	51,46	6,14	7	41	0	46800	630
12	51,54	6,25	11	42	3600	46800	990
13	51,44	6,01	1	43	0	46800	90
14	51,34	6,02	1	44	7200	46800	90
15	51,57	6,26	1	45	7200	46800	90
16	51,21	5,76	3	46	0	36000	270
17	51,46	6,12	3	47	3600	46800	270
18	51,55	6,16	1	48	3600	46800	90
19	51,21	5,76	9	49	0	36000	810
20	51,60	6,25	10	50	0	46800	900
21	51,49	6,22	2	51	0	54000	180
22	51,49	6,22	5	52	0	46800	450
23	51,47	6,24	9	53	3600	34200	810
24	51,40	6,13	2	54	7200	34200	180
25	51,38	5,78	1	55	0	46800	90
26	51,49	6,22	2	56	0	46800	180
27	51,26	5,89	5	57	0	46800	450
28	51,38	6,24	3	58	10800	50400	270
29	51,39	6,25	3	59	0	86400	270
30	51,44	6,01	13	60	0	46800	1170
31	52,26	4,79	-1	1	0	46800	24
32	51,38	6,24	-42	2	0	54000	1008
33	52,03	4,54	-3	3	7200	54000	72
34	52,00	4,23	-12	4	14400	46800	288
35	52,26	4,80	-2	5	0	46800	48
36	52,00	4,23	-12	6	0	46800	288
37	52,00	4,23	-6	7	0	46800	144
38	52,26	4,80	-1	8	0	46800	24
39	52,26	4,80	-3	9	0	46800	72
40	52,03	4,54	-43	10	3600	54000	1032
41	52,00	4,23	-7	11	0	46800	168
42	52,26	4,80	-11	12	3600	46800	264
43	52,26	4,80	-1	13	0	46800	24
44	52,26	4,80	-1	14	7200	46800	24
45	52,00	4,23	-1	15	7200	46800	24
46	52,04	5,61	-3	16	0	36000	72
47	...	...	...	...	...	...	...

Table E.3: VZT_3

Location ID	Latitude	Longitude	Demand	Paired PI or DI	LB TW	UB TW	Service time
0	51,40	6,14	0	0	0	0	0
1	51,47	6,24	6	31	3600	36000	540
2	51,47	6,24	3	32	3600	36000	270
3	51,60	6,25	6	33	10800	82800	540
4	51,52	6,24	2	34	0	46800	180
5	51,33	6,03	1	35	0	46800	90
6	51,34	6,06	6	36	0	34200	540
7	51,44	6,01	8	37	3600	46800	720
8	51,38	6,24	1	38	1800	46800	90
9	51,44	6,01	5	39	3600	46800	450
10	51,55	6,16	4	40	1800	36000	360
11	51,38	5,78	1	41	3600	46800	90
12	51,46	6,12	1	42	0	46800	90
13	51,53	5,65	2	43	0	36000	180
14	51,57	6,26	31	44	14400	57600	2790
15	51,40	6,13	3	45	0	73800	270
16	51,60	6,25	4	46	10800	46800	360
17	51,33	5,63	1	47	0	46800	90
18	51,52	6,24	9	48	0	46800	810
19	51,44	6,01	1	49	3600	46800	90
20	51,55	6,22	5	50	3600	46800	450
21	51,38	5,78	4	51	3600	46800	360
22	51,34	6,06	13	52	0	36000	1170
23	51,45	6,17	4	53	0	36000	360
24	51,37	5,96	2	54	0	50400	180
25	51,49	6,22	1	55	0	46800	90
26	51,55	6,16	10	56	1800	46800	900
27	51,33	5,95	2	57	0	50400	180
28	51,54	6,25	4	58	7200	36000	360
29	51,45	6,17	2	59	0	36000	180
30	51,34	6,02	1	60	0	54000	90
31	52,00	4,23	-6	1	3600	36000	144
32	52,26	4,80	-3	2	3600	36000	72
33	51,41	6,14	-6	3	10800	82800	144
34	52,26	4,80	-2	4	0	46800	48
35	52,26	4,79	-1	5	0	46800	24
36	52,00	4,23	-6	6	0	34200	144
37	52,26	4,80	-8	7	3600	46800	192
38	52,26	4,80	-1	8	1800	46800	24
39	52,26	4,80	-5	9	3600	46800	120
40	52,26	4,80	-4	10	1800	36000	96
41	52,00	4,23	-1	11	3600	46800	24
42	52,27	4,78	-1	12	0	46800	24
43	51,38	6,24	-2	13	0	36000	48
44	52,25	4,79	-31	14	14400	57600	744
45	52,04	5,61	-3	15	0	73800	72
46	52,26	4,80	-4	16	10800	46800	96
47	...	...	...	...	...	...	...

Table E.4: VZT_4

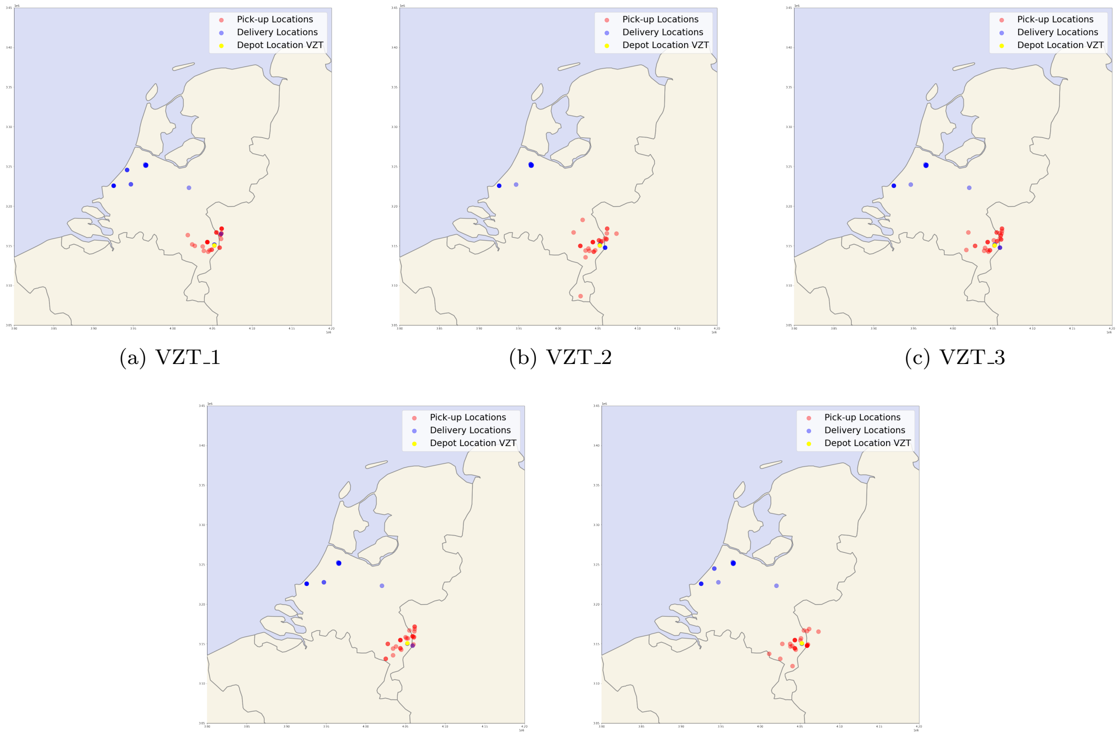
Location ID	Latitude	Longitude	Demand	Paired PI or DI	LB TW	UB TW	Service time
0	51,40	6,14	0	0	0	0	0
1	51,53	5,65	2	31	0	36000	180
2	51,46	6,12	1	32	0	46800	90
3	51,33	6,03	1	33	0	46800	90
4	51,33	5,95	2	34	0	50400	180
5	51,48	6,25	1	35	0	50400	90
6	51,33	6,03	3	36	0	54000	270
7	51,44	6,15	2	37	0	50400	180
8	51,49	6,22	2	38	0	46800	180
9	51,46	6,12	1	39	0	46800	90
10	51,68	5,80	2	40	0	36000	180
11	51,40	6,13	2	41	0	46800	180
12	50,82	5,84	3	42	0	57600	270
13	51,45	6,15	1	43	0	46800	90
14	51,54	6,43	2	44	0	46800	180
15	51,34	5,88	6	45	0	46800	540
16	51,60	6,25	8	46	10800	46800	720
17	51,60	6,25	5	47	10800	46800	450
18	51,44	6,01	13	48	3600	46800	1170
19	51,26	5,89	2	49	0	54000	180
20	51,45	6,17	4	50	0	36000	360
21	51,38	5,78	25	51	3600	54000	2250
22	51,34	6,06	13	52	0	36000	1170
23	51,38	5,78	1	53	3600	46800	90
24	51,38	5,78	2	54	3600	46800	180
25	51,47	6,24	6	55	3600	36000	540
26	51,36	5,93	2	56	10800	46800	180
27	51,44	6,01	6	57	3600	54000	540
28	51,44	6,01	34	58	3600	54000	3060
29	51,54	6,25	16	59	7200	46800	1440
30	51,44	6,01	28	60	3600	57600	2520
31	52,26	4,80	-2	1	0	36000	48
32	52,27	4,78	-1	2	0	46800	24
33	52,26	4,79	-1	3	0	46800	24
34	51,41	6,14	-2	4	0	50400	48
35	51,41	6,14	-1	5	0	50400	24
36	51,38	6,24	-3	6	0	54000	72
37	51,41	6,14	-2	7	0	50400	48
38	52,26	4,80	-2	8	0	46800	48
39	52,26	4,79	-1	9	0	46800	24
40	52,26	4,80	-2	10	0	36000	48
41	52,26	4,80	-2	11	0	46800	48
42	52,27	4,78	-3	12	0	57600	72
43	52,26	4,79	-1	13	0	46800	24
44	52,00	4,23	-2	14	0	46800	48
45	52,00	4,23	-6	15	0	46800	144
46	52,26	4,80	-8	16	10800	46800	192
47	...	...	...	...	...	...	...

Table E.5: VZT_5

Location ID	Latitude	Longitude	Demand	Paired PI or DI	LB TW	UB TW	Service time
0	51,40	6,14	0	0	0	0	0
1	51,52	6,24	3	31	0	46800	270
2	51,38	6,24	13	32	1800	36000	1170
3	51,60	6,25	20	33	10800	46800	1800
4	51,50	5,65	5	34	0	50400	450
5	51,38	5,78	5	35	3600	46800	450
6	51,55	6,16	4	36	0	36000	360
7	51,48	6,25	4	37	0	50400	360
8	51,40	6,13	2	38	0	46800	180
9	51,38	6,24	10	39	0	46800	900
10	51,52	6,24	3	40	0	54000	270
11	51,33	5,95	5	41	0	75600	450
12	51,35	6,09	4	42	0	36000	360
13	51,55	6,16	11	43	0	46800	990
14	51,33	6,03	1	44	0	46800	90
15	51,44	6,01	33	45	0	46800	2970
16	51,60	6,25	1	46	0	46800	90
17	51,40	5,73	7	47	5400	36000	630
18	51,34	6,06	19	48	0	34200	1710
19	51,44	6,01	7	49	0	46800	630
20	51,44	6,01	1	50	0	46800	90
21	51,44	6,01	8	51	0	46800	720
22	51,38	5,93	2	52	0	50400	180
23	51,55	6,16	4	53	0	54000	360
24	51,44	6,01	28	54	0	54000	2520
25	51,54	6,25	24	55	0	46800	2160
26	51,35	6,09	7	56	0	36000	630
27	51,44	6,01	1	57	0	46800	90
28	51,54	6,25	2	58	0	46800	180
29	51,60	6,25	8	59	0	46800	720
30	51,60	6,25	3	60	7200	50400	270
31	52,00	4,23	-3	1	0	46800	72
32	52,26	4,80	-13	2	1800	36000	312
33	52,00	4,23	-20	3	10800	46800	480
34	51,41	6,14	-5	4	0	50400	120
35	52,26	4,80	-5	5	3600	46800	120
36	52,04	5,61	-4	6	0	36000	96
37	51,41	6,14	-4	7	0	50400	96
38	52,19	4,45	-2	8	0	46800	48
39	52,26	4,80	-10	9	0	46800	240
40	52,03	4,54	-3	10	0	54000	72
41	51,41	6,14	-5	11	0	75600	120
42	52,26	4,80	-4	12	0	36000	96
43	52,00	4,23	-11	13	0	46800	264
44	52,26	4,79	-1	14	0	46800	24
45	52,00	4,23	-33	15	0	46800	792
46	52,26	4,80	-1	16	0	46800	24
47	...	...	...	...	...	...	...

Appendix F

Location Distribution



(a) VZT_1 (b) VZT_2 (c) VZT_3

(d) VZT_4 (e) VZT_5

Figure F.1: Location distributions five created instances for the case study at VZT

Appendix G

Solutions TIME

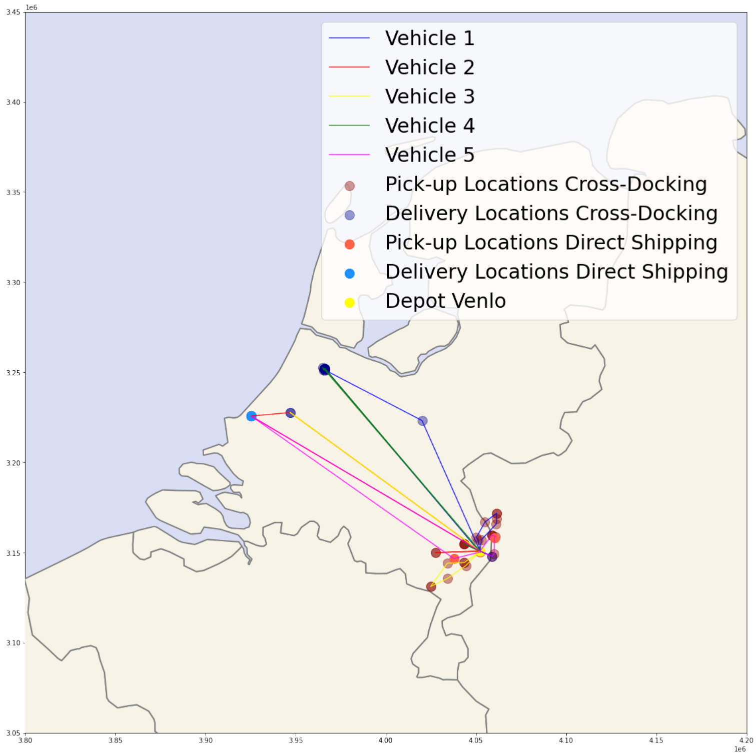
(a) Dropped Nodes VZT_1 TIME

Figure G.1: VZT_1

(b) Routes VZT_1 TIME

Figure G.1: VZT_1

(a) Dropped Nodes VZT_2 TIME



(b) Routes VZT_2 TIME

Figure G.2: VZT_2

(a) Dropped Nodes VZT_3 TIME

(b) Routes VZT_3 TIME

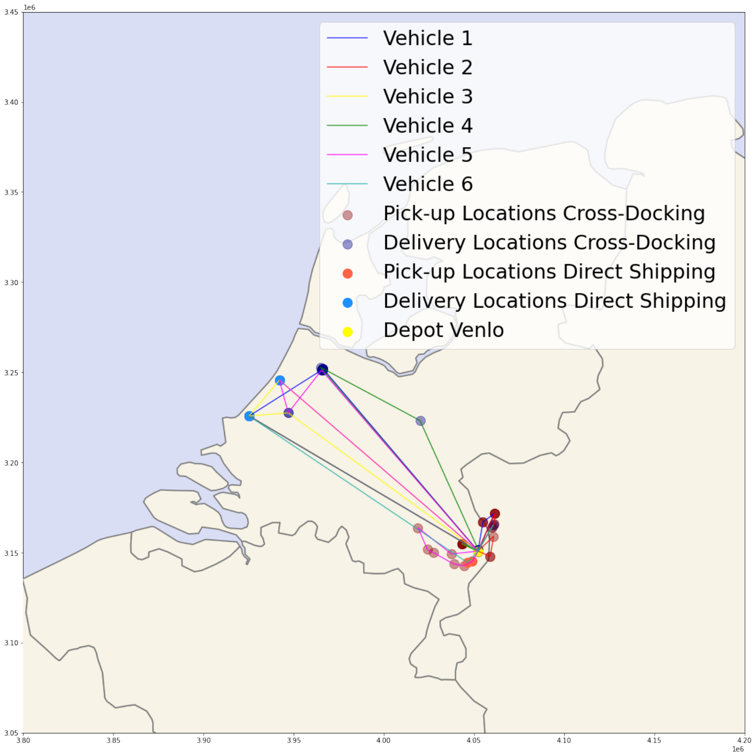
Figure G.3: VZT_3

(a) Dropped Nodes VZT_4 TIME

(b) Routes VZT_4 TIME

Figure G.4: VZT_4

(a) Dropped Nodes VZT_5 TIME



(b) Routes VZT_5 TIME

Figure G.5: VZT_5

Appendix H

Routing Solutions Direct Shipping

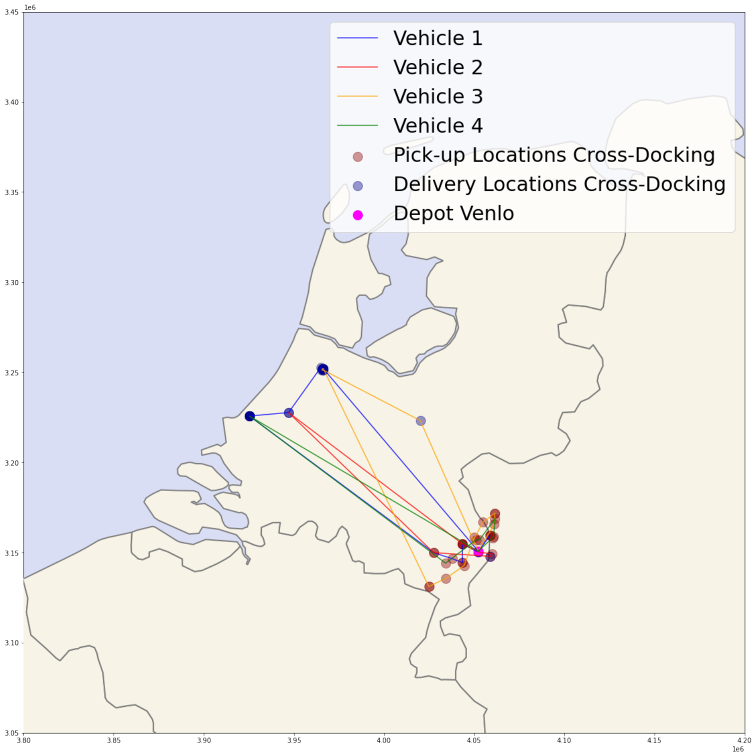


Figure H.1: Vehicles Time

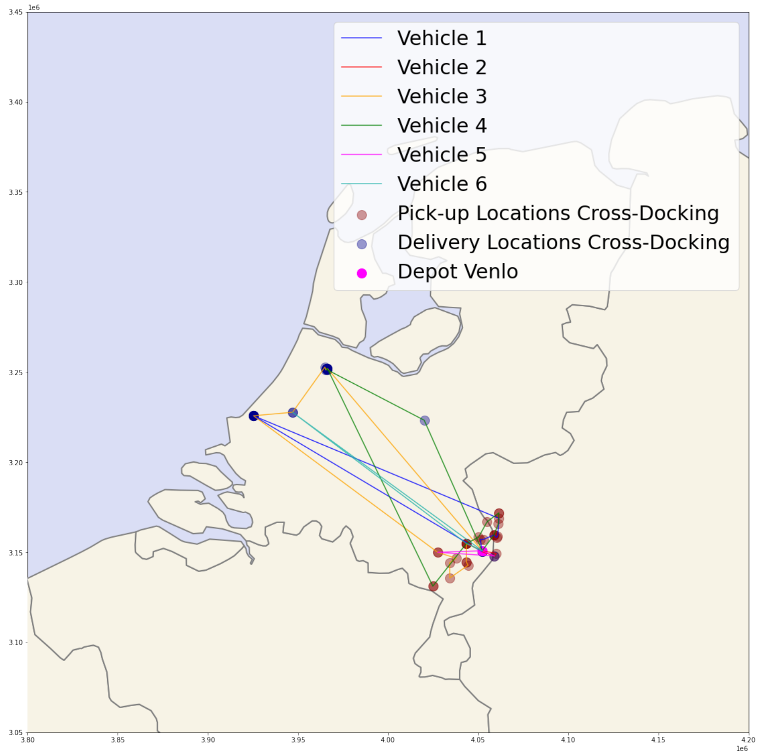


Figure H.2: Vehicles Time

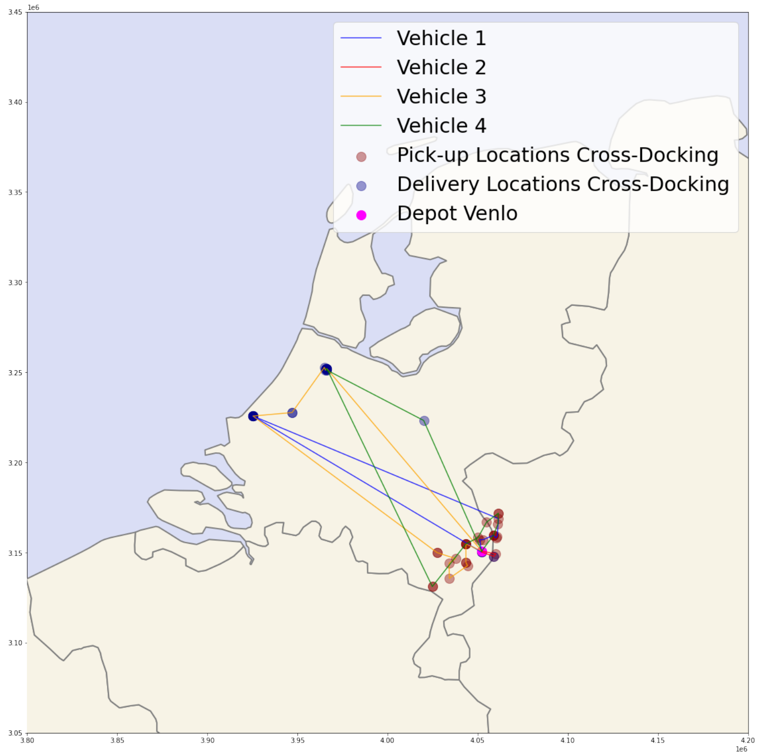


Figure H.3: Vehicles Time