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The future of the first and last mile of parcel delivery
pickup and delivery using hubs and couriers

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The future of the first and last mile of parcel delivery: Pickup and delivery using hubs and couriers

Master Thesis

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Acknowledgement

This thesis is the result of a graduation project that has been conducted at Wuunder in the completion of the Master Operations Management & Logistics at Eindhoven University of Technology.

Recently, a friend asked me if I would get rid of the Master Thesis Project if I could recreate the education system of the university from scratch. I answered him that I would not. Although at times during this project I felt stressed, hopeless, worried that I would never finish, overwhelmed, sometimes frustrated, it was also the period in which I learned most about my studies, my capabilities, and my personality. It took me great effort (2 laptops, at least 145 handwritten pages, 19.5 gigabytes of files and folders, over 200 000 runs of the created model), but it led to enormous rewards. These rewards included; A driver's license (after 3 attempts), 4$^{\text{th}}$ place when we went go-kart racing with Wuunder, 6 externally visible rectus abdominis muscles, 81 days (and counting) of sobriety, and running 42,195 meters in the Eindhoven marathon without any prior training (in 4 hours, 18 minutes and 9 seconds). Oh, and obviously this thesis.

It has not all been smooth sailing, but I was lucky enough to have friends, roommates, parents, siblings, teammates, and bartenders, who were always able to distract me, listen to my frustrations, and cheer me up when I hit an obstacle. More importantly, you all celebrated the small victories and cheerful moments with me as well, which made them all the better.

My mentor Tom van Woensel deserves a special mention. Quite a few times I came to a meeting at wits end, but every time you were able to show how we could get to the finish line in clear steps. The same goes for my company supervisor, Bart Takkenkamp. Keeping me updated on all the Wuunder activities and figuring out the goals of the model together were always welcome talks. Lastly, I would like to thank Luuk Veelenturf. We did not meet very often, but your detailed feedback was much appreciated.

Overall, living in the university library for eight months was a fun time. I will miss timing the placement of our cups under the coffee machine, dancing with lunch ladies, laughing and relaxing in the many necessary coffee therapy sessions, trying to get in without showing your campus card during exam weeks and the many more things we did to make our time in Meta tolerable. Time to see if we can get away with it out there in the real world.

Dreas de Kerf

Abstract

This research is conducted at Wuunder, a company that developed a platform through which sending and delivering documents, packages, and pallets is facilitated. The platform integrates the transportation systems of carriers and couriers via hubs, called Wuunder points. In this report, a model is developed based on continuous approximation, that supports the tactical and strategic decision making at Wuunder. The characteristics of vans, cargo bikes, and bikes are considered. More specifically, the speeds, capacities, and fixed and variable costs are taken into account. A disk-shaped service region with a given radius and number of customers with certain assumptions on time window characteristics is then analyzed. The resulting model cannot be solved to optimality within reasonable time. Hence, an upper and a lower bound are created to approximate the optimal solution. The generated output comes in the form of the optimal number of Wuunder points, required trips per vehicle type, layout specifications for the region, and total costs of the system. The factors that impact the outcomes most significantly are given by the capacity of a Wuunder point, followed by cargo bike characteristics, vehicle variable costs, and cargo bike and bike capacities. The impact of time windows is such that more and stricter time windows lead to more required Wuunder points and (cargo) bike trips and higher costs. It is shown that not every proportion of the Wuunder platform coexisting with the current system leads to environmental benefits. Furthermore, it is shown that scenarios with more customers do not necessarily require more Wuunder points. Therefore, future optimal configurations should be taken into account when deciding upon the number of Wuunder points to partner up with.

Executive summary

This research is conducted at Wuunder, a company that developed a platform through which sending and delivering documents, packages, and pallets is facilitated. The platform integrates the transportation systems of carriers and couriers via hubs, called Wuunder points. This system is visualized in Figure 1. This research is aimed at finding optimal costs and configurations for selected scenarios. A configuration in this report is defined by the number of Wuunder points, required number of trips per vehicle type, and layout specifications for the region to be serviced. Both the economic and environmental impact of the platform is evaluated in this report.

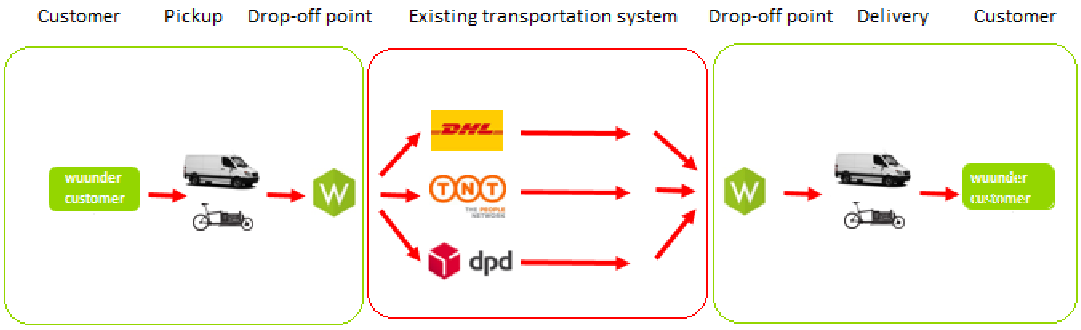

Figure 1: The pickup and delivery process as envisioned by Wuunder

Context

Wuunder does not possess, nor intend to possess its own vehicles or hubs. The operational control over routes is therefore limited. On a **strategic and tactical level**, Wuunder does have control over the number of Wuunder points they choose to operate and how many couriers they partner up with. To assess this, an optimization module is developed in this report.

The input parameters are the following: For the vehicle types; the speeds, capacities, and fixed and variable costs are required. Furthermore, the radius of the region and the number of customers should be inserted into the model, as well as the proportion of customers with time windows and the associated distance penalty. A duration limit (if any) and estimated proportion of customers with time windows and distance penalty, related to the tightness of the time windows, can be included in the model. The types of vehicles of most interest to Wuunder are delivery **vans, cargo bikes, and bikes**. The model determines the **optimal number of Wuunder points** and the estimated number of trips required per vehicle type for given parameter settings. In Figure 3.2, the model requirements are depicted.

The main research question dealt with in this report is the following:

How can Wuunder arrange the parcel delivery system in a city in the most cost effective way by using Wuunder points and couriers?

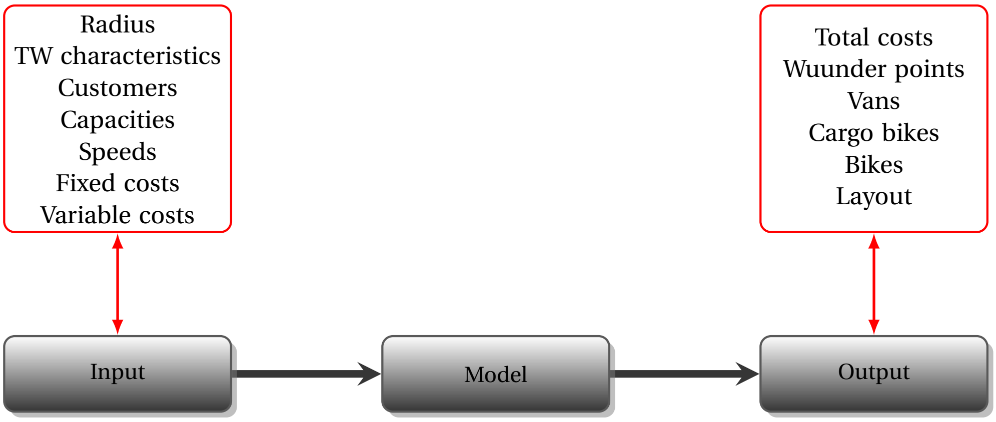

Figure 2: The process performed by the model transforming input into output

Process

In Figure 3.1, the procedure applied in this report is visualized. A **continuous approximation** model with aggregated data is used. The model is based on the fleet composition with continuous approximation model (FCCA) developed by Jabali et al. (2012) adapted by the incorporation of time windows. The time window formulas are derived from the work of Figliozzi (2009) and Vercammen (2016).

Eindhoven is selected for the base case scenario, with a radius of 18 kilometers and a hypothetical 1000 customers. The service region is approximated by a **disk-shaped district**. A **ring-radial topology** is used, where the inner ring is partitioned into triangularly shaped zones and outer rings are divided into zones with the shape of circular trapezoids. The division of the region into districts each serviced from a single Wuunder point is done by assuming a region can be serviced by congruent (equal in size) non-overlapping disks covering the same surface area. Time windows are incorporated by adjusting the constraints and objective function of the FCCA model of Jabali et al. (2012) with the factors and estimates established by Vercammen (2016). Data concerning the vehicle characteristics is gathered through interviews with partners of Wuunder.

The resulting model cannot be solved to optimality within a reasonable time. Therefore, an **upper** and a **lower bound** are created to approximate the optimal solution, and the validities of these bounds are tested. The parameter values applicable to the setting are then inserted and subsequently, the model is analyzed.

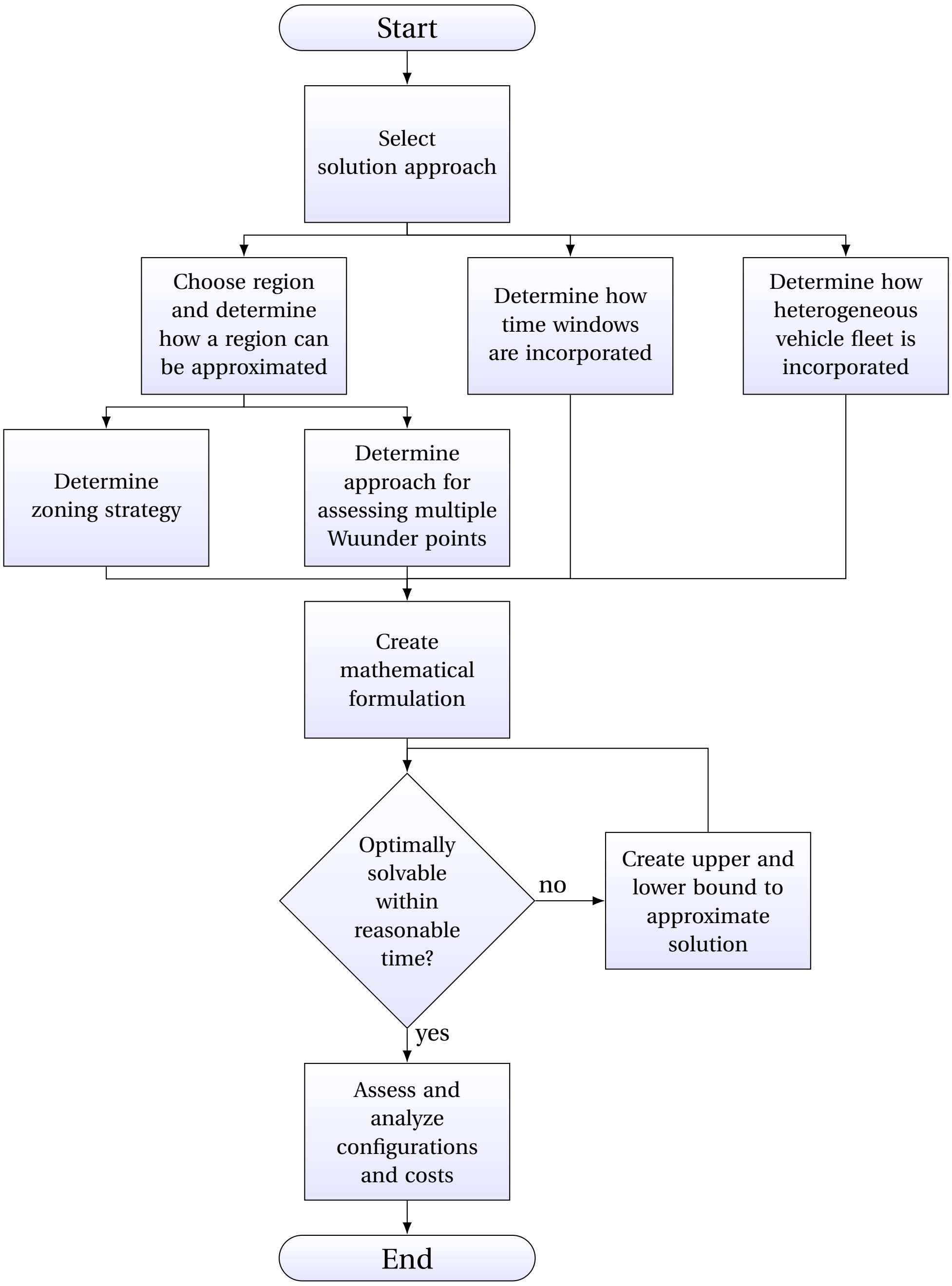

Figure 3: The procedure applied in this report to analyze the problem

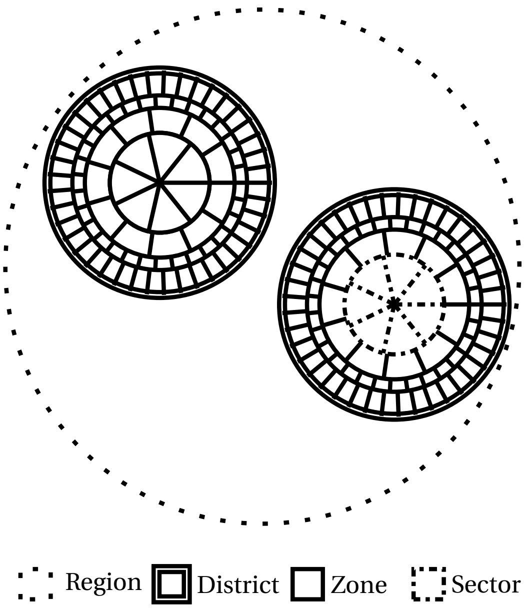

Figure 4: Visualization of the different types of areas within the region

Findings

Firstly, the effect of **time windows** is analyzed. When time windows are incorporated, the global optimum changes from the initially optimal solution with a single district serviced by bikes and vans to a novel optimal solution with multiple districts serviced by cargo bikes and bikes. When the penalty of the time windows is more severe, the required number of Wuunder points and (cargo) bikes further increases.

Secondly, the role of the **duration limit** is assessed. When a trip should be completed within 90 minutes, the first effects are noticeable. More Wuunder points and (cargo) bikes are required to shorten the distance between depots and customers. For a very small duration limit (50 minutes), it becomes optimal to service all customers by bike. This implies an increased amount of required Wuunder points (up to three times as many as compared to when the duration limit is non restricting).

Subsequently, the **number of customers** is varied to determine its implications for the costs and configurations. As expected, costs per customer decrease as the number of customers increases. Future scenarios should also be taken into account when deciding upon opening Wuunder points. Scenarios with more customers do not necessarily require more Wuunder points, thus suboptimal performance might be preferred in the short term.

Next, the **environmental** aspect of the Wuunder system is analyzed. Potential savings in kilometers driven by vans of 63.4% are achieved by adapting the Wuunder platform in a city such as Eindhoven. However, not all stages of Wuunder coexisting with the current parties are beneficial for the environment. For instance, if 30% of packages in Eindhoven are sent via Wuunder, the total amount of kilometers driven to ship the parcels is 5.4% higher compared to the original system.

Finally, the effect of the **radius** is evaluated. Every kilometer increase of the radius leads to an approximate increase of 190€ and for small regions, the capacity of a Wuunder point forces the model to find a more expensive solution.

Sensitivity analysis

A sensitivity analysis is conducted to gauge the effect of certain parameters on the model. For the distance penalty and proportion of clients with time windows, a similar effect is found. Beyond a critical point, the tightness of a time window (and the associated distance penalty), as well as the proportion of clients with specified time windows have a positive relationship with regards to costs, Wuunder points and vehicles required in the optimal solution.

Similarly, all vehicle characteristics are analyzed and it is found that the **characteristics of cargo bikes, mainly the variable costs, have the most impact on the costs** and configurations obtained by the model. Of all characteristics, the **variable costs influence the total costs the most**. For instance, a reduction of variable costs of vans by 30% leads to a cost decrease of 17.25%. The **capacities of cargo bikes impacts the configurations most significantly**. The capacities of these vehicles are close to the critical point where other vehicle types are required. This in turn also has considerable effects on the costs.

Conclusions and recommendations

Sending parcels via the Wuunder platform has the potential to create a more efficient parcel delivery system. A model has been developed that determines optimal configurations in terms of Wuunder points, required trips per vehicle type, layout specifications, and the corresponding costs. The costs and configurations depend to a great extent on the proportion of clients that specify time windows and the impact of time windows on driven distance. It is therefore recommended that Wuunder gathers **data on time window characteristics**. Specifically, the proportion of customers with time windows and the distances driven for both customers with and without time windows to assess its effects.

It is shown that **environmental benefits** may be achieved as well, although data specific to the existing system is not expected to be disclosed by the current active parties. Furthermore, it is shown that not all stages of adaptation of the Wuunder platform necessarily result in a decrease in the distance driven by delivery vans.

One of the main findings of this report is that the **capacity of a Wuunder point** has a considerable impact on the optimal solution. For some cases, the estimated costs have been found to be 18.86% higher compared to when the capacity of a Wuunder point is disregarded.

Additional aspects could be incorporated into the model or variations of the model to increase the validity of the model. The development of these variations on the model should be the result of the combined effort of both developments in literature and collection of case specific data. Summarized, these possible additional aspects would be given by the inclusion of:

- Failed deliveries,
- Average distance relative to ring,
- Time window distance penalty related to vehicle type,
- Variation in number of packages ordered per customer,
- Cost assessment of dedicated Wuunder points and capacities,
- Load sharing between districts,
- Rectangular-grid network comparison.

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Abbreviations

ACM	Authoriteit Consument & Markt (Authority Consumer & Market, the Netherlands)
B2B	Business-to-business
B2C	Business-to-consumer
CA	Continuous approximation
FCCA	Fleet composition with continuous approximation
FSMVRP	Fleet size and mix vehicle routing problem
GRASP	Greedy randomized adaptive search procedure
ILP	Integer Linear Programming
LAP	Location-allocation problem
LRP	Location-routing problem
MDVRP	Multiple depot vehicle routing problem
MILP	Mixed integer linear programming
MMLRP	Many-to-many location routing problem
NP	Non-deterministic Polynomial-time
TW	Time window
VRP	Vehicle routing problem
QMIP	Quadratic mixed integer programming

Nomenclature

A	Size of area
K	Set of rings, where ring 1 represents the inner most ring
M	A large number
Q	Set of vehicle types
α	$\frac{c_q\sqrt{6\delta}}{c_1\gamma\delta}$
δ	Customer density
γ	$0.95\sqrt{\frac{3}{2\delta}}$
μ	Service time in minutes
c_i	Capacity of vehicle $i \in Q$ in number of packages
d_i	Variable costs of vehicle $i \in Q$ in euros
e	Total number of customers
f_i	Fixed costs of vehicle $i \in Q$ in euros
k_d	Estimate for connecting distance
k_l	Estimate for local distance
k_t	Distance penalty per time window
k_{t_i}	Estimate for distance penalty per time window of orders of type i
l_{ij}	Decision variable for the radius of the inner ring (if $j = 1$) or length of the circular trapezoidin ring (if $j > 1$)
n	Amount of orders
n_{ij}	Decision variable for the number of vehicles of type i assigned to ring j
n_{t_i}	mount of time window orders of type i
m	Amount of vehicles
m_d	Amount of vehicles required without time window restrictions
p	Number of Wuunder points
p_{max}	Maximum number of Wuunder points
p_t	Proportion of clients with time windows
r	Radius of the district
$\bar{r}$	Average distance from depot to customer
r_{min}	Smallest possible radius of a district
r_r	Radius of the region
t	Duration limit in minutes
v_i	Speed of vehicle $i \in Q$ in kilometers per minute
w^*	Optimal width of a circular trapezoid
x'	$2\alpha^2 - \alpha\sqrt{4\alpha^2 + 8\alpha + 3}$
x_{ij}	Binary decision variable if vehicle type i is assigned to ring j
y_{ij}	Decision variable for the distance traversed by vehicle of type i from the depot to the inner edge of ring j
z_{ij}	y_{ij}/α

Chapter 1

Introduction

The parcel delivery industry is a big and growing one. This is signified by the fact that in 2015, carriers delivered 208 million parcels within the Netherlands. Cross-border package delivery grew to 92 million parcels. These are increases of 11.3% and 12.7% respectively in comparison to 2014 (ACM, 2016). That this growth is part of a bigger trend, is shown in Figure 1.1. This is in part the result of thriving online retail sales. Between 1999 and 2005, online retail sales grew by 1,403 percent in the Netherlands (Weltevreden, 2007). The increasing popularity of online shopping leads to a growing amount of delivery vehicles in residential areas to deliver the packages to consumers' homes.

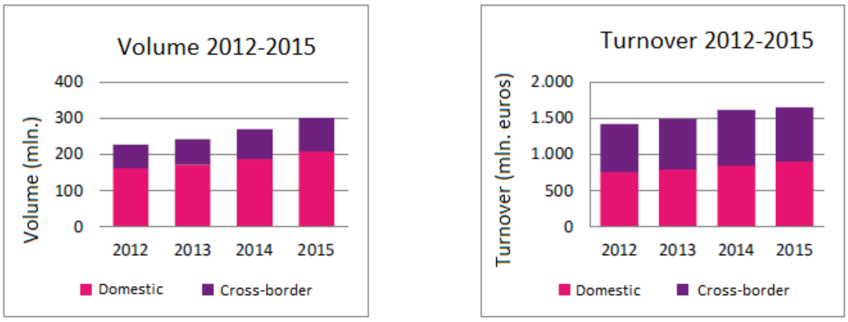


Figure 1.1: Volume and turnover for the package delivery market 2012-2015

The market for domestic parcel delivery is highly concentrated. Two parties, DHL Parcel and PostNL make up the biggest share of the market (ACM, 2016). The market for cross-border package delivery is more equally distributed amongst the various parties. An overview of the distribution of market shares in both segments is given in Figure 1.2. Even though the companies with the biggest market shares should benefit from economies of scale, these benefits are barely noticeable in the tariffs handled by these companies (ACM, 2016). This could indicate a lack of competition or unexploited room for efficiency.

In the industry, some variations exist in what terms are used to describe the various parties. In this report, the standard terminology for the different parties in the package delivery market is handled that is used by the ACM and defined in the Dutch Postal law of 2009. For clarification, this terminology is explained in Table 1.1.

The carriers are mainly nationally oriented and operate almost exclusively using road transport, such as trucks. Examples of carriers in the Netherlands include PostNL and DHL Parcel. Express delivery can be seen as additional premium transport services. They make use of integrated air and ground networks and are oriented at the European and global economy. FedEx and UPS are examples of these type of transporters (ACM, 2016). Couriers are often times much smaller companies than the other players and some operate using only bikes. This report focuses mainly on carriers and couriers and the

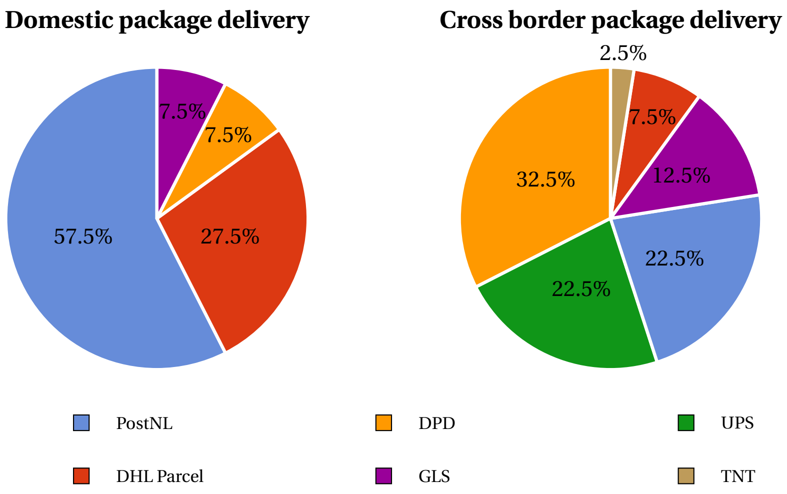


Figure 1.2: Distribution of market shares in domestic and cross-border package delivery in the Netherlands, 2015

Terminology	Description
Carrier	Mainly nationally oriented, almost exclusively using road transport
Express	Separate agreements made between sender and transportation company
Courier	Door-to-door delivery without using transshipment points

Table 1.1: Explanation of the terminology used in this report for the parties active in the parcel delivery industry

potential benefits of these parties collaborating through the Wuunder platform.

It should be noted that the parties mainly compete on price and secondarily on service aspects such as same day delivery, weekend or night delivery, speed or time of delivery (ACM, 2016). Similarly, price remains the key decision criterion for the majority of customers, followed by same day delivery and time window reliability (Joerss et al., 2016). The focus on price means that carriers pay great attention to the cost levels of their services. Larger web shops make the entire chain of collecting, transporting, sorting, and delivering more efficient for the carrier. As a consequence, larger web shops are able to demand smaller prices for the transportation and get earlier access to new services compared to smaller web shops (ACM, 2016).

The growth of home shopping market has challenged the goods distribution process, which plays a key role in the home shopping transaction. The increasing popularity of online shopping leads to a growing amount of delivery vehicles in residential areas to deliver the packages to consumers' homes (Weltevreden, 2008). The retail sector is reliant on efficient distribution systems and the success of a business is highly dependent on whether the consumer is satisfied with the delivery service. The increases in delivery vehicle activity related to e-commerce and home shopping have raised concerns over the number of logistics providers operating 'less-than-truck-load' vehicles and its environmental implications (Song et al., 2011). In the UK for example, the growth in vans and large goods vehicles accounted for 29 percent of the total growth in vehicle-kilometers, but have collectively accounted for over 97 percent of the increase in road-transport CO_2 emissions over the same period (Song et al., 2011).

The remainder of this chapter is composed as follows: Firstly, Wuunder and its concept are explained in Section 1.1. The research context is introduced in Section 1.2. The problem is stated in Section 1.3 and subsequent research questions are specified in Section 1.4. The scope is detailed in

Section 1.5. Finally, the structure of the rest of this thesis is outlined in Section 1.6.

1.1 Company introduction

Wuunder is a company based on the concept of optimal shipment delivery. Wuunder strives to tackle some of the issues arising in the first and last mile of both business-to-business (B2B) and business-to-consumer (B2C) parcel delivery. This entails delivery of a shipment (pallet, parcel or document) to the exact specifications of the customer while minimizing the transport movements in the first and last mile and offering the best price. By implementing this optimization, Wuunder hopes to achieve an increase in life satisfaction for both customers and city residents through better service and fewer vehicle movements as well as a reduction in CO_2 emissions.

In order to achieve this goal, Wuunder employs so-called Wuunder points, these are hubs that are used as drop-off and pickup points, and arrange contracts with couriers (first and last mile delivery) and carriers (long haul). Thereby, they hope to eventually manipulate the system from the current situation as depicted in Figure 1.3 and Figure 1.4 to an integrated system as depicted in Figure 1.5. As this system combines the strengths of both carriers and couriers, efficiencies can be exploited. The new system has the reach and economies of scale usually enjoyed by transporting via a carrier while offering the service and ecological benefits related to the service of a courier.

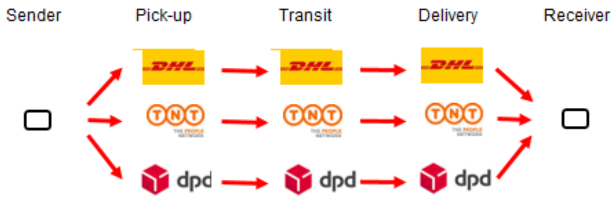


Figure 1.3: Existing long haul pickup and delivery process

Figure 1.4: Existing short haul pickup and delivery process

As depicted in these figures, Wuunder collaborates with actors in the current system. It should be noted that Wuunder does not own, nor intend to own any vehicles or Wuunder points, but endeavors to manage the system using the existing parties in a more coordinated way.

At the start of this project, in February 2017, Wuunder carried out around 300 shipments a week. For most of these packages, Wuunder would act as a comparison platform for different transporters. When a client sends a shipment via the platform, Wuunder extracts rates from the known carriers and selects the lowest rate for the specified package(s). Since Wuunder passes along the shipments of all clients combined, it gets a better rate than each client would get individually while saving time for the

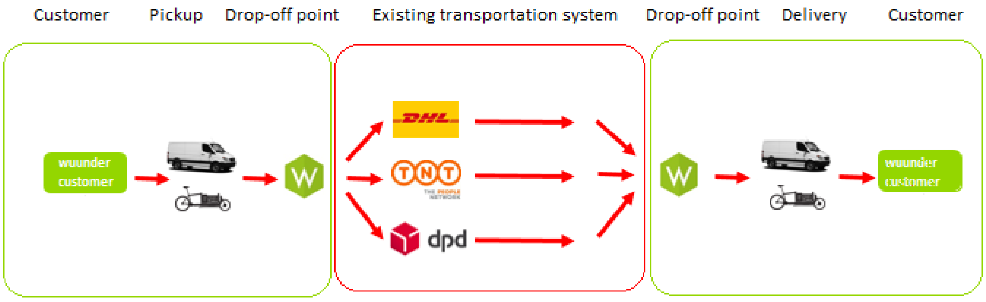


Figure 1.5: The pickup and delivery process as envisioned by Wuunder

client. The added benefits for the customer include that all shipments can be tracked via one platform. Furthermore, sender and receiver are connected through this platform creating a transparent shipping process, thus reducing misunderstandings and common mistakes in areas such as track-and-trace, pricing, and billing.

This idea is in line with the philosophy of the sharing economy, a rising pattern in consumption behavior that is based on accessing and reusing products to utilize idle capacity (Bonciu, 2016; Kathan et al., 2016). The enormous potential for price advantages, environmental sustainability, convenience, new consumption experiences, and social interactions affirms that the sharing economy will further thrive (Kathan et al., 2016). Joerss et al. (2016) conclude that the most likely scenario for future parcel delivery in the last mile is a dedicated bike courier model, similar to that already used by many prepared-food start-ups.

1.2 Research context

By deploying their concept, Wuunder intends to create a higher efficiency in the first and last mile using Wuunder points and couriers. This is a relatively new concept in parcel delivery. Therefore, scientific research is needed to validate the viability of the concept with regards to the arrangement of the system.

The introduction of hubs to a pickup and delivery system is expected to lead to a better use of vehicles, thereby lessening the driven distance in a system (Escuín et al., 2012). However, the capacities of couriers are limited in comparison to carriers. This is expected to lead to more trips than in the traditional system. If fixed costs are incurred when using these couriers, the cost savings due to reduced distances between hubs and customers are not necessarily offset by the increased fixed costs. Hence, both fixed costs related to the number of trips, as well as variable costs linked to distance should be considered.

In the planning horizon of just one day, a route needs to be determined for parcels. Carriers have specific times at which they need to have collected all packages in order to be able to deliver them in compliance with their service agreements. Customers have time windows in which they prefer or require to have their package picked up or delivered. Wuunder makes use of a heterogeneous fleet of vehicles, including bicycles and vans, to cater to the demand in the last mile. These vehicles have different capacities and since parcels come in all shapes and sizes, dimensions have a notable effect on these capacities. This heterogeneous vehicle fleet also has implications for travel time, since speeds vary for the different vehicles. Other factors such as congestion and restrictions by municipalities (in some cities, certain vehicles are restrained from entering various areas), complicate the matter of travel times further. The Wuunder points also have limited capacity which may vary from one point to another. During the execution of the route, new demands for pickups may arise which need to be incorporated into the route. Variability in quantities and sizes of pickup requests implies that input is stochastic in nature. This makes for a dynamic problem with stochastic inputs.

Demand locations are not all known beforehand and varies on a daily basis, especially in the last mile (first mile demand often comes from partners whose locations are known). Additionally, Wuunder accepts letters, parcels, and pallets, each with their own implications for required vehicle types. Furthermore, as home delivery increases so does the number of failed deliveries. Many parcels do not fit through mail- or letterboxes or require consignee signature, which implies that customers need to be at home when the parcel is delivered. However, often consumers are not at home when a package is delivered, which leads to increased delivery cost as the packages need to be redelivered or returned to the sender (Weltevreden, 2008). Failed first-time home deliveries may result in carrier's repeated delivery journeys as well as consumer's trips to retrieve their failed deliveries from the carrier's depot. Failed deliveries are clearly undesirable from all viewpoints: the carrier suffers additional costs in trying to make further attempts to deliver and through call center operations; the customer is inconvenienced and may have to travel to the carrier's depot personally to collect, and there are environmental costs due to added vehicle trips for all parties. This rate for failed first-time deliveries has been found to be between 12 and 60 percent (Song et al., 2011).

To optimally solve this problem the number and location of facilities as well as the routing needs to be considered, making it a location-routing problem (LRP). LRPs are essentially strategic decisions concerning facility location. The aim is to solve a facility location problem (the "master problem"), but in order to achieve this, a vehicle routing problem VRP (the "subproblem") must simultaneously be solved. This comprehensive approach and simultaneous solving of logistics problems prevents the local optimization of dependent problems (Nikbakhsh and Zegordi, 2010). These decisions are important in the sense that they greatly affect the level of service for customers and the total logistic system cost (Wu et al., 2002). However, in the case of parcel delivery, this subproblem varies daily. Furthermore, demands regularly arrive during the planning horizon, meaning that the planning should be adapted while in execution. As such the problem can be described as dynamic. Furthermore, due to the rate for failed first-time deliveries and unpredictable events such as incorrect client input and vehicle breakdowns, the problem also encompasses stochastic components.

1.3 Problem statement

If all the characteristics mentioned in the previous section were to be included in one theoretical problem, one could speak of the "Dynamic and Stochastic Dimensionally Capacitated Multi Commodity Dynamic Many-to-Many Pickup and Delivery Location Routing Problem with Time Windows, Heterogeneous Fleet, and Congestion" or the *DSDCMCDMMPDLRPTWHFC*.

The problem in its entirety is too multifaceted to be tackled while incorporating every aspect. Therefore, a focus on the most important features is necessary to create a relevant and relatively fast model, such that it is usable and still generates valuable output.

The question then becomes where the focus should be to create a model that is relevant in both its resemblance to reality as in its speed. In collaboration with Wuunder, certain key elements and goals have been identified. The goals that Wuunder identified related to the number of transport movements and utilization of vans in a city as well as customer satisfaction. By visiting customers only once a day and better utilizing the capacity of vehicles in the last mile, the total driven distance in the system is minimized. This leads to a safer and cleaner environment while saving costs. The means of bringing about this goal of a better environment at a lower cost are Wuunder points and couriers. As such the model presented in this report focuses on using those means to best achieve the goals set out by Wuunder.

Hence, this work emphasizes on the question of how the system can be optimally arranged in terms of number and type of courier trips as well as number of Wuunder points. In this problem, the different speeds, capacities, and costs (both fixed and variable) of the types of vehicles are considered, and the effect of time windows on the tours is taken into account.

1.4 Research questions

Based on the problem statement, it has been concluded that Wuunder requires a model which supports Wuunder in the decision-making process to determine how many Wuunder points and couriers are needed to optimally arrange the parcel delivery system. The optimal arrangement is that in which the least costs are incurred. Therefore, the main question this Master Thesis Project focuses on is as follows:

How can Wuunder arrange the parcel delivery system in a city in the most cost-effective way by using Wuunder points and couriers?

In this context, arranging the system is to link senders and receivers via couriers, carriers, and Wuunder points. Specifically, the intracity connections between Wuunder points via couriers are investigated, as this is the area over which Wuunder has influence. The effects are measured in costs since all aspects of the model can be rewritten using costs as a common denominator. When available, this report uses real values provided by partners of Wuunder. Otherwise, assumptions are made based on qualitative information and scientific literature.

To answer this research question, some sub-questions are formulated. Firstly, it is key to determine how many Wuunder points and couriers are needed for a certain scenario.

1. *Given a certain Wuunder maturity (number of customers), what is the optimal number of Wuunder points and what are the corresponding costs?*

Since Wuunder intends to grow and evolve as a company, it is interested in assessing the order in which they should implement the concept in cities given a growing customer base, whether it is to partner up with more couriers or more Wuunder points to facilitate the grow optimally. Thus, the following sub-question is of interest:

2. *What should the order of priority be for Wuunder to achieve the biggest savings in distance for different numbers of customers?*

As mentioned above, Wuunder is also interested in the environmental perspective of the concept. Therefore, an indication of the reduced environmental impact is researched in this report. The final research question regards this aspect:

3. *What are the effects of implementing the Wuunder concept in a city in terms of CO_2 and kilometers driven by vans?*

A clear delineation is necessary to effectively answer the questions mentioned in this section. The following section lays out the scope in which the proposed model operates.

1.5 Scope

It is important to note that Wuunder does not intend to own any of the Wuunder points or vehicles. The result of this is that Wuunder thereby has limited control over decisions. When all or most transport moves within a city are performed through Wuunder, Wuunder is able to perform route optimizations because of the high level of control and overview. However, even if this scenario is achieved within a city, there will be new cities and regions where Wuunder intends to implement their platform starting from a point of high uncertainty and no control. This research, therefore focuses on the savings that are achieved despite the limited of control on the transport moves within a city.

The location problem of the Wuunder points within a city is in practice also dependent on factors such as rent, distance, availability, and traffic. Again, these factors are considered too region specific to be included, for the model to be effective. The tactical decisions, specifically selection of suitable locations, customer assignment to hubs, and routing between hubs and mode selection (Zäpfel and Wasner, 2002) are not included. It is assumed in this report that couriers handle rationally according to the decisions made in terms of the number of locations and required couriers. This is fairly realistic since operational decisions follow from tactical decisions (Zäpfel and Wasner, 2002).

As discussed in the problem statement, the problem at hand is a highly convoluted one. To create a flexible and applicable model that is adaptable to different settings, some assumptions are needed, due to the many characteristics that make up the problem. Some of the characteristics are essential to the problem and on these, the report focuses. This includes the **time windows** that customers specify, capacities of vehicles and Wuunder points and the different types of vehicles. The **proportion** of customers with time windows as well as the **distance penalty** related to the time windows is included.

It is assumed throughout this report that couriers accept every order that Wuunder places. In practice, this can be (and sometimes already is) achieved through a contract with couriers. How couriers choose to incorporate pickups and deliveries in their routes is not a part of this project.

Included in the scope is the **modality** used for the delivery. Wuunder incorporates multiple modalities; **cargo bicycle, bike**, and **van**. These modalities all have diverse characteristics, of which **speed** and **capacity** are included. Additionally, the **fixed** and **variable costs** of these vehicles is also taken into account. The speed of a vehicle is assumed constant and thus independent of time of day and irregularities such as traffic jams or accidents. Vehicle capacity is estimated in the number of packages, which is equal for all vehicles of a certain type. The model calculates the required number of **trips** per vehicle type, that is to say, that not the required number of individual vehicles is calculated, but the number of trips per vehicle type required to service the region. From that number, Wuunder or the courier partner company decides how many vehicles and drivers are required to perform those trips.

In this report, only **parcels** are considered. Even though Wuunder also accepts shipments in the form of pallets or documents, shipping parcels is the core business activity. Furthermore, pallets require different modes of transportation, while documents could be considered a parcel. Therefore, by creating the model for parcels, the relevancy of the model is least reduced. Furthermore, it is assumed that a customer has a single transportation request. That is, the number of parcels is equal to the number of customers in the system.

The hubs or Wuunder points are assumed to be a single type facility. Wuunder points accept parcels from all carriers and no distinction between first and last mile is made for these hubs. The capacities are also considered equal for all Wuunder points. Direct interactions among facilities are not included in this report.

1.6 Thesis outline

The rest of this thesis is structured as follows: Chapter 2 presents the literary findings related to this topic. Chapter 3 explains the used methodology in further detail and describes how parameter values are determined. Chapter 4 describes the model formally and mathematically and presents the solution bounds. The results of the model are included in Chapter 5. The effects of certain parameter values are analyzed exhaustively in Chapter 6. Finally, the conclusions and recommendations based on this research are detailed in Chapter 7.

Chapter 2

Literature review

In this section, a brief overview of the related literature and the common findings are described. For a more exhaustive review the interested reader is referred to the complete literature review regarding hub-and-spoke systems in the first and last mile by de Kerf (2017). The remainder of this chapter is structured as follows: Firstly, the importance of optimizing the first and last mile of parcel delivery are described in Section 2.1. The type of problem that arises when this optimization is performed is called the Location-Routing Problem, which is described in detail in Section 2.2. Subsequently, Section 2.3 depicts the solution techniques which can be found in literature. Finally, Section 2.4 explains and analyzes continuous approximation models for this context.

2.1 Reasons for optimizing the first and last mile

The last mile delivery usually concerns the delivery process from the warehouse or distribution center to the recipient, either at the recipient's home or a collective point (e.g., a retail store). The last mile is generally considered the least efficient in the entire supply chain (Lin et al., 2016). Urban delivery consolidation has received increasing academic and practical attention among new, innovative city logistics strategies. With the right setting, it is believed to bring cost savings (Lin et al., 2016). In addition to improving efficiency, delivery consolidation could significantly reduce urban congestion and vehicle emissions if set up properly (Lin et al., 2016). The two main motives that have been identified for optimizing the first and last mile are environmental benefits and cost savings. In Sections 2.1.1 and 2.1.2 below, the potential benefits of a more efficient first and last mile for these issues is further elaborated on.

2.1.1 Environmental benefits

The increasing growth of online purchasing and home delivery has contributed to the recent growth in van traffic, vehicles that consume more fuel and release more emissions per metric ton moved than larger vehicles (Mangiaracina et al., 2015). In the review by Mangiaracina et al. (2015), three of the four main types of indicators used to assess the environmental implications of e-commerce logistics are directly linked to location and routing problems as were two of the four themes they discovered in the literature. Though the last-mile of local delivery is often reported as the largest contributor to fossil fuel consumption, CO_2 and local air emissions, comprising 30-55 percent of the total impact of the retail system, the benefits of coordinated drops by delivery companies tend to outweigh the highly inefficient vehicle miles associated with personal shopping trips to and from retail locations. This is due to the fact that personal car trips to and from shops generally use much more energy and emit more CO_2 per tonne-km of freight movement than home delivery vans (Edwards et al., 2011). Customer transport to and from the retail store for traditional retail account for up to 65% of primary energy expenditure and CO_2 equivalent emissions on average. Online retailing can therefore play a role in reducing the high impact of personal vehicle miles. However, significant potential still exists for improvement in the environmental performance of the home-delivered last mile (Suh et al., 2012).

Previous research (e.g. Weber et al., 2009) suggests that the last mile accounts for a large proportion of the total CO_2 (approximately 32% for e-commerce of primary energy expenditure and CO_2 equivalent emissions on average) emitted from a retail supply chain, thus dominating the calculation. Last mile energy intensity was rated the third most important category for CO_2 impact in retail and most important factor for e-commerce retail (Weber et al., 2009). With online retailing becoming so important and some research advocating the environmental benefits of online over conventional shopping (Edwards et al., 2011; Weber et al., 2009), optimizing the last mile seems the logical first step for the most impactful gains in CO_2 emission reduction. Transportation decisions in this area can significantly impact the environmental performance of an entire distribution process (Mangiaracina et al., 2015).

Closely related to the environmental factor is the political aspect. In Europe for example, break-bulk operations may be required due to street design or policy regarding certain types of vehicles. Drop-off points can perform these break-bulk operations so that the outbound shipments can be carried out by smaller (and cleaner) commercial vehicles (Lin et al., 2016).

2.1.2 Economic benefits

Logistics costs often represent a large portion of company expenses (Prins et al., 2007; Prodhon and Prins, 2014). Transportation is a key logistics activity, whose efficiency plays a crucial role in total costs of supply chains and business success (Rieck et al., 2014). The last mile is of particular importance, as the costs for this segment account for up to between 28-50 percent of total delivery costs (Hübner et al., 2016; Wang et al., 2016), because it involves many small product flows towards end-customers or retailers (Prodhon and Prins, 2014) and many deliveries are unattended (Wang et al., 2016). Thus, significant cost benefits might be achieved by increasing the efficiency of the last mile segment (Ghilas et al., 2016). This might be easier said than done since it is known that complex and costly vehicle routing remains an issue in home delivery of parcels (Hübner et al., 2016).

The economic benefits that can be realized in the last mile through hub-and-spoke systems are mostly related to economies of scale (Campbell and O'Kelly, 2012; Contreras et al., 2011; Greasley and Assi, 2012) and vehicle utilization (Greasley and Assi, 2012), thereby lessening the driven distance (Escuín et al., 2012). The decrease in transportation cost can and should outweigh the increase in handling cost at the hub (Lin and Chen, 2008). In recent literature, it has been shown that consolidation within a city could become a more attractive alternative to direct delivery, solely based on monetary cost, maximizing the utilization of the vehicle capacity by consolidation (Lin et al., 2016). It is furthermore noted by Lin et al. (2016) that urban consolidation could be both economic and environmentally sustainable when there is an economy of scale or high customer density.

2.2 The Location-Routing Problem

Logistic costs often represent a large portion of company expenses. To reduce them, depot location and vehicle routing are crucial choices. Most of the time, these two levels of the decision are tackled separately, but, unfortunately, it has been shown that this strategy often leads to suboptimal solutions. The location-routing problem (LRP) integrates these two decision levels (Prins et al., 2007). The two main sub-problems of LRP are the Location-Allocation Problem (LAP) and the Vehicle Routing Problem (VRP) (Nikbakhsh and Zegordi, 2010).

In LRPs, the objective is to locate one or many depots within a set of sites (representing customer locations or cities) and to construct delivery routes from the selected depot or depots to the remaining sites at least system cost (Laporte et al., 1986). It can be thought of as an approach to modeling and solving locational problems. Location-routing can be defined as location planning with tour planning aspects taken into account (Nagy and Salhi, 2006). The LRP is also sometimes described as a multiple depot vehicle routing problem (MDVRP) in the literature (Sajjadi et al., 2010). LRPs are essentially strategic decisions concerning facility location. The aim is to solve a facility location problem (the "master problem"), but in order to achieve this, a VRP (the "sub-problem") must simultaneously be solved. This comprehensive approach and simultaneous solving of logistics problems prevents the local optimization of dependent problems (Nikbakhsh and Zegordi, 2010). These decisions are important in the sense that they greatly affect the level of service for customers and the total logistic system costs (Wu et al., 2002).

The LRP is applicable to a wide variety of fields, parcel delivery being one of them (Yu et al., 2010). In the case of parcel delivery, the problem is sometimes described as the many-to-many location-routing problem (MMLRP), corresponding with the postal flow between localities (Nagy and Salhi, 2006).

It should be noted that this is an NP-hard problem, as it encompasses two NP-hard problems (the facility location problem and the vehicle routing problem) (Campbell and O'Kelly, 2012; Contardo et al., 2014; Nagy and Salhi, 2006; Nikbakhsh and Zegordi, 2010).

2.3 Solution techniques

Recent researches in the design of logistic networks have shown that the overall distribution cost may be excessive if routing decisions are ignored when locating depots. LRPs constitute a difficult class of NP-hard combinatorial optimization problems combining location and network design decisions. Their main difficulty stems from the inherent interrelation between two levels of the decision process (Contreras et al., 2011). Solution techniques should overcome this drawback by simultaneously tackling location and routing decisions (Belenguer et al., 2011). Solution approaches for the LRP can be divided roughly into heuristics and exact methods. There are more papers using heuristic methods, but exact methods are often very successful for special cases of the LRP (Nagy and Salhi, 2006).

Logistics and operations researchers have done extensive research on the design and operations of local delivery systems to determine the most cost-effective methods of delivery. Due to the complexity of the problem, only very small LRP instances can be solved exactly by linear programming solvers. A few exact approaches are available, but they begin to fail beyond 50 customers. Therefore, heuristics are required to obtain appropriate solutions in acceptable running times on the large instances that can be met in practical applications (Liu et al., 2003; Prodhon and Prins, 2014). A comprehensive list of the solution techniques used in the papers that were studied, is given in Table A.1 in Appendix A.

Most solution techniques have been tested on sets of standard benchmarks with the number of customers varying from 10 to 318 and the number of (sometimes uncapacitated) depots varying from 2 to 20. Furthermore, not all benchmark sets include capacitated vehicles. The remainder of this section will go into detail about the three different types of solution techniques for these problems and their characteristics.

2.3.1 Exact solution techniques

Despite the considerable efforts already made by many researchers, the optimal solution of LRPs remains challenging, particularly when considering more realistic, large scale instances (Contreras et al., 2011). Literature has been less devoted to exact algorithms and it is recognized that these algorithms are only applicable to relatively small instances (Belenguer et al., 2011; Correia et al., 2011). In general, finding the exact solution via optimization approaches has remained theoretically and computationally challenging (Mahmoudi and Zhou, 2016).

However, some problem instances within this area can be solved exactly. For a problem where weight is assigned to sites (customer locations or cities) and a homogeneous vehicle fleet with a given capacity, an exact algorithm is capable of solving problems with up to 20 sites (Laporte et al., 1986). Another algorithm, developed by Belenguer et al. (2011) is able to solve instances with five potential hubs and up to 40 customers optimally.

2.3.2 Heuristics

As mentioned before, heuristic solution techniques are efficient tools for arriving at near optimal solutions within a reasonable time frame. A few heuristics have been proposed in the last decade for location-routing problems (Prodhon and Prins, 2014). Most of the heuristics separate the decision levels into sub-problems and handle them sequentially or iteratively (Belenguer et al., 2011).

Nagy and Salhi (2006) discuss four types of LRP heuristics, namely iterative, clustering-based, hierarchical, and sequential. *Iterative algorithms* improve the solution by repeating the algorithm. *Clustering algorithms* start by classifying the customer set into clusters and then assigning clusters to potential depots (or vehicle routes). Then, the algorithm solves location (routing) and routing (location) sequentially. A *hierarchical based algorithm* consists of two sub-algorithms: main algorithm and subroutine. The main algorithm solves the location problem and subroutine, which receives feedback from main algorithm at each step, solves the routing part. In addition to these three heuristics solutions, LRP models have been solved using sequential methods as well. The *sequential method* considers location and routing problem as two individual problems and solves two problems separately leading to sub-optimal solutions. For this reason, sequential solution methods are not considered as a LRP solution method although it is used some times in the literature (Sajjadi et al., 2010). Examples of heuristics used on LRPs include the Local Improvement heuristic by Contardo et al. (2014) and the Fix-and-Optimize heuristic by Rieck et al. (2014).

2.3.3 Metaheuristics

On average, metaheuristics give better results than heuristics (Prodhon and Prins, 2014). Nonetheless, faster and simpler methods are always useful to assist in finding quickly feasible solutions to large instances or initialize a more sophisticated algorithm.

The cooperative metaheuristic presented in Prins et al. (2007) is on average the most effective on benchmark instances from the literature: it alternates between a location sub problem, solved by Lagrangian relaxation, and a multi-depot VRP, solved by a granular tabu search (Belenguer et al., 2011). Sajjadi et al. (2010), propose two metaheuristics for a related problem. One is based on simulated annealing and the other is based on a combination of simulated annealing as well as an ant colony system. Overall it can be said that no specific method is used disproportionately often in the literature, as many new solution techniques are still being developed, tested and reviewed.

Although exact algorithms are suitable for small size instances, as problems become large and heavily constrained exact methods are no longer suitable to solve the problem and often fail to get an optimal solution owing to the computational time required (Zainudin et al., 2015). On the other hand, approximate algorithms can obtain satisfactory solutions in competition time, but there is no guarantee to find global optimal solutions (Zainudin et al., 2015). As mentioned above, these algorithms can be classified as classical heuristics and meta-heuristics. From Nagy and Salhi (2006) we gather that these can be classified into sequential, clustering-based, iterative, and hierarchical methods. Meta-heuristic combines basic heuristic strategies in higher level frameworks in order to explore search space more efficiently. Since these algorithms have good abilities to explore search space and are unquestionably efficient to get from a local optimum, they are candidate algorithms for solving combinatorial optimization problems (Zainudin et al., 2015).

2.4 Continuous approximation models

Encompassing very detailed routing aspects in strategic fleet composition is impractical because of the difficulty in accurately predicting data and in solving the corresponding models. In such contexts, Francis and Smilowitz (2006) advocate the development of continuous approximation models in which aggregated data are used instead of detailed inputs (Jabali et al., 2012).

Aggregating data smooths minor dynamic and stochastic variations in input parameters which are less critical in strategic planning. Furthermore, this approach yields simplified models which enable the solution of large instances. For example, the continuous approximation model developed by Nourinejad and Roorda (2017) is able to solve experiments with 200-300 customers and three vehicle types in less than 1 second, as its computation time is independent of problem size. Jabali et al. (2012) were the first to apply continuous approximation models to the fleet composition problem. The widespread use of continuous approximation models in freight distribution provided a strong incentive for their application to this problem. Jabali et al. (2012) introduce a continuous approximation model rooted in the works of Daganzo (1984a) and Daganzo (1984b), which can be used at an aggregate level to analyze various cost and capacity scenarios. At the operational level, the model can be complemented by solving the corresponding FSMVRP. Specifically, they build upon the work of Newell and Daganzo (1986) who introduced a continuous approximation model for the VRP. Their model designs vehicle routes based on partitioning a ring-radial region into zones, each of which is serviced by a single vehicle. Mixed vehicle fleet considerations are incorporated into the model of Newell and Daganzo (1986) to yield the Fleet Composition with Continuous Approximation (FCCA) model presented by Jabali et al. (2012). This modeling approach can also be directly applied to assess the impact of new vehicular technologies on fleet composition, and thus to incorporate environmental considerations in the planning process (Jabali et al., 2012).

Francis and Smilowitz (2006) develop a continuous model which is an approximation of the discrete formulation. They show that the continuous approximation is quite accurate in estimating the objective value for a test case in the literature. Furthermore, the continuous approximation model can be solved easily with a few modifications. The modified continuous approximation model yields solutions for large instances which may arise in the strategic planning phases of periodic distribution systems. Thus, the continuous model is not suggested as a replacement for the discrete modeling approach; rather, it is a complementary model that can be used to estimate costs and develop design guidelines (Francis and Smilowitz, 2006). The paper focuses on the use of the continuous approximation method for strategic decision making, estimation, and the selection of parameters. After parameters have been chosen, the operational/tactical decisions can be made using the discrete method.

The accuracy of the continuous approximation formulas improves with problem size quite dramatically. This is fortunate, as it means both that the formulas describe the optimum costs of large complex problems well, and that the CA discretization algorithm complements conventional methods where they would have the most difficulty (Ouyang and Daganzo, 2006).

Continuous approximations are useful in developing models that are easy for humans to interpret and comprehend. Discrete approximations are useful in developing models that are easy for computers to 'comprehend'. When the number of discrete objects is large enough, a continuous function closely approximates a discrete function or discrete data. Therefore, the models do not compete with each other; they complement each other (Hall, 1986).

Chapter 3

Methodology

In this chapter, the methodology of how the problem is dealt with is illustrated. The procedure applied in this report is visualized in Figure 3.1. This figure depicts the procedure from start to end and specifies in which section further details concerning the process are given.

The initial process concerns the selection of the solution approach. A model with continuous approximation has been selected due to the suitability of its characteristics to the problem at hand, as discussed in Section 2.4. After the solution approach is selected, three decisions are made. Firstly, a region is selected and it is determined how this region is approximated by a simple shape, described in Section 3.1. This in turn affects how the zoning within the region is approached (Section 3.1) as well as how the optimal number Wuunder points is assessed (detailed in Section 3.2). Secondly, the incorporation of time windows into the model is decided upon. In Section 3.3, this aspect is discussed in more detail. Thirdly, the inclusion of a heterogeneous vehicle fleet in the model is determined, which is presented in Section 3.4.

When all these determinations are made, a mathematical formulation of the model is made. This formulation is presented in Section 4.3. The resulting model is then reviewed. Specifically, it is evaluated whether or not the model can be solved optimally within a reasonable time. If this is not the case, an upper and lower bound are created to approximate the optimal solution. Section 4.4 describes this process. Finally, an analysis of the model is made to determine optimal configurations and costs for the selected scenarios. These results are presented in Chapters 5 and 6.

The resulting model accomplishes the following process: Input in the form of vehicle and region characteristics should be ‘transformed’ into valuable output. Specifically, the optimal solution should provide the costs and the corresponding configuration. Figure 3.2 gives a visualization of the process performed by the model. A **configuration** in this report is given by the set of the following items required to service a region:

1. Number of districts/Wuunder points;
2. Number of van trips;
3. Number of cargo bike trips;
4. Number of bike trips;
5. Layout specifics of the region

The remainder of this chapter is structured as follows: Firstly, the zoning strategy is described in Section 3.1. Secondly, Section 3.2 details how the number of Wuunder points is evaluated in this report. Thirdly, the inclusion of time windows in the model is described in Section 3.3. Finally, Section 3.4 presents the incorporation of the different types of vehicles and their characteristics.

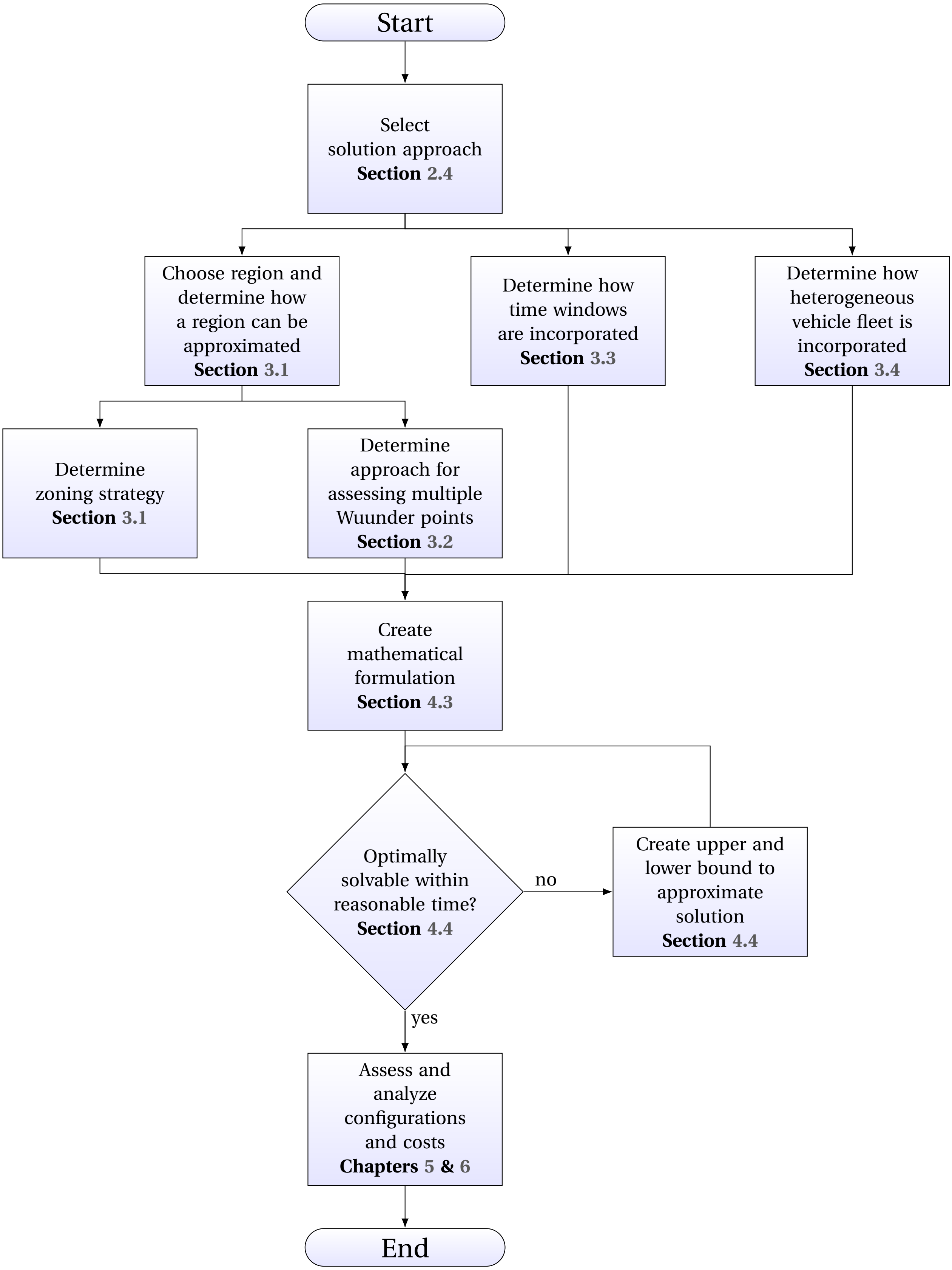


Figure 3.1: The procedure applied in this report to analyze the problem

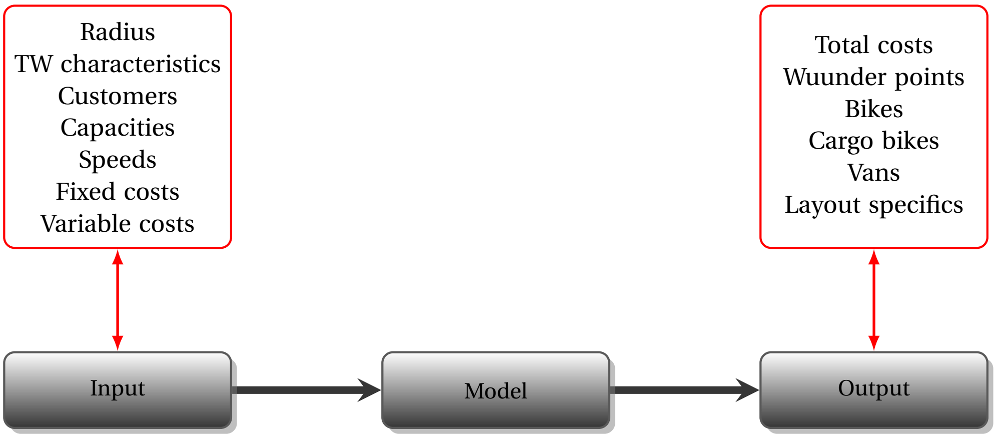


Figure 3.2: The process performed by the model transforming input into output

3.1 Zoning strategy

It is assumed that every region and district can be approximated by a disk-shaped district. While this may not be true for every city, Daganzo (1984a) has shown that 10-20% deviations of the relative dimensions of a sector affect the distance traveled within a sector by only 1 or 2%. In Figure 3.3 it is shown how the Eindhoven region is approximated by a disk-shaped district. The depot is located in the center of this region.

Figure 3.3: Approximation of the Eindhoven region using a single Wuunder point

Partitioning a service region into zones, often called districting, is a common practice in distribution management. It facilitates the planning of consistent routes, which makes managerial sense and yields solutions in which customers are regularly served by the same driver (Ouyang and Daganzo, 2006). This practice is also particularly well suited to stochastic problems in which several parameters are uncertain when the problem is solved. In recent years, continuous approximation models have been embedded within combined stochastic districting and routing algorithms. As Chapter 2 showed, this is an apt methodology for the problem at hand. The wording for some concepts varies throughout literature. For clarity, this report uses the following terminology, of which a visualization is given in Figure 3.4:

- **Region**: The entire area to be serviced by one or multiple Wuunder points, such as a city.
- **District**: The area serviced by one Wuunder point.
- **Zone**: An area containing one or more customers, served by one vehicle.
- **Sector**: The triangularly shaped partitioning of the inner ring in a district (also a zone).

The service region is made up of an inner circle (called inner ring) partitioned into sector-shaped zones, and of outer rings divided into zones having the shape of circular trapezoids. In Figure 3.4 a decomposition of the region into zones is shown.

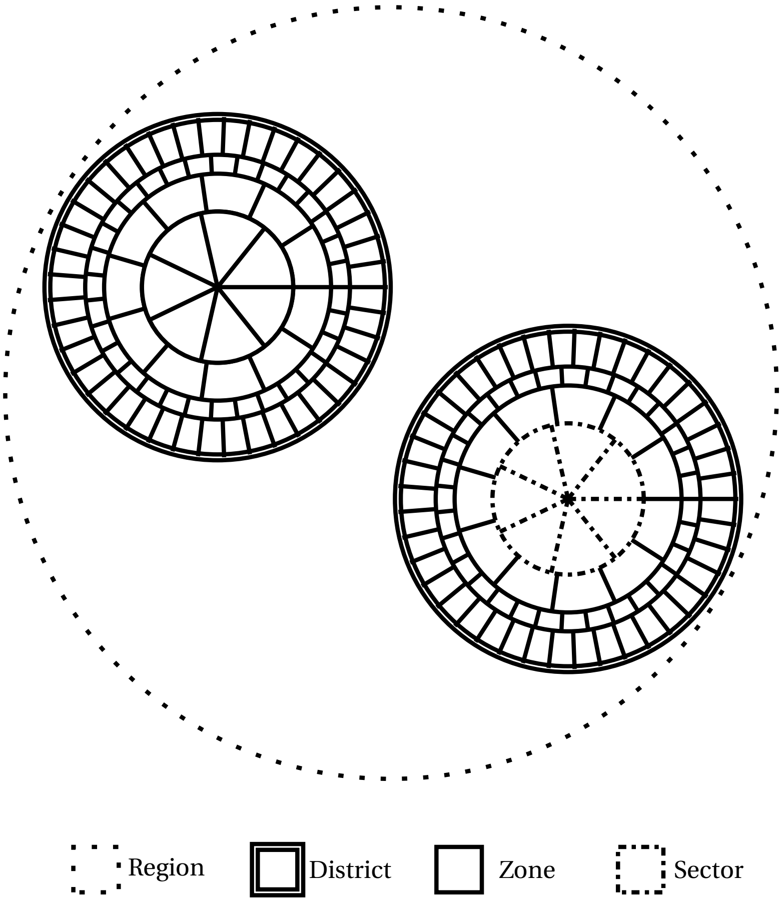


Figure 3.4: Visualization of the different types of areas within the region

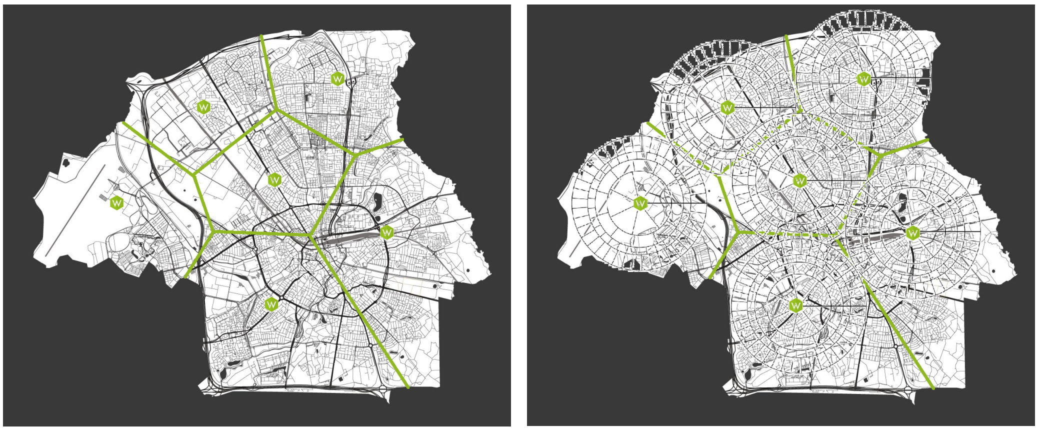
Models based on ring-radial delivery zones have been employed by Newell and Daganzo (1986) and Langevin and Soumis (1989) to approximate the cost of a routing solution with a large number of customers in a deterministic context. For a given ring-radial zoning these models determine the number and sizes of cost-effective zones within each ring. They provide a good approximation of the solution structure and cost without requiring a detailed treatment of customer locations. Therefore, they can be used as a means of computing strategic solutions to routing problems (Jabali et al., 2012).

One could also argue for using a rectangular grid network as opposed to a ring-radial network. Nourinejad and Roorda (2017) propose a continuous approximation model for solving the fleet composition problem in rectangular grid networks. This is very well suited for cities where the infrastructure resembles a Manhattan type of street grid. In the Netherlands however, this is often times not the case. In the ring-radial approach technically requires two roads converging at the depot for each zone in the inner ring. This is not realistic, but it gives more coherent zones than a rectangular grid. However, there are a few downsides to rectangular grid networks. Firstly, it requires a square-shaped service region in contrast to a circular shaped region. Secondly, the model has more decision variables and requires more algorithms to compute costs, making the process more tedious. Lastly, literature has devoted more attention to the ring-radial network and the only downside mentioned in the paper by (Nourinejad and Roorda, 2017) concerns the unrealistic aspect of different radial roads meeting at the depot. Therefore a ring-radial network is chosen in this report as the upsides are perceived to outweigh the downsides for this case. The official requirement of two different roads per sector is overlooked here and the same road can be used for inbound and outbound transportation, as this is not immensely different from the theoretical framework.

3.2 Multiple Wuunder points

This report assumes homogeneous customer demand and therefore uniform hub density. Ouyang and Daganzo (2006) show how the system could be designed if customer demand is inhomogeneous, but this is considered outside of the scope of this research. After calculating the distances for a single depot in the region, the region could be split up using a Voronoi tessellation. This approach entails that a region is divided by the line for which the distance to the two nearest depots is equal, known as an equidistant line. An example of this approach is depicted in Figure 3.5a. The last step for the shape of the districts is then to assume that this Voronoi diagram is approached by congruent (equal in size) non-overlapping circular service districts, designed as described above. For Eindhoven, it is shown how 6 districts could approximate the region in Figure 3.5.

To assess the added value of Wuunder points, the region is partitioned into districts as described above. To ensure the districts cover the same area, the radius of the region is divided by $\sqrt{p}$ to obtain the radius for a district. This implies that the total number of customers in the region is divided by the number of Wuunder points p to derive the number of customers per district. In this manner, the customer density remains equivalent. The value for the objective function in the optimum is then multiplied by p to derive the total costs of this configuration for the region. The initial value for p is set to 1, even if the number of customers exceeds the maximum Wuunder point capacity, i.e. $\lceil \frac{e}{240} \rceil > 1$, where e denotes the total number of customers and 240 packages is determined to be the maximum capacity of a Wuunder point. In later stages, it is then determined if the capacity of a Wuunder point influences the optimal value for the objective function. The value of p is then incrementally increased until a termination condition is met.



(a) A Voronoi tessellation for the Eindhoven region using 6 Wuunder points

(b) Example of a partitioning of the Eindhoven region using 6 Wuunder points

Figure 3.5: Example of distribution of the Eindhoven region when 6 Wuunder points are used

3.3 Time Windows

Since time windows play a crucial role in the first and last mile of parcel delivery, modeling choices are made to incorporate for this effect. Figliozzi (2009) accounts for this effect by including regression factors in the initial model developed by Daganzo (1984a) to assess the impact of the time windows on the expected route length. Given a set of n orders, V^n, the total amount of distance traveled using a vehicle routing problem, $VRP(V^n)$, is approximated. Factors for the connecting distance, local distance, and time window penalties are estimated by applying linear regression to historical data. Generally speaking, the model can be fitted in a few steps:

1. Drafting model(s) with regression factors;
2. Optimally solve the problem for many small instances;
3. Estimate the values for the regression factors using statistical analysis;
4. Depending on if multiple models are evaluated: choose the model with the best fit.

Vercammen (2016) applies this method to approximate the route length in the case of Van Opzeeland, a freight distribution company. A variation of the model applied by Figliozzi (2009) is used, where the values for the distance penalties related to types of time windows are estimated.

As mentioned before, to apply this method in this problem context, small instances are required to be able to solve the model optimally within a reasonable time. The downside of this method is that the values determined through this analysis might not hold for larger instances. Therefore, this report makes use of a model and estimates adapted from literature and test the values for the estimates rigorously in Chapter 6. The model used in this report is adapted from Figliozzi (2009) and Vercammen (2016) and is described by the expression in Equation 3.1.

$$VRP(V^n) \approx k_l * \sqrt{An} + k_d m_d \bar{r} + \sum_{i=1}^{4} k_{t_i} n_{t_i} \bar{r} \tag{3.1}$$

Where,

A = size of area
n = amount of orders
n_{t_i} = amount of time window orders of type i
m = amount of vehicles
m_d = amount of vehicles required without time window restrictions
$\bar{r}$ = average distance from depot to customer
k_l = estimate for local distance
k_d = estimate for connecting distance
k_{t_i} = estimate for distance penalty per time window orders of type$i$

In the research of Vercammen (2016), a significant estimate was found for the smallest time window of $k_{t_1} = 0.036$ as well as for second largest of $k_{t_3} = 0.2$. Following the proposed model this means that any customer with a very tight time window impacts the route length with a factor of $0.036 * \bar{r}$. This estimate is based on regression analysis of the historical data at Van Opzeeland, which is specialized in delivering to retail stores. Therefore, this only gives an indication of the range in which the estimate is situated in the current case. The contribution of time windows to the distance traveled per customer is bounded as in the worst case scenario an additional trip is required for every customer with a specified time window that cannot be included in current routes. Time windows, being additional constraints, cannot reduce the VRP distance (Figliozzi, 2009). It is evident that the proportion of customers with time windows is bounded between 0 and 100 percent. Using the literature, an extensive analysis is required on the impact of these factors on the solution obtained by the model in this report. In Chapter 6 the effects of the exact values assigned to time window penalties on route duration, costs and fleet composition are examined.

Rationally, more and tighter time windows imply a greater driven distance if no other restrictions, such as capacity or time constraints, become binding. The reason for this is that time windows require a different than optimal routing or more frequent trips to the depot to comply with the specified time windows. For vans, it is more likely that time windows require a suboptimal routing. For (cargo) bikes, it is more likely that time windows require additional trips, due to the smaller capacity. In this report, the distances and costs are estimated by adjusting the FCCA model established by Jabali et al. (2012) and implementing the formulas developed by Figliozzi (2009) and Vercammen (2016) into the constraints.

3.4 Heterogeneous vehicle fleet

Another important aspect of the problem is concerning the heterogeneous vehicle fleet. In the model, the three types of package delivery vehicles are considered that are most commonly used by Wuunder. These are bicycles, cargo bicycles, and delivery vans. The characteristics that are included in the model are the fixed and variable costs, expected capacity in a number of packages, and average speed of the type of vehicle. The values for these attributes are obtained by interviewing the current partners of Wuunder.

For the **vans**, information is disclosed about the price for one stop and an hourly rate. The speed of a van as well as the service time per stop is also known. Using these variables two points could be derived and consequently a system of equations could be solved. These calculations are shown in Equation B.1 in Appendix B. The speed and capacities of these vehicles required no further calculations as they were specified in the form as they are required by the model.

The **couriers using (cargo) bicycles** have tariffs for certain destinations instead of explicit fixed and variable costs. These values are given in Table B.1. However, the model only accepts fixed and variable costs. Therefore, an approximation is made on these costs.This is done by calculating the slope and intersection of the line starting in the middle of tariff 1 (6.50 € for 0-4.4 km) and tariff 4 (18.00 € for 11-14 km). This system of equations is then solved. Additionally, the Area Under Curve (AUC) of both functions is compared for validation. In Equations B.2 and B.3 a detailed elaboration of these operations is given. The tariffs handled for cargo bicycles are identical, except for an additional 2,50 € applied to all destinations. Hence the fixed and variable costs for these vehicle types are derived. Similarly to the specifications disclosed for the vans, the speed and capacity characteristics required no further calculations.

Chapter 4

Model formulation

The problem definition of the fleet composition and hub selection problem is given in this chapter. This chapter is structured as follows: In Section 4.1, the formal description of the fleet composition and explanation of the units used is given. A concise overview of the assumptions made in the fleet composition model is shown in Section 4.2. In Section 4.3, the mathematical formulation of the fleet composition model is given, followed by the adaptations made to create solution bounds for the model that can be solved by state of the art solvers in Section 4.4. Finally, Section 4.5 describes how the optimal number of Wuunder points is determined.

4.1 Formal description

In this section, the mathematical formulation of the problem is given. It is an adaptation of the model presented by Jabali et al. (2012) with the addition of different vehicle speeds per vehicle type and customer time windows. A circular district of radius r is considered, with the depot located at its center, at which vehicles start and end their tours.

Each zone is assigned to a single vehicle. A total of e customers are randomly distributed with a density $\delta = \frac{e}{\pi r^2}$. A set $Q = (1, \ldots, q)$ of q different vehicle types is given. Let c_i denote the capacity of vehicle type i, equal to the number of customers it can serve. Vehicle type i has a fixed cost f_i, a variable cost d_i per kilometer, and a speed v_i in kilometers per minute. The fixed and variable costs of a vehicle should increase with its capacity. Thus, we relabel the vehicle types such that $f_1 \geq \ldots \geq f_q$, $d_1 \geq \ldots \geq d_q$ and $c_1 \geq \ldots \geq c_q$. These relations stem from the fact that larger vehicles yield economies of scale but are more expensive to operate than smaller ones. Therefore, a trade-off must be made between operating several low-cost vehicles or fewer more expensive larger vehicles. No such theories are related to the speeds of the vehicles. In fact, some larger vehicles, such as cargo bikes, might be slower than smaller vehicles such as bikes, whereas vans are faster than both vehicle types. Therefore, no relations between the speeds of vehicle types are assumed. Time windows are incorporated as well. The characteristics are given by the proportion of all customers with time windows p_t, and the distance penalty k_t that is incurred for each time window. This distance penalty is multiplied by the average distance from depot to customer, which simply is $\frac{r}{2}$ in this case. A limit t on the duration of a vehicle route is considered. We design the zones and determine a vehicle type for each of them, and we assume that each ring is serviced by a unique vehicle type. The zone width for outer rings is fixed to $w^* = \sqrt{\frac{3}{2\delta}}$, the optimal width of a circular trapezoid. For ease of notation the term $\gamma = l_1 \Theta = 0.95\sqrt{\frac{3}{2\delta}}$ is introduced. In Table 4.1 an overview is given of the variables used in this model along with their definitions in order of appearance in the objective function and constraints depicted in Section 4.3.

Notation	Description
Q	Set of vehicle types
K	Set of rings, where ring 1 represents the innermost ring
f_i	Fixed costs of vehicle $i \in Q$ in euros
d_i	Variable costs of vehicle $i \in Q$ in euros
c_i	Capacity of vehicle $i \in Q$ in a number of packages
v_i	Speed of vehicle $i \in Q$ in kilometers per minute
p_t	Proportion of clients with time windows
k_t	Distance penalty per time window
r	Radius of the district
w^*	Optimal width of a circular trapezoid
δ	Customer density
γ	$0.95\sqrt{\frac{3}{2\delta}}$
M	A large number
μ	Service time in minutes
t	Duration limit in minutes
e	Total number of customers
r_r	Radius of the region

Table 4.1: Notation and description of the units used in the model

4.2 Modeling assumptions

The assumptions of the model are summarized as follows:

- Customer demand density is constant throughout the region;
- One single vehicle type is assigned to each ring and one vehicle is assigned to each zone;
- Each vehicle type can serve a limited number of customers;
- A vehicle starts and ends its tour at the depot;
- The fixed and variable costs of a vehicle increase with its capacity;
- There is one type of time window a client can specify.

4.3 Mathematical formulation

An exhaustive clarification of the constitution of the constraints is given by Jabali et al. (2012). In this report, only the essence of this explanation is given.

The number of outer rings depends on the vehicle fixed and variable costs, on their capacities, and on the route duration limit t. Thus, determining the number of rings is rather involved. It is assumed that there can be at most k rings in the model, the computation of which is detailed below. An additional vehicle type 0 with $f_0 = d_0 = c_0 = v_0 = 0$ is defined. If the solution requires $k' \leq k$ rings, a dummy vehicle of type 0 will be assigned to the $k - k'$ residual rings of zero length. In order to compute the potential number of rings k, including the inner ring, it is assumed that only the vehicle with the smallest capacity

c_q is available. Let j index the rings in increasing value of their distance from the depot. The following decision variables are defined:

$n_{ij} =$ the number of vehicles of type i assigned to ring j;

$$x_{ij} = \begin{cases} 1 & \text{if vehicle type } i \text{ is assigned to ring } j, \\ 0 & \text{otherwise;} \end{cases}$$

$$l_{ij} = \begin{cases} \text{the radius of the inner ring for vehicle type } i \text{ if } j = 1, \\ \text{the length of the circular trapezoidin ring } j \text{ for vehicle type } i \text{ if } j > 1; \end{cases}$$

$y_{ij} =$ the distance traversed by vehicle i from the depot to the inner edge of ring j :

$$\begin{aligned} \text{(FCCA) Minimize} \sum_{i=0}^{q}\sum_{j=1}^{k} f_i n_{ij} + \left(1 + p_t k_t \frac{r}{2}\right) * \Bigg[\frac{2\pi}{w^*} \sum_{i=0}^{q}\sum_{j=2}^{k} d_i \left(y_{ij} + \frac{l_{ij}}{2}\right)^2 \\ + 2\delta\pi\sqrt{\frac{2}{3\delta}} \sum_{i=0}^{q}\sum_{j=2}^{k} d_i \left(y_{ij} + \frac{l_{ij}}{2}\right) l_{ij} + \frac{2\pi}{\gamma}\sum_{i=1}^{q} d_i l_{i1}^2 + \frac{\delta\gamma\pi}{3}\sum_{i=1}^{q} d_i l_{i1}^2 \Bigg] \end{aligned} \tag{4.1}$$

Subject to:

$$\frac{\pi l_{i1}}{\gamma} * \left(1 + p_t k_t \frac{r}{2}\right) \le n_{i1} \qquad (i = 1, \ldots, q), \tag{4.2}$$

$$\frac{\pi}{w^*}\left(y_{ij} + \frac{l_{ij}}{2}\right) * \left(1 + p_t k_t \frac{r}{2}\right) \le n_{ij} \qquad (i = 0, \ldots, q; j = 2, \ldots, k), \tag{4.3}$$

$$\sum_{i=1}^{q} x_{i1} = 1, \tag{4.4}$$

$$\sum_{i=0}^{q} x_{ij} = 1 \qquad (j = 2, \ldots, k), \tag{4.5}$$

$$n_{ij} \le M x_{ij} \qquad (i = 0, \ldots, q; j = 1, \ldots, k), \tag{4.6}$$

$$y_{ij} \le M x_{ij} \qquad (i = 0, \ldots, q; j = 1, \ldots, k), \tag{4.7}$$

$$l_{ij} \le M x_{ij} \qquad (i = 0, \ldots, q; j = 1, \ldots, k), \tag{4.8}$$

$$\sum_{m=0}^{q} \left(y_{m,j-1} + l_{i,j-1}\right) - M(1 - x_{ij}) \le y_{ij} \qquad (i = 0, \ldots, q; j = 2, \ldots, k), \tag{4.9}$$

$$\delta\gamma l_{i1} * \left(1 + p_t k_t \frac{r}{2}\right) = c_i x_{i1} \qquad (i = 1, \ldots, q), \tag{4.10}$$[1]

$$2\delta w^* l_{ij} * \left(1 + p_t k_t \frac{r}{2}\right) \le c_i \qquad (i = 0, \ldots, q; j = 2, \ldots, k), \tag{4.11}$$

$$\sum_{i=0}^{q} \left[\frac{1}{v_i} \left(2\left(y_{ij} + \frac{l_{ij}}{2}\right) + 2\delta w^* l_{ij}\sqrt{\frac{2}{3\delta}} \right) * \left(1 + p_t k_t \frac{r}{2}\right) + 2\delta w^* l_{ij}\mu \right] \le t \qquad (j = 2, \ldots, k), \tag{4.12}$$

$$\sum_{i=0}^{q}\sum_{j=1}^{k} l_{ij} = r, \tag{4.13}$$

$$\sum_{i=0}^{q}\sum_{j=1}^{k} c_i n_{ij} \ge e, \tag{4.14}$$

$$x_{ij} \in (0,1);\ n_{ij} \in \mathbb{Z}_+;\ y_{ij} \ge 0;\ l_{ij} \ge 0 \qquad (i = 0, \ldots, q; j = 1, \ldots, k). \tag{4.15}$$

The objective function 4.26 is the sum of five cost functions. $\sum_{i=0}^{q}\sum_{j=1}^{k} f_i n_{ij}$ represent the fixed costs for the trips. $\frac{2\pi}{w^*}\sum_{i=0}^{q}\sum_{j=2}^{k} d_i\left(y_{ij}+\frac{l_{ij}}{2}\right)^2$ make up the line-haul costs for the outer rings. The total transverse costs for the outer rings are given by $2\delta\pi\sqrt{\frac{2}{3\delta}}\sum_{i=0}^{q}\sum_{j=2}^{k} d_i\left(y_{ij}+\frac{l_{ij}}{2}\right) l_{ij}$. $\frac{2\pi}{\gamma}\sum_{i=1}^{q} d_i l_{i1}^2$ denote the line-haul costs for the inner ring. Lastly, $\frac{\delta\gamma\pi}{3}\sum_{i=1}^{q} d_i l_{i1}^2$ are the transverse costs. These costs are multiplied with the factor $\left(1+p_t k_t \frac{r}{2}\right)$ to account for the time windows.

The number of vehicles of type i serving the inner ring is expressed by the Constraints 4.2. Similarly, Constraints 4.3 express the number of vehicles of type i serving the outer rings. Equations 4.4 and 4.5 specify that a ring is served by only one vehicle type for the inner ring and outer rings respectively. The inner ring cannot be served by a vehicle of type 0, which is why the summations are dissimilar. Constraints 4.6-4.8 ensure the values for n_{ij}, y_{ij}, and l_{ij} can only become positive if vehicle type i is assigned to ring j. Decision variable y_{ij} is expressed by Constraints 4.9. Constraints 4.10 and 4.11 are the capacity constraints for the inner ring and outer rings respectively. Constraints 4.12 ensure the time limit four route duration is not violated. Constraint 4.13 ensures the entire district is serviced, and Constraint 4.14 means that the total allocated capacity is at least equal to the number of customers. This constraint is not necessary because it is implied by other constraints, but imposing it strengthens the continuous relaxation of the model (Jabali et al., 2012). Finally, Constraints 4.15 denote the domains for the decision variables.

In order to compute the potential number of rings k, including the inner ring, the assumption is made that only the vehicle with smallest capacity c_q is available. Using constraint 4.10 for $i = q$, l_{q1} is determined. The construction of circular trapezoids for the outer rings is continued using $l*$, provided the route duration limit t is not attained; otherwise, the length of the rectangle is determined by constraint 4.12. The process terminates when the entire service region is covered, and the resulting number of rings is k. As previously mentioned, a solution may effectively use fewer than k rings; this is balanced by the use of vehicle type 0 for the additional rings.

4.4 Solution bounds

The FCCA formulation is a mixed integer non-linear program which cannot be solved to optimality by state-of-the-art solvers in a reasonable time unless the objective function is positive semidefinite. Since this is not the case in the FCCA model, such solvers can only identify locally optimal feasible solutions which yield an upper bound (Jabali et al., 2012). Therefore, an upper and lower bound are proposed. In the paper by Jabali et al. (2012), these bounds are tested extensively. In all experiments, the gap between the lower and upper bound never exceeds 1%. Therefore, it is expected that these bounds give a highly specific cost indication. Whether or not this indication is accurate is dependent on how closely the model represents the real-life application. As it is a study with numerous necessary assumptions, it is not certain that the actual costs are within the indicated bounds. Nonetheless, they yield useful insights regarding the costs and trends. An upper and lower bound, adapted from Jabali et al. (2012), are presented in this section.

4.4.1 Upper bound

Upper bound U2 from Jabali et al. (2012), the saw fleet composition (SFC) model, is selected for its simplicity and speed. It solves several mixed integer linear programs as opposed to one mixed integer non-linear and non-convex program. Fundamentally, it is assumed that a certain vehicle type is assigned to the inner ring, and determines the fleet composition associated with a 'saw' lying outside the inner ring. A saw is defined as a succession of circular trapezoids of widths $2w^*$ and of variable lengths as depicted in Figure 4.1. The solution of the saw fleet composition problem (SFC) is then used to evaluate the total cost over the entire region. The model is as follows:

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[1] In the paper by Jabali et al. (2012), x_{i1} is omitted. As this constraint can only hold for one vehicle type, it is included in this report.

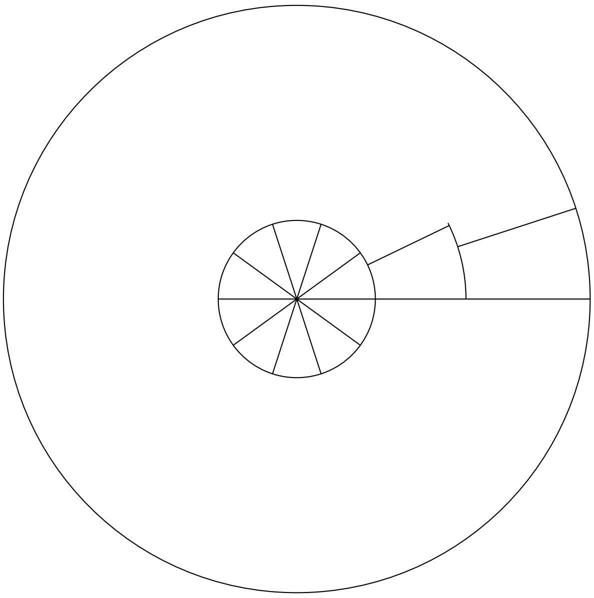

Figure 4.1: Visualization of zones in an inner ring and a saw

$$\text{(U) Minimize} \sum_{i=0}^{q}\sum_{j=1}^{k} f_i x_{ij} + \left(1 + p_t k_t \frac{r}{2}\right) * \left[2\sum_{i=0}^{q}\sum_{j=2}^{k} d_i \left(y_{ij} + \frac{l_{ij}}{2}\right) + 2\delta w^* \sqrt{\frac{2}{3\delta}} \sum_{i=0}^{q}\sum_{j=2}^{k} d_i l_{ij}\right] \qquad (4.16)$$

Subject to:

$$\sum_{i=0}^{q} x_{ij} = 1 \qquad (j = 2, ..., k), \qquad (4.17)$$

$$y_{ij} \leq M x_{ij} \qquad (i = 0, ..., q; j = 1, ..., k), \qquad (4.18)$$

$$l_{ij} \leq M x_{ij} \qquad (i = 0, ..., q; j = 1, ..., k), \qquad (4.19)$$

$$\sum_{m=0}^{q} \left(y_{m,j-1} + l_{i,j-1}\right) - M(1 - x_{ij}) \leq y_{ij} \qquad (i = 0, ..., q; j = 2, ..., k), \qquad (4.20)$$

$$2\delta w^* l_{ij} * \left(1 + p_t k_t \frac{r}{2}\right) \leq c_i \qquad (i = 0, ..., q; j = 2, ..., k), \qquad (4.21)$$

$$\sum_{i=0}^{q} \left[\frac{1}{v_i}\left(2\left(y_{ij} + \frac{l_{ij}}{2}\right) + 2\delta w * l_{ij}\sqrt{\frac{2}{3\delta}}\right) * \left(1 + p_t k_t \frac{r}{2}\right) + 2\delta w^* l_{ij}\mu\right] \leq t \qquad (j = 2, ..., k), \qquad (4.22)$$

$$\sum_{i=0}^{q}\sum_{j=2}^{k} l_{ij}{}^{[2]} = r - \sum_{i=0}^{q} l_{i1}, \qquad (4.23)$$

$$\sum_{i=0}^{q}\sum_{j=2}^{k} c_i x_{ij} \geq 2w^*\delta\left(r - \sum_{i=0}^{q} l_{i1}\right), \qquad (4.24)$$

$$x_{ij} \in (0,1);\; y_{ij} \geq 0;\; l_{ij} \geq 0 \qquad (i = 0, ..., q; j = 1, ..., k). \qquad (4.25)$$

The SFC model is derived from the FCCA model by assigning a single vehicle type to each of the circular

---

[2] In Jabali et al. (2012), the summation starts at $j = 1$, this is incorrect and can even lead to infeasibility if $l_{i1} > r/2$.

trapezoids of the saw. The procedure used to compute the upper bound U works as follows. The SFC model is solved q times, where at each iteration a different vehicle type is assigned to the inner ring. Furthermore, the assignment of vehicles to rings and the lengths of the various circular trapezoids are used to design routes over the entire circular region. The solution yielding the lowest total cost provides an upper bound on the FCCA optimum.

4.4.2 Lower bound

Let $\alpha = \frac{c_q\sqrt{6\delta}}{c_1\gamma\delta}$, $x' = 2\alpha^2 + 2\alpha - \alpha\sqrt{4\alpha^2 + 8\alpha + 3}$, and $z_{ij} = y_{ij}/\alpha$ for $i = 0, ..., q; j = 2, ..., k$, then

$$\begin{aligned}\text{(L) Minimize} \sum_{i=0}^{q}\sum_{j=1}^{k} f_i n_{ij} + \left(1 + p_t k_t \frac{r}{2}\right) * \Bigg\{ & \frac{2\pi}{\gamma}\sum_{i=1}^{q} d_i l_{i1}^2 + \frac{\delta\gamma\pi}{3}\sum_{i=1}^{q} d_i l_{i1}^2 \\ & + \frac{2\pi}{w^*}\left[\sum_{i=0}^{q} d_i \sum_{j=2}^{k}\left(\alpha^2 z_{ij}^2 + 2\left(\alpha - \frac{x'}{2}\right) z_{ij} l_{ij} + \left(\frac{3}{4} + x'\right) l_{ij}^2\right)\right]\Bigg\}\end{aligned} \tag{4.26}$$

subject to the FCCA constraints yields a lower bound on the FCCA optimum. Jabali et al. (2012) proof that L can be optimally solved by state-of-the-art solvers, for moderate size instances.

4.5 Multiple Wuunder points

To asses the added value of Wuunder points, the region is partitioned into districts as described in Section 3.1. For each number of districts, equivalent to the number of Wuunder points, the optimal costs and corresponding configuration are calculated. This is done by calculating the cost for a single district as mentioned in Section 3.2, and multiplying these costs with the number of districts p in the region. The maximum number of Wuunder points is bounded by Constraints 4.10 and 4.13. If the radius of the inner ring exceeds the radius of the district, the problem becomes infeasible. Assuming the vehicle with the smallest capacity serves the inner ring, the smallest possible radius of a district equals r_{min} and the maximum number of Wuunder points or districts is given by p_{max}. In Equations C.1 and C.2 in Appendix C it is shown how these values are determined.

The value of p is incrementally increased from 1, until this termination condition is met. In Algorithm 1 this process is described. Generally, the effect of additional Wuunder points is that the variable costs decrease and the fixed costs increase, as distances from depots to customers shorten and therefore more shorter trips are required. At various points, one of the two cost components outweighs the other. From that, conclusions are drawn on what the optimal configurations are, specific to the case.

Algorithm 1 Wuunder point calculator

```
Initialize:   Set $cost \leftarrow 100000$                ▷ Random large number
              Set $wp \leftarrow 0$                       ▷ Short for Wuunder point, integer
for $1 \le p \le p_{max}$ do
    Compute potential number of rings $k$                 ▷ See 4.3 for this computation
    Update radius $r \leftarrow \frac{r_r}{\sqrt{p}}$
    Update average distance $\bar{r} \leftarrow \frac{r}{2}$
    Solve model to optimality
    if $model.ObjVal * p < cost$ then
        Update $cost \leftarrow model.ObjVal * p$
        Update $wp \leftarrow p$
    end if
end for
```

Chapter 5

Results

The upper and lower bound are coded in C# and solved by Gurobi 7.5.1. with a MILP solver for the upper bound model and a QMIP solver for the lower bound model. All experiments are conducted on an ASUS laptop with an AMD Quad Core A8 running at up to 2.5 GHz and 8GB of RAM under a Windows environment.

This chapter is structured as follows: Firstly, the model validity is assessed in Section 5.1. Secondly, the results for the bounds without time windows are represented in Section 5.2. Subsequently, the results for the bounds with the inclusion of time windows are presented along with a comparison of the models in Section 5.3. Section 5.5 describes the influence of the number of customers on costs and configurations. Finally, the ecological impact of Wuunder is assessed in Section 5.6. It should be noted that from Section 5.5 onwards, all calculations are made using the L_{TW} model. L_{TW} is the base case lower bound model with the inclusion of time windows. The most important motivation for this decision is that this model automatically evaluates all vehicle types for assignment to the innermost ring.

5.1 Model validity

Firstly, the validity of the model is checked by making small adaptations and cross-validating the findings with those obtained by Jabali et al. (2012). This means that the parameter values for time window characteristics are set to $p_t = k_t = 0$. In the model of Jabali et al. (2012), variable costs are regarded as dependent on time, whereas the model of this report considers variable costs dependent on distance. Jabali et al. (2012) assume an equal speed of 60 km/h for all vehicle types, which translates to 1 km/minute. This has no effect (the only operation regarding vehicle speed is dividing by 1) and therefore no formulas have to be adapted to suit this difference in perspective.

Both models are tested for all circumstances provided by Jabali et al. (2012), where several values of t, d_2, f_1, and δ are experimented with. The models consistently yield the same results across all metrics[1], except for exact run times, which is to be expected. These findings indicate that both bounds are accurately implemented.

5.2 Base case without time windows

In the base case, time windows are neglected. The characteristics of the vehicles considered for the experiments are summarized in Table 5.1. A radius r of 18 km is assumed, $n = 1000$ customers, service time μ of 5 minutes and a (non-restricting) maximum route duration of 500 minutes. It is assumed the region is serviced out of a single Wuunder point. This is later altered by incrementing the number of Wuunder points and adjusting the problem accordingly.

In Table 5.2 the results for the Lower (L) and Upper (U) bound are given when the number of Wuunder points (W) is incremented from 1 to 40. The number of required trips per vehicle type as well as

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[1] Table 2 in Jabali et al. (2012) depicts a higher cost for bound L1 than for bound U1, this is an error and is later restored.

Vehicle type	Capacity (c_i)	Fixed cost (f_i)	Variable cost (d_i)	Speed (km/h)
1 (Van)	200	17.86	1.29	40
2 (Cargo Bike)	10	6.54	1.12	15
3 (Bike)	3	4.04	1.12	20

Table 5.1: Characteristics of the vehicles considered in the base case without time windows

the values for the radii for the inner rings and lengths of circular trapezoidin rings are mostly identical for both the upper and lower bound. The only exception being the cases with 5 and 36 Wuunder points as is shown in the footnote of Table 5.2. The time it takes for both models to find an optimum is always shorter than 1.5 seconds. The gap between the two bounds is at most 4.05 percent, except for the two cases where different configurations are used. Furthermore it is shown that the gap is decreasing for an increasing amount of Wuunder points. In other words, the solution bounds are converging for increasing numbers of Wuunder points.

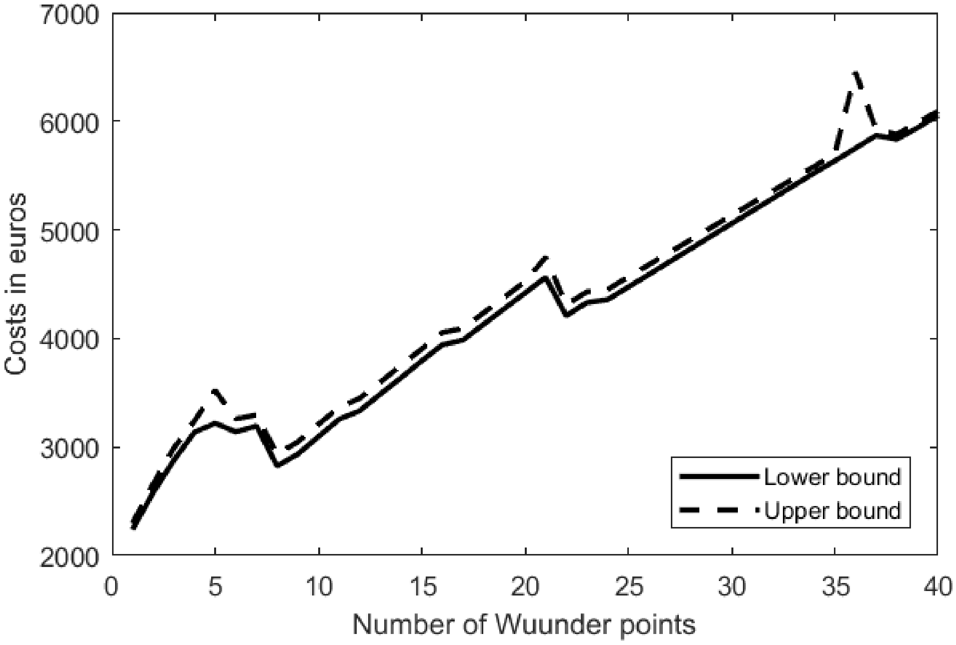

Figure 5.1: Visualization of the costs for the upper and lower bound from Table 5.2

The graph in Figure 5.1 depicts the progression of costs for an increasing number of Wuunder points for both the lower and upper bound. In the graph, some trends can be identified, which are explained through analyzing Table 5.2. Firstly, an increasing cost function is shown from 1 to 5 Wuunder points. This increase is occurring because at this stage the increase in fixed costs for vans and bikes that are needed when more Wuunder points are used outweighs the decreasing variable costs because less driven distance is required.

At 5 Wuunder points, a first peak is reached. This turning point is the result of the radius and number of customers per district being reduced to where vans are no longer needed and only cargo bikes and bikes distribute the packages. Between 5 and 8 Wuunder points, a decreasing function can be seen. It appears that less trips are required when the number of districts increases. Hence, less variable costs and less fixed costs are incurred (the exception being the case when the region is divided into 7 districts,

W points	Costs L (€)	Costs U (€)	Gap (%)	Van	Cargo	Bike	l_{i1}	$\sum_{i=1}^{q}$ l_{i2}	l_{i3}
1	2241.44	2296.68	2.46	27		7	2.60	15.40	
2	2581.01	2659.37	3.04	40		14	2.60	10.13	
3	2877.45	2990.43	3.93	51		21	2.60	7.79	
4	3136.20	3240.34	3.32	60		28	2.60	6.40	
5[1]	3219.10	3522.10	9.41		125	35	2.60	1.33	4.12
6	3140.10	3258.87	3.78		84	90	2.60	4.75	
7	3193.05	3294.01	3.16		91	98	2.60	4.20	
8	2825.79	2935.82	3.89		96	56	2.60	3.76	
9	2933.88	3046.17	3.83		99	63	2.60	3.40	
10	3094.68	3208.62	3.68		110	70	2.60	3.09	
11	3254.95	3364.79	3.37		121	77	2.60	2.83	
12	3333.90	3449.19	3.46		120	84	2.61	2.59	
13	3488.40	3598.45	3.15		130	91	2.60	2.39	
14	3638.16	3753.07	3.16		140	98	2.61	2.20	
15	3793.78	3902.91	2.88		150	105	2.59	2.05	
16	3941.48	4054.55	2.87		160	112	2.61	1.89	
17	3984.91	4091.62	2.68		153	119	2.60	1.77	
18	4130.76	4236.38	2.56		162	126	2.59	1.65	
19	4274.82	4378.69	2.43		171	133	2.59	1.54	
20	4417.56	4524.73	2.43		180	140	2.60	1.42	
21	4563.08	4748.03	4.05		189	147	2.59	1.34	
22	4209.25	4310.80	2.41			352	2.61	1.22	
23	4330.72	4429.55	2.28			368	2.62	1.14	
24	4357.03	4450.27	2.14			360	2.59	1.08	
25	4473.28	4567.75	2.11			375	2.60	1.00	
26	4589.70	4679.62	1.96			390	2.62	0.91	
27	4706.96	4795.12	1.87			405	2.60	0.86	
28	4823.65	4906.16	1.71			420	2.59	0.81	
29	4940.76	5020.35	1.61			435	2.62	0.72	
30	5057.35	5133.93	1.51			450	2.61	0.67	
31	5173.83	5247.02	1.41			465	2.61	0.62	
32	5290.34	5359.75	1.31			480	2.61	0.57	
33	5407.06	5472.24	1.21			495	2.61	0.52	
34	5524.13	5584.64	1.10			510	2.62	0.47	
35	5635.30	5697.09	1.10			525	2.58	0.46	
36[2]	5752.30	6452.71	12.18			540	2.59	0.41	
37	5870.09	5920.40	0.86			555	2.60	0.36	
38	5835.37	5879.30	0.75			532	2.62	0.30	
39	5940.12	5988.30	0.81			546	2.58	0.30	
40	6055.67	6093.05	0.62			560	2.60	0.24	

W points: Number of Wuunder points/districts in a region, Cargo: Cargo bikes.
L: lower bound. U: Upper bound.
[1] Model U uses 70 vans and no cargo bikes in this scenario. $l_{i1} = 2.60$, $l_{i2} = 5.45$ km.
[2] Model U uses an additional 36 vans. $l_{i1} = 2.64$, $l_{i2} = 0.36$ km.

Table 5.2: Resulting fleet compositions and costs for base case scenarios

requiring more trips than for 6 districts).

The second local optimum (the first being located at the start of the graph) is then reached at 8 Wuunder points. After this point, the costs are climbing once again. From 8 districts on, every new Wuunder point requires more trips. As these increasing fixed costs are not offset by the decreasing variable costs, a rising cost function is the result. Another local minimum appears at 22 Wuunder points. As depicted in Table 5.2, this is the effect of switching from cargo bikes to more, but less expensive bikes.

A visualization of the fleet composition and partitioning for a situation where 3 and 4 Wuunder points are operated is given in Figure 5.2. This would be the partitioning of one of four and five identical districts respectively. Note that the district on the left is slightly larger than the one on the right. This is due to the fact that the left district covers an area with a radius of $\frac{r}{\sqrt{4}} = 9$ kilometers, whereas the right is one of 5 districts, each covering areas with radii of $\frac{r}{\sqrt{5}} \approx 8.05$ kilometers.

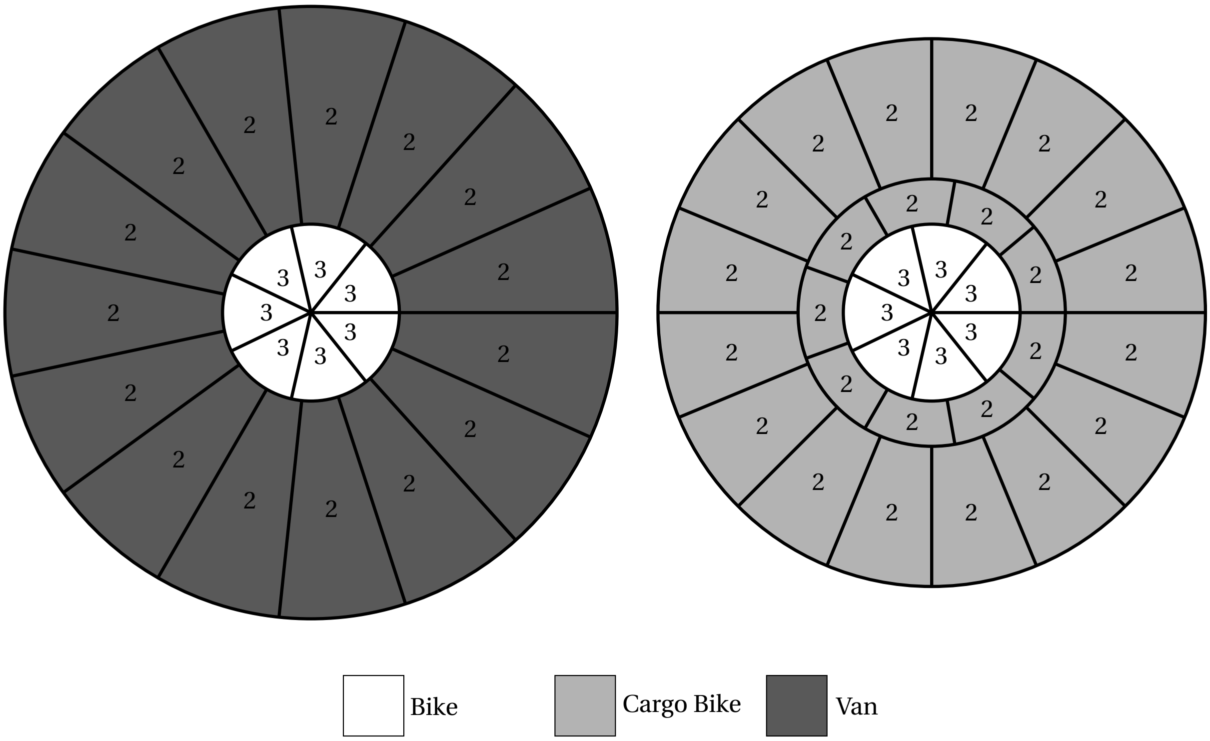

Figure 5.2: Visualization of the assignment of zones to vehicles in a single district for the base case with 4 (left) and 5 (right) Wuunder points

5.3 Base case with time windows

The approximated distance for route length increases when time windows are in place. To account for this additional distance, distance approximation models have been formulated by Figliozzi (2009) and Vercammen (2016). A combined total of 13 models have been developed and tested for benchmark instances and data at Van Opzeeland. The adjusted R-squared, mean percentage error (MPE) and mean absolute percentage error (MAPE) are measured to find the model that best fits the data. As no other applications of the models presented in Figliozzi (2009) were found in the literature, the values found in the model of Vercammen (2016) are used. Vercammen (2016) found a highly significant (p<0.01) value for the estimate for the distance penalty of the third most restricting type of time window of 0.200. This means that each additional time window of that type (n_{t_3}) results, on average, in an additional $0.2\bar{r}$ (as $k_{t_3} = 0.2$) kilometers of distance. All other effects were less significant and had a smaller effect on distance.

In the case of Van Opzeeland, this type of time window has the biggest impact on route length. As no data is available at Wuunder, this estimate is used for all types of time windows. In Chapter 6, both this estimate as well as the proportion of clients with time windows are varied to discover the impact of variations in these values on the approximation for the total distance and costs. For now, the proportion of clients with time windows is set to 50% and the estimate for distance penalty per time window is set to 0.200. The other parameters are equal to those of the base case. The resulting costs and configurations are shown in Table D.1 in Appendix D.

A more severe penalty is also investigated. Both the distance penalty and the proportion of clients with this time window are set to 0.8. In Figure 5.3 the costs of the different cases are shown.

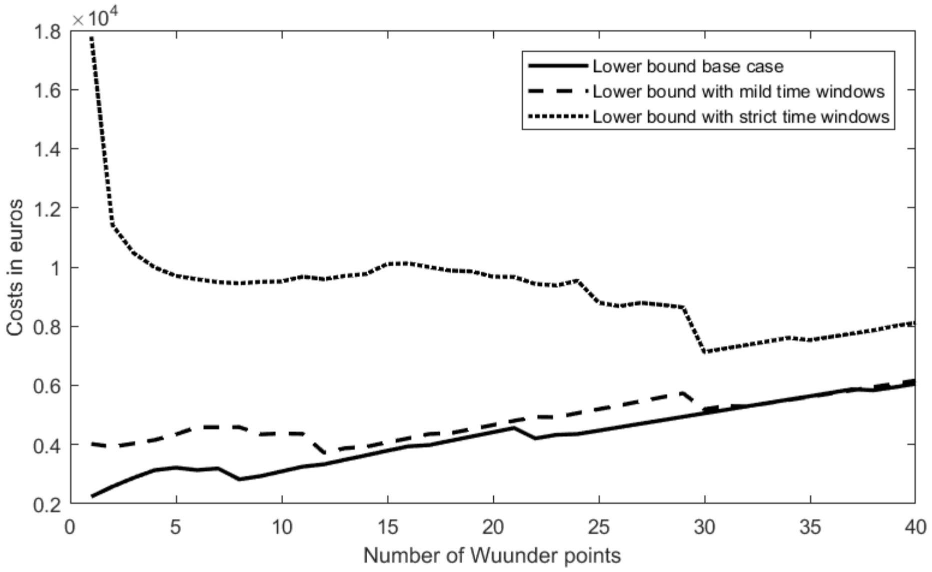

Figure 5.3: Depiction of the effects of time windows on the lower bound of the solution

It is noticeable that the effects of time windows are biggest with few Wuunder points, when districts are relatively large. The cost progression differs greatly as well, leading to varying optima. For the base case it was shown that the costs were lowest when a single Wuunder point was operated. It is shown that 12 Wuunder points are optimal when 'mild' time window penalties are in place. For very strict time windows, this optimum shifts even further towards 35 Wuunder points. The impact of time windows therefore not only impacts the costs in a straightforward fashion, but the compositions in terms of Wuunder points and required vehicle trips as well.

5.4 Duration limit

Up until now, the maximum duration of the routes has not been considered. This section aims to provide insight into the effect the duration has on costs and configurations. In this section, the capacity of Wuunder points has been taken into account. Therefore, at least 5 Wuunder points $\left(\left\lceil \frac{1000}{240} \right\rceil\right)$ are required to service the area.

There are two factors that have an effect on the route duration; speed of the vehicle and service time at a customer. Firstly it is analyzed at what point the duration limit becomes the restricting constraint. The duration limit is decreased stepwise from 120 to 30 minutes. The resulting costs and configurations are shown in Table 5.3.

From Table 5.3 it can be deduced that the duration limit has no effect until it drops below approximately 90 minutes. At that point, a stricter limit implies that more Wuunder points are required and thus more (cargo) bikes to shorten the distance between depots and customers. When the limit is re-

Duration limit	Costs	Cargo	Bikes	W points
120	3728.71	144	84	12
115	3728.71	144	84	12
110	3728.71	144	84	12
105	3728.71	144	84	12
100	3728.71	144	84	12
95	3728.71	144	84	12
90	3869.14	156	91	13
85	3928.09	154	98	14
80	4067.36	165	105	15
75	4211.02	176	112	16
70	4351.42	187	119	17
65	4517.25	190	133	19
60	4795.06	210	147	21
55	4925.26	207	161	23
50	5192.97		480	30
45	5192.97		480	30
40	5192.97		480	30
35	5289.92		480	32
30	5727.14		540	36

W: Number of Wuunder points, Cargo: Cargo bikes.
Costs in euros.

Table 5.3: The effect of the duration limit in minutes on the costs and configurations, $\mu = 5$ minutes

duced to 50 minutes and lower, the local optimum where all customers are serviced by bikes becomes the global optimum. Below 35 minutes, once again more Wuunder points are needed. Costs increase fairly steadily, with an increase of approximately 29% for the case when the duration limit is 60 minutes and 54% for the case when the duration limit is set to 30 minutes.

The service time is an important factor in the route duration. Therefore, two scenarios have been considered with other service times. The scenarios where the service time μ equals 2.5 and 1.5 minutes are depicted in Table 5.4.

As expected, a faster service time moderates the effect of a more restricting duration limit. Where a limit of 90 minutes required additional Wuunder points in the scenario where $\mu = 5$, this point is reached at 65 minutes for $\mu = 2.5$ and at 50 minutes for $\mu = 1.5$.

For the case of non-restricting duration limits (120 minutes for example), service time has no effect, but as the duration limit becomes restricting, reducing service time significantly reduces incurred costs. For instance, if a duration limit of 60 minutes is in place, reducing service time could save 15 to 22 percent of costs.

	$\mu = 2.5$				$\mu = 1.5$			
Duration limit	**Costs**	**Cargo**	**Bikes**	**W**	**Costs**	**cargo**	**bikes**	**W**
120	3728.71	144	84	12	3728.71	144	84	12
115	3728.71	144	84	12	3728.71	144	84	12
110	3728.71	144	84	12	3728.71	144	84	12
105	3728.71	144	84	12	3728.71	144	84	12
100	3728.71	144	84	12	3728.71	144	84	12
95	3728.71	144	84	12	3728.71	144	84	12
90	3728.71	144	84	12	3728.71	144	84	12
85	3728.71	144	84	12	3728.71	144	84	12
80	3728.71	144	84	12	3728.71	144	84	12
75	3728.71	144	84	12	3728.71	144	84	12
70	3728.71	144	84	12	3728.71	144	84	12
65	3869.14	156	91	13	3728.71	144	84	12
60	4067.36	165	105	15	3728.71	144	84	12
55	4351.42	187	119	17	3928.09	154	98	14
50	4517.25	190	133	19	4211.02	176	112	16
45	4925.26	207	161	23	4517.25	190	133	19
40	5192.97		480	30	4925.26	207	161	23
35	5192.97		480	30	5192.97		480	30
30	5192.97		480	30	5192.97		480	30

W: Number of Wuunder points, Cargo: Cargo bikes.
Costs in euros, duration limit in minutes

Table 5.4: The effects of duration limit on costs and configurations for the cases of a service time of $\mu = 2.5$ and $\mu = 1.5$ minutes

5.5 Number of customers

The number of customers in a region greatly affects the costs and fleet compositions in that area. As this number is very likely to have high variation in relation to the maturity of Wuunder in a city, it is important to assess the impact of this parameter. The number of customers is varied from 200 to 5000. The effects of customers on the optimal quantity of Wuunder points, total costs of the configurations and costs per package, as well as number of types of vehicle trips required are measured. The results are shown in Table 5.5.

As expected, the costs per package decrease as the number of customers increases. This is due to the fact that the increased density leads to shorter average distances between customers. From Table 5.5 it can be concluded that when the number of customers exceeds 1600, the optimal number of Wuunder points plunges from 16 to two and remains there for all exceeding number of customers. It is unlikely that Wuunder would knowingly invest time and/or money into Wuunder points that will go unused when the number of customers grows. In this setting, it is reasonable that Wuunder partners up with a maximum of two Wuunder points to not have to end partnerships when more than 1400 packages are sent through the platform. Table 5.6 surmises the effect this decision has on the costs and configurations. From this table it follows that the costs are at most 11.38% higher than in the previously determined optimal case. It should be noted that this gap is closing quickly, with only a 0.9% difference in courier costs when 1400 customers make use of the platform, while it ‘saves’ the effort and money of partnering up with 14 Wuunder points.

Customers	Costs	Costs/e	W	Vans	Cargo	Bikes
200	1738.81	8.69	4		44	28
400	2349.07	5.87	6		72	42
600	2846.95	4.74	8		96	56
800	3303.20	4.13	10		120	70
1000	3728.71	3.73	12		144	84
1200	4141.57	3.45	14		168	98
1400	4536.21	3.24	16		192	112
1600	4860.04	3.04	2	74		14
1800	5131.01	2.85	2	78		14
2000	5391.45	2.70	2	82		14
2200	5642.86	2.56	2	86		14
2400	5886.44	2.45	2	90		14
2600	6123.11	2.36	2	94		14
2800	6317.94	2.26	2	96		14
3000	6542.99	2.18	2	100		14
3200	6727.36	2.10	2	102		14
3400	6942.93	2.04	2	106		14
3600	7118.67	1.98	2	108		14
3800	7290.61	1.92	2	110		14
4000	7494.78	1.87	2	114		14
4200	7659.99	1.82	2	116		14
4400	7822.18	1.78	2	118		14
4600	8017.28	1.74	2	122		14
4800	8174.03	1.70	2	124		14
5000	8328.30	1.67	2	126		14

W: Number of Wuunder points, Cargo: Cargo bikes.
Costs in euros.

Table 5.5: Costs, number of Wuunder points, and fleet compositions per district in the optimal configuration for increasing numbers of customers

Customers	Costs	Gap (%)	W	Vans	Bikes
200	1936.8	11.38	1	23	7
400	2629.4	11.93	1	31	7
600	3133.7	10.07	2	48	14
800	3546.1	7.35	2	54	14
1000	3924.4	5.25	2	60	14
1200	4277.9	3.29	2	66	14
1400	4576.6	0.89	2	70	14

W: Number of Wuunder points, Cargo: Cargo bikes.
Gap relative to optimal scenario. Costs in euros.

Table 5.6: Impact of limiting the number of Wuunder points on configurations and costs

Customers	Costs	Gap (%)	W	Cargo	Bikes
200	1738.81	0.00	4	44	28
400	2349.07	0.00	6	72	42
600	2846.95	0.00	8	96	56
800	3303.20	0.00	10	120	70
1000	3728.71	0.00	12	144	84
1200	4141.57	0.00	14	168	98
1400	4536.21	0.00	16	192	112
1600	4913.61	1.10	18	216	126
1800	5148.11	0.33	19	228	133
2000	5507.03	2.14	21	252	147
2200	5868.70	4.00	23	276	161
2400	6215.36	5.59	25	300	175
2600	6426.10	4.95	26	312	182
2800	6766.32	7.10	28	336	196
3000	7102.13	8.55	30	360	210
3200	7299.92	8.51	31	372	217
3400	7630.65	9.91	33	396	231
3600	7957.91	11.79	35	420	245
3800	8281.99	13.60	37	444	259
4000	8465.48	12.95	38	456	266
4200	8785.71	14.70	40	480	280
4400	8968.02	14.65	41	492	287
4600	9284.82	15.81	43	516	301
4800	9599.27	17.44	45	540	315
5000	9899.28	18.86	47	564	329

W: Number of Wuunder points, Cargo: Cargo bikes.

Gap relative to scenario without limiting capacity of Wuunder points. Costs in euros.

Table 5.7: Impact of the capacity of Wuunder points on costs and configurations for increasing numbers of customers

5.6 Ecological effects

A key focal point of the Wuunder concept is the environmental aspect. For Eindhoven, the number of households is 110 085[2] for the Netherlands, this number is 7 720 787 [3]. In a day, on average 208/365 million packages are sent domestically ACM (2016). In a day in Eindhoven, this would amount to roughly $\frac{208\text{mln}}{365} * \frac{110085}{7720787} \approx 8125$ packages. Following the distribution of market shares in the Netherlands as shown in Figure 1.2, this would mean the four biggest parties in domestic package delivery in the Netherlands would then ship the number of packages as shown in Table 5.8. All packages are assumed to be delivered with vans having a capacity of 200 packages (see Figure E.1) and only the distance starting and ending at one fictional central depot for each company is measured. Furthermore, the very optimistic case of no time windows is reviewed for these companies.

Arguably, these characteristics are favorable towards the existing system. The setting is approached by the L_{TW} model as above but without (cargo)bikes. The distance driven by vans in these scenarios as well as the number of vehicles required is also depicted in Table 5.8. Note that no comparison can be made based on the optimal number of hubs for these companies, as the cost structures are (most likely) very different for Wuunder, than for PostNL for example.

Company	Packages	Vans	Bikes	Van kilometers
Wuunder	**8125**	**183**	**21**	**5503.45**
PostNL	4672	94		6228.88
DHL	2235	65		4308.21
DPD	609	34		2248.88
GLS	609	34		2248.88
Total	**8125**	**227**		**15034.86**

Table 5.8: Vehicles and distance required in the current setting and via the Wuunder concept to supply Eindhoven of packages for a day

It can be clearly seen that the Wuunder concept is capable of decreasing the amount of distance driven by vans in a city drastically. The CO_2 target is set at 175g CO_2/km by the EU (Regulation(EU) No 510/2011). Just for the case of a single day of package delivery in a region like Eindhoven, this means that the Wuunder concept could save $(15034.86-5503.45)*0.175 = 1668.0$ kilograms of carbon dioxide. This is equivalent to 910.4 cubic meters of gas[4]. These results are preliminary, but indicate that vast savings are achieved through exploitation of efficiencies of cooperation between carriers as well as between carriers and couriers via the Wuunder concept.

It is also analyzed what the total savings are when only a proportion of packages in a city are sent via the Wuunder platform. In Table 5.9, the kilometers driven by vans in the different phases of Wuunder adaptation are shown. It is shown that not all stages of Wuunder coexisting alongside the existing system are beneficial for the environment. Between an adaptation of roughly 15-45%, the total amount of kilometers driven by vans is actually more than in the existing system. These findings are very dependent of the specific time window characteristics as well as other parameters, so an unambiguous conclusion would be too candid. These results merely indicate that the adaptation of the Wuunder platform is not necessarily more efficient for every case.

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[2] https://www.stadindex.nl/eindhoven, accessed 07/10/2017

[3] http://statline.cbs.nl/statweb/publication/?vw=t&dm=slnl&pa=71486ned&d1=0-2,23-26&d2=0&d3=0,5-16&d4=(l-1)-l&hd=090402-0910&hdr=t,g3&stb=g1,g2), accessed 07/10/2017

[4] At 21°C and 1 atmosphere pressure

Via Wuunder	Distance driven by vans for:					Total	Savings
(%)	PostNL	DHL	DPD	GLS	Wuunder		(%)
0	6228.88	4308.21	2248.88	2248.88	0	15034.86	0.0
10	5909.37	4087.64	2133.28	2133.28	0	14263.58	5.1
20	5571.58	3853.38	2011.05	2011.05	2681.17	16128.23	(7.3)
30	5211.14	3603.93	1880.89	1880.89	3266.49	15843.34	(5.4)
40	4824.70	3337.13	1741.02	1741.02	3761.09	15404.97	(2.5)
50	4404.48	3047.05	1588.90	1588.90	4195.74	14825.06	1.4
60	3939.70	2724.75	1423.49	1423.49	4588.72	14100.15	6.2
70	3412.18	2360.59	1232.78	1232.78	4950.12	13188.44	12.3
80	2785.04	1926.69	1006.56	1006.56	4931.88	11656.73	22.5
90	1969.32	1360.85	711.74	711.74	5225.62	9979.29	33.6
100	0	0	0	0	5503.45	5503.45	63.4

W: Number of Wuunder points, Cargo: Cargo bikes.
Gap relative to scenario without limiting capacity of Wuunder points. Costs in euros.

Table 5.9: Kilometers driven by vans in different phases of adaptation of the Wuunder platform ($e = 8125$)

5.7 Radius

As established, the Eindhoven region is approximated by a disk with a radius of 18 kilometers. However, not all cities are approximated by similarly sized disks. Therefore, an analysis is required to measure how the resulting configurations and costs look in those cases. The radius is varied in the range of 9 to 36 kilometers to assess this effect. Furthermore, the case with uncapacitated Wuunder points is separately investigated. The results are shown in Table 5.10.

It can be concluded that every kilometer increase of the radius results in a cost increase of approximately 197 € and 190 €, for the uncapacitated and capacitated scenario respectively (see Figures G.1 and G.2). For relatively small regions, the capacity of the Wuunder points affect the configurations and costs. This amounts to a 12.5% above optimum cost for the case where the region has a 9 km radius.

	$W_{cap} = \infty$					$W_{cap} = 240$			
Radius	**W**	**Costs**	**Vans**	**Cargo**	**Bikes**	**W**	**Costs**	**Cargo**	**Bikes**
9.00	1	1909.29	37		7	10	2182.01	120	70
10.80	1	2274.84	39		7	10	2422.35	120	70
12.60	1	2669.14	41		7	11	2800.75	132	77
14.40	11	3054.96		132	77	11	3054.96	132	77
16.20	11	3315.05		132	77	11	3315.05	132	77
18.00	12	3728.71		144	84	12	3728.71	144	84
19.80	12	4002.69		144	84	12	4002.69	144	84
21.60	13	4424.39		156	91	13	4424.39	156	91
23.40	13	4710.14		156	91	13	4710.14	156	91
25.20	13	5001.42		156	91	13	5001.42	156	91
27.00	14	5458.19		168	98	14	5458.19	168	98
28.80	14	5761.66		168	98	14	5761.66	168	98
30.60	15	6223.09		180	105	15	6223.09	180	105
32.40	15	6537.13		180	105	15	6537.13	180	105
34.20	15	6856.40		180	105	15	6856.40	180	105
36.00	16	7345.20		192	112	16	7345.20	192	112

W: Number of Wuunder points, Cargo: Cargo bikes. Radius in kilometer.

Table 5.10: The effects of the radius on costs and configurations

Chapter 6

Sensitivity Analysis

Up until now, the parameter values as used in Chapter 5 are based on the presented characteristics by the partners Wuunder currently interacts with and literature. These values are not set in stone and may vary over time or in different cities. Therefore, extensive analysis is required to identify how certain factors affect the costs and compositions of the fleet. Through this analysis, it is determined which parameters require extensive examination.

The model used for the sensitivity analysis is model $\mathrm{L_{TW}}$. The motivation for this is twofold. Firstly, as is shown by the smoothness of the lines in Figure 5.1, there is less variation in the results obtained by this model. More importantly, the model used to compute the upper bound requires that the user runs it for all three possible vehicle types assigned to the inner ring. This is more tedious than the model for computing the lower bound, which compares this automatically.

6.1 Time window characteristics

The characteristics of the time windows are of great importance to Wuunder. The degree to how tightly time windows are specified is a service component of the Wuunder platform. Picking up parcels within 60, 30, or even 15 minutes is a service that Wuunder is contemplating. The impact that these tighter time window specifications could have on costs and configurations is therefore assessed in this section.

The variables that specify the time windows are p_t and k_t, the proportion of customers with time windows and the distance penalty per time window respectively. The variable p_t is bounded between 0 and 1. This is the range from no customers with specified time windows to all customers having specified a time window. The value k_t is multiplied with the average distance from the depot to a customer. This implies that if k_t takes on the value of 2, an additional trip is necessary for every single client with a time window. On the other hand, if k_t were to be 0, it would mean that no additional distance is required for additional customers with time windows, i.e. no route has to be changed or additional vehicle dispatched. For this distance penalty, values in the range of $k_t \in [0;1]$ are analyzed. This is the difference between no detours and every time window requiring an additional $\frac{r}{2}$ kilometers. The value of p_t is set to 0 and subsequently increased by 0.05 until it reaches 1, and the value of k_t is set to 0 and increased by 0.02 until its limit of 1 is reached. The 3D graph of the combination of these effects on the optimal costs of the L_{TW} model is shown in Figure 6.1.

The distance penalty and the proportion of customers with time windows appear to have an analogous effect on the costs of the configurations. When reviewing the time window factor in the constraints and objective function of the model, this makes sense. The factor $\left(1 + p_t k_t \frac{r}{2}\right)$ is equally dependent on the values of p_t and k_t. Linear regression is performed on the data, the results of which are shown in Figure 6.2. The estimated effects of these variables are roughly equal (3617.5 for the distance penalty and 3666.3 for the proportion of customers with time windows) and highly significant ($p << 0.05$). For the proportion of customers with time windows, this translates to the following statement: An increase

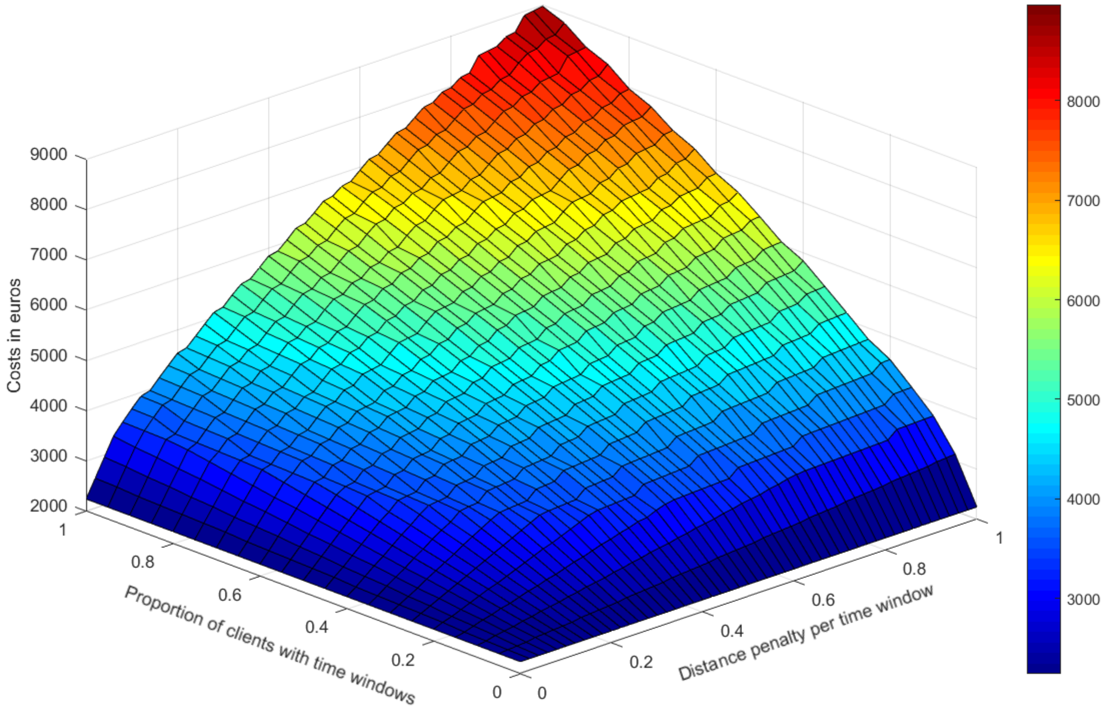
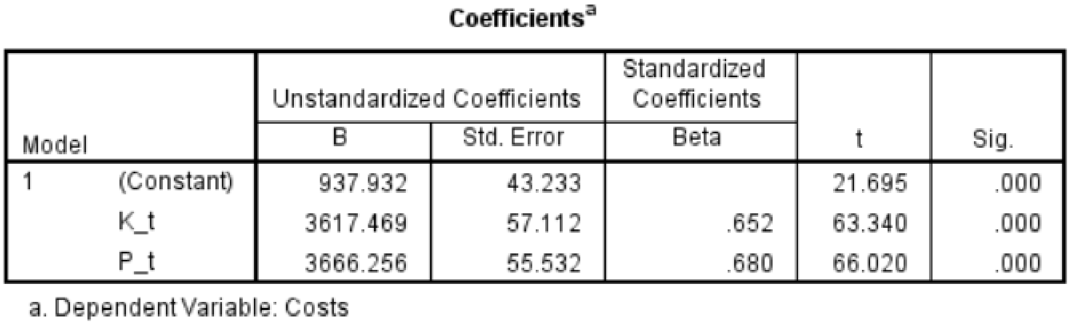


Figure 6.1: The effects of the time window properties on the optimal costs

in p_t by one percentage point leads to an estimated cost increase of 36.17€. The R^2 of this model is equal to .887, meaning 89% of the total variance in the costs is explained by the model. Regression is also been applied to see if the square root of the variables and the variables squared are better predictors of the costs. However, both options yield lower values for R^2, .847 and .810 respectively.



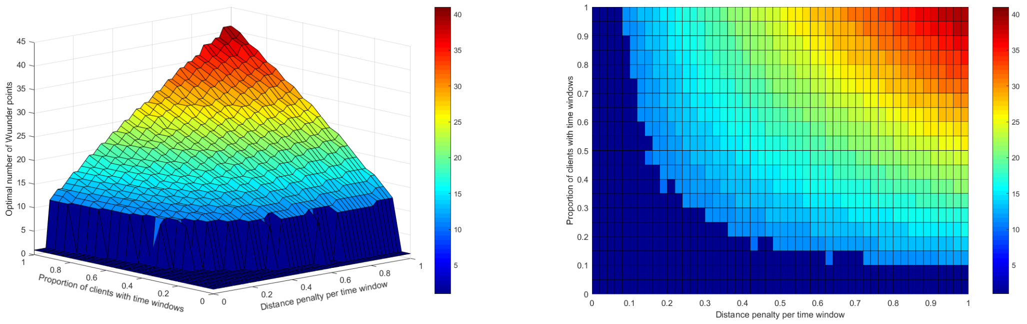
Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	937.932	43.233		21.695	.000
	K_t	3617.469	57.112	.652	63.340	.000
	P_t	3666.256	55.532	.680	66.020	.000

a. Dependent Variable: Costs

Figure 6.2: Regression values for the coefficients determined through linear regression

Next, it is analyzed how many Wuunder points are used in the optimal configurations. As the p_t and k_t increase, it becomes more attractive to partition the region into more districts. The reason for this is that more districts imply a shorter average distance from the depot to a customer within that district. Therefore, it becomes very interesting to examine the optimal number of Wuunder points for different



(a) 3D visualization

(b) 2D heat map

Figure 6.3: The of optimal number of Wuunder points for different time window characteristics

properties of time windows. To examine this, Algorithm 2 is run. The resulting optimal number of Wuunder points is visualized in Figure 6.3. In Figure 6.3a it is clearly seen that the number of Wuunder points in the optimal configuration is 1 until the time windows become too restricting. It then jumps to 10 and gradually increases along with the values for p_t and k_t to 41 points. The jump is explained by the fact that at that point, the local optimum where vans are replaced by cargo bikes becomes the overall optimal solution. Figure 6.3b is included for clarity. In this figure it is shown which exact configuration yields what optimal number of Wuunder points. For instance, when $p_t = 0.5$ and $k_t = 0.7$, the number of Wuunder points in the optimal configuration is 21.

Algorithm 2 Time window characteristics sensitivity analysis

```
for $0 \le v \le 20$ do
    for $0 \le w \le 50$ do
        $cost \leftarrow 100000$                                    ▷ Random large number
        $wp \leftarrow 0$                                           ▷ Short for Wuunder point, integer
        Update TW proportion $p_t \leftarrow 0.05 * v$
        Update TW penalty $k_t \leftarrow 0.02 * w$
        Update $p_{max}$                                            ▷ See Appendix C for this computation
        for $1 \le p \le p_{max}$ do
            Update $NumberOfCustomers \leftarrow \frac{e}{p}$
            Update radius district $r \leftarrow \frac{r_r}{\sqrt{p}}$
            Update average distance $\bar{r} \leftarrow \frac{r}{2}$
            Optimally solve model $\mathrm{L_{TW}}$
            if $model.ObjVal * p < bar$ then
                Update $bar \leftarrow model.ObjVal * p$
                Update $wp \leftarrow p$
            end if
        end for
        Print $p_t$ on x-axis
        Print $k_t$ on y-axis
        Print $wp$ in matrix
    end for
end for
```

Lastly, Figure 6.4 is included to offer a complete insight. This figure shows how costs relate to the number of Wuunder points when the distance penalty increases. In this case, distance penalty is the value of the proportion multiplied with the distance estimate ($p_t * k_t$). Here the development of the cost function in relation to the time window tightness becomes clear. As expected, costs increase when time window penalties increase for all number of Wuunder points. However, another interesting development comes to light. The first section, between 1 and 5 Wuunder points, changes most drastically under the influence of time windows. The remainder of the function is more or less an amplification of the cost function for the base case. Each trend that was identified in the cost function for the base case has a similar effect when distance penalties for time windows increase.

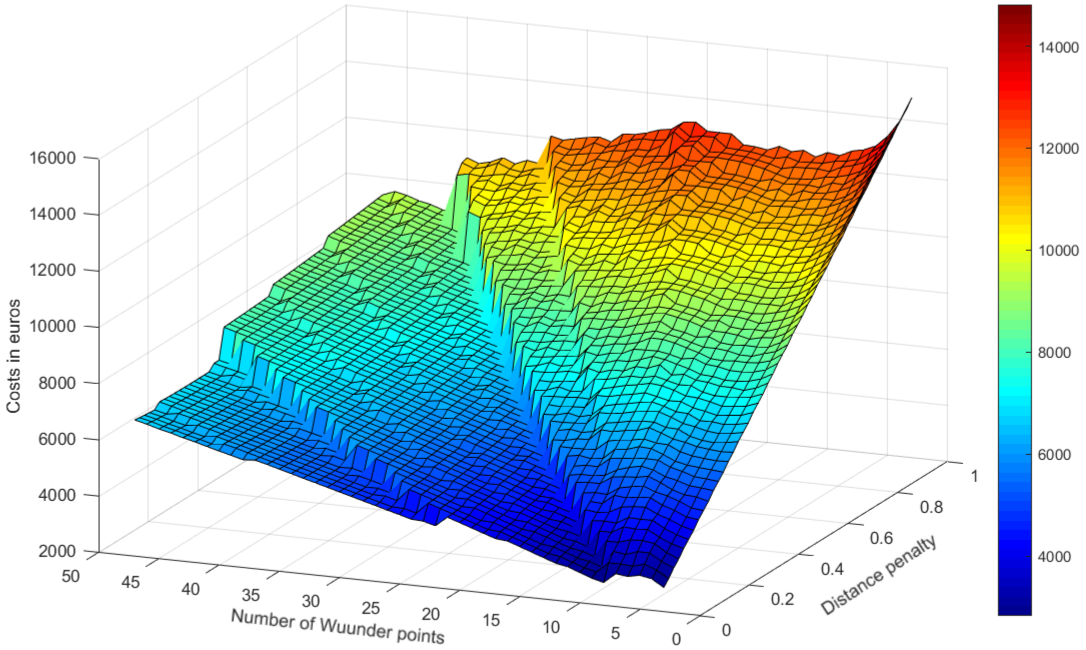


Figure 6.4: The effects of the time window properties on the optimal costs

6.2 Vehicle characteristics

Currently, the vehicle characteristics have been determined based on the information provided by the partners of Wuunder. As Wuunder expands to more cities and customers, the vehicle characteristics and contracts with courier partner companies might vary for different cities. Therefore, the effects of the vehicle characteristics are examined in this section. Each characteristic is evaluated in the range of 0.5-2 times its original setting. The restriction of Wuunder point capacity is relaxed to inspect the effects of the characteristics more completely.

Table 6.1 depicts the effects of the vehicle capacity on the costs and configurations. Vans are not used in the optimal solution for the base case with time windows. Reviewing the table, this does not change when the capacity of the vans is altered. Therefore it is concluded that halving or doubling the van capacity has no impact on the costs and configurations in this scenario. This is not the case for the capacities of bikes and cargo bikes. For cargo bikes, it is shown that if its capacity is between 5 and 8 packages, vans are required in the optimal solution. The costs are 5.25 percent higher for this scenario compared to the base case with time windows. When the capacity of a cargo bike exceeds 9 packages, it starts to have an impact on the costs and configurations. From that point on, increased cargo bike capacity translates into fewer (cargo) bikes and Wuunder points required as well as reduced costs. The potential cost savings add up to more than 16% if the capacity is doubled. The capacity of bikes has an unexpected effect on the solution. Reduced capacity forces the model to use more Wuunder points with fewer bikes and more cargo bicycles. The costs for those scenarios are lower than in the original setting. Similarly, increased capacity leads to increased costs. At 4 packages, it becomes advantageous to use vans over cargo bikes. For a doubled capacity, the costs are 15.32% higher compared to the original setting.

This counterintuitive effect is due to Constraint 4.10 that determines the radius of the inner ring. This is optimal if a single district is considered, but proves to be suboptimal if a region is partitioned into multiple districts. Omitting this anomaly, the most crucial capacity is that of the cargo bike. A lower or higher capacity impacts the costs and solutions drastically. Furthermore, the current capacity is very close to the point at which vans become the cheaper option. Hence, it should be verified meticulously whether the capacity is correct and can be increased.

Table 6.2 depicts the effects of fixed costs. If the fixed costs of vans drop 20 percent or more, they become more cost efficient to use than cargo bikes. Relative to the original fixed costs, every 10% the fixed costs drop over 20, implies a total cost decrease of roughly 3%. As vans are not used in the optimal solution, higher fixed costs have no impact on the base case scenario with time windows. A change in the fixed costs of both cargo bikes and regular bikes has a direct effect on the costs. For cargo bikes, a 2.5% change in total costs is expected for every 10% change in fixed costs relative to the current 6.54 €. When the costs are more than 30% higher relative to the original scenario, vans become more cost efficient. At that point, the fixed costs of cargo bikes no longer impact the total cost, which remains stable at 5.25% above the original costs. For bikes, a 10% change in the fixed costs results in a 0.9% change in total costs. This effect is smaller than for cargo bikes because fewer bikes are used and the original costs are lower and thus have a lesser effect on the total costs. When the fixed costs of bikes exceeds 6.87 €, the optimal solution shifts to a situation where fewer bikes and, as a result, fewer Wuunder points are used. To comply with the constraints, vans are used to service the region in that scenario. Because the number of bike trips declines to one-sixth of the original value, an increase in the fixed costs have a smaller effect on that configuration (roughly 0.14% for every subsequent 10% increase relative to 4.04 €.

If a severe increase in the fixed costs for bikes occurs, this has the biggest effect on the total cost. However, within a frame of at most a 50% decrease or increase in prices, the fixed costs of cargo bikes is most relevant. It should be noted that in the case of a decrease of the fixed costs for vans, the shift of optimal configuration is most imminent.

Lastly, Table 6.3 shows the effects of the variable costs. Again, increasing the costs of vans has no effect as they are already not used in the original case. However, a decrease has an immediate effect on the configuration. Significant cost reductions occur when the variable costs of vans decrease. Similarly, when cargo bikes become only 10% more expensive, the scenario with the use of vans becomes most cost efficient. At that point, a cost increase has no further effect. Thus the scenario remains 5.25% more expensive compared to the base case with time windows. Every 10% decrease in the variable costs of cargo bikes results in a decrease in overall costs of approximately 5.3%. Every 10% change in the variable costs of bikes results in a 1.3% change in the overall costs. If an increase of more than 50% is the case, however, the configuration changes to require fewer bike trips and thus fewer Wuunder points.

For variable costs, the biggest savings are achieved if the variable costs of vans are to be reduced. For small deviations from the base case scenario with time windows, the effect of variable costs of cargo bikes is most impactful. The most substantial cost increases are brought about by severe increases in the variable costs of bikes. The effect of variable costs overall is bigger than the effect of fixed costs. This is due to the proportion of line-haul and transverse costs being larger than the proportion of fixed costs in the total costs, roughly distributed in a 75%-25% ratio (Nourinejad and Roorda, 2017; Jabali et al., 2012).

d_1	**Costs**	**%**	**Van**	**Cargo**	**Bike**	**W**	d_2	**Costs**	**%**	**Van**	**Cargo**	**Bike**	**W**	d_3	**Costs**	**%**	**Van**	**Cargo**	**Bike**	**W**
100	3728.71			144	84	12	5	3924.40	5.25	60		14	2	1.5	3261.44	-12.53		153	68	17
120	3728.71			144	84	12	6	3924.40	5.25	60		14	2	1.8	3348.33	-10.20		144	80	16
140	3728.71			144	84	12	7	3924.40	5.25	60		14	2	2.1	3460.24	-7.20		150	75	15
160	3728.71			144	84	12	8	3924.40	5.25	60		14	2	2.4	3618.89	-2.95		154	84	14
180	3728.71			144	84	12	9	3869.14	3.77		156	91	13	2.7	3661.13	-1.81		143	91	13
200	3728.71			144	84	12	10	3728.71			144	84	12	3	3728.71			144	84	12
220	3728.71			144	84	12	11	3653.07	-2.03		143	77	11	3.3	3810.53	2.19		143	88	11
240	3728.71			144	84	12	12	3512.05	-5.81		130	70	10	3.6	3976.60	6.65		143	99	11
260	3728.71			144	84	12	13	3425.29	-8.14		126	63	9	3.9	4029.32	8.06		140	100	10
280	3728.71			144	84	12	14	3425.29	-8.14		126	63	9	4.2	4127.55	10.70	64		20	2
300	3728.71			144	84	12	15	3278.32	-12.08		112	56	8	4.5	4158.67	11.53	49		11	1
320	3728.71			144	84	12	16	3176.60	-14.81		105	49	7	4.8	4180.49	12.12	49		12	1
340	3728.71			144	84	12	17	3176.60	-14.81		105	49	7	5.1	4216.60	13.08	50		12	1
360	3728.71			144	84	12	18	3176.60	-14.81		105	49	7	5.4	4239.37	13.70	50		13	1
380	3728.71			144	84	12	19	3114.42	-16.47		102	42	6	5.7	4262.60	14.32	50		14	1
400	3728.71			144	84	12	20	3114.42	-16.47		102	42	6	6	4300.13	15.32	51		14	1

Table 6.1: Effects of capacities of the vehicle types on costs (absolute and relative to the base case with time windows) and configurations

d_1	**Costs**	**%**	**Van**	**Cargo**	**Bike**	**W**	d_2	**Costs**	**%**	**Van**	**Cargo**	**Bike**	**W**	d_3	**Costs**	**%**	**Van**	**Cargo**	**Bike**	**W**
10.72	3495.8	-6.25	60		14	2	3.92	3352.0	-10.10		144	84	12	2.42	3593.0	-3.64		144	84	12
12.50	3602.9	-3.37	60		14	2	4.58	3446.2	-7.58		144	84	12	2.83	3626.9	-2.73		144	84	12
14.29	3710.1	-0.50	60		14	2	5.23	3540.4	-5.05		144	84	12	3.23	3660.8	-1.82		144	84	12
16.07	3728.7			144	84	12	5.89	3634.5	-2.53		144	84	12	3.64	3694.8	-0.91		144	84	12
17.86	3728.7			144	84	12	6.54	3728.7			144	84	12	4.04	3728.7			144	84	12
19.65	3728.7			144	84	12	7.19	3822.9	2.53		144	84	12	4.44	3762.6	0.91		144	84	12
21.43	3728.7			144	84	12	7.85	3917.1	5.05		144	84	12	4.85	3796.6	1.82		144	84	12
23.22	3728.7			144	84	12	8.50	3924.4	5.25	60		14	2	5.25	3830.5	2.73		144	84	12
25.00	3728.7			144	84	12	9.16	3924.4	5.25	60		14	2	5.66	3864.5	3.64		144	84	12
26.79	3728.7			144	84	12	9.81	3924.4	5.25	60		14	2	6.06	3898.4	4.55		144	84	12
28.58	3728.7			144	84	12	10.46	3924.4	5.25	60		14	2	6.46	3932.3	5.46		144	84	12
30.36	3728.7			144	84	12	11.12	3924.4	5.25	60		14	2	6.87	3964.0	6.31	60		14	2
32.15	3728.7			144	84	12	11.77	3924.4	5.25	60		14	2	7.27	3969.6	6.46	60		14	2
33.93	3728.7			144	84	12	12.43	3924.4	5.25	60		14	2	7.68	3975.3	6.61	60		14	2

Table 6.2: Effects of fixed costs of the vehicle types on costs (absolute and relative to the base case with time windows) and configurations and configurations

d_1	**Costs**	**%**	**Van**	**Cargo**	**Bike**	**W**	d_2	**Costs**	**%**	**Van**	**Cargo**	**Bike**	**W**	d_3	**Costs**	**%**	**Van**	**Cargo**	**Bike**	**W**
0.65	2459.4	-34.04	47		7	1	0.56	2742.2	-26.46		144	84	12	0.56	3491.4	-6.36		144	84	12
0.77	2772.5	-25.64	47		7	1	0.67	2939.5	-21.17		144	84	12	0.67	3538.9	-5.09		144	84	12
0.90	3085.6	-17.25	47		7	1	0.78	3136.8	-15.87		144	84	12	0.78	3586.3	-3.82		144	84	12
1.03	3377.3	-9.42	60		14	2	0.90	3334.1	-10.58		144	84	12	0.90	3633.8	-2.55		144	84	12
1.16	3650.9	-2.09	60		14	2	1.01	3531.4	-5.29		144	84	12	1.01	3681.3	-1.27		144	84	12
1.29	3728.7			144	84	12	1.12	3728.7			144	84	12	1.12	3728.7			144	84	12
1.42	3728.7			144	84	12	1.23	3924.4	5.25	60		14	2	1.23	3776.2	1.27		144	84	12
1.55	3728.7			144	84	12	1.34	3924.4	5.25	60		14	2	1.34	3823.6	2.55		144	84	12
1.68	3728.7			144	84	12	1.46	3924.4	5.25	60		14	2	1.46	3871.1	3.82		144	84	12
1.81	3728.7			144	84	12	1.57	3924.4	5.25	60		14	2	1.57	3918.5	5.09		144	84	12
1.94	3728.7			144	84	12	1.68	3924.4	5.25	60		14	2	1.68	3954.8	6.06	60		14	2
2.06	3728.7			144	84	12	1.79	3924.4	5.25	60		14	2	1.79	3960.9	6.23	60		14	2
2.19	3728.7			144	84	12	1.90	3924.4	5.25	60		14	2	1.90	3966.9	6.39	60		14	2

Table 6.3: Effects of variable costs of the vehicle types on costs (absolute and relative to the base case with time windows) and configurations

Chapter 7

Conclusions

In this chapter, the research is summarized and recommendations for future research are given. Firstly, the research questions from Section 1.4 are answered. Secondly, Section 7.1 details the recommendations for future research, both at Wuunder and in more general scientific studies.

The first subquestion asked in this report is the following:

1. *Given a certain Wuunder maturity (number of customers), what is the optimal number of Wuunder points and what are the corresponding costs?*

In this research, a model is presented that is capable of determining the optimal number of Wuunder points and required trips per vehicle type along with the affiliated costs. In Table 5.2 such an overview is given. The model allows for adjustment of the parameters to suit the preferred situation and select the optimal configuration in terms of the number of Wuunder points and fleet composition as well as simply displaying all options and costs.

Since Wuunder intends to grow and evolve as a company, it is interested in assessing the order in which they should implement the concept in cities given a growing customer base, whether it is to partner up with more couriers or more Wuunder points to facilitate the growth optimally. To that end, the following sub-question is answered in this report:

2. *What should the order of priority be for Wuunder to achieve the biggest savings in distance for different stages in terms of customers?*

As can be seen in Table 5.5, the model presented is capable of determining the optimal settings for different scenarios. For a city with the characteristics of Eindhoven, it can be seen that only bikes and cargo bikes are required under the current parameter settings when between 200 and 1400 customers make use of the Wuunder platform. The number of additional Wuunder points required equals 1 for every additional 100 customers. Each Wuunder point then services its district with 7 bike trips and approximately 12 cargo bike trips. Beyond this point, however, the optimal solution requires 2 districts, serviced by 7 bicycle courier trips each and increasing amounts of van trips to satisfy demand. Alternatively, if the capacity of Wuunder points remains at 240 packages, solutions of up to 18.9% more expensive are required to service the region. In these settings, no vans are required throughout the growth of the Wuunder concept.

Wuunder can use tables such as these to determine at what point it becomes relevant to start opening Wuunder points in a certain city. Similarly, when a certain customer growth is expected within a period, decisions can be made based on those expectations. For instance, when Wuunder expects 2000 customers in Eindhoven within 3 months, but currently has 1200, it makes sense to use 2 Wuunder points instead of 14, which is the optimal number of points for that amount following Table 5.5. In the short term, this means that Wuunder will operate at 3.29 percent above optimal in terms of courier related costs (see Table 5.6). Naturally, this depends on the ease with which Wuunder expects to partner up with these points and how easily the partnership can be terminated.

Lastly, the indication of the reduced environmental impact is researched in this report, related to the final research sub-question asked in this thesis:

3. *What are the effects of implementing the Wuunder concept in a city in terms of CO_2 / kilometers*

Tables 5.8 and 5.9 best illustrate these effects. The adoption of the Wuunder platform could lead to a daily reduction of 1668 kilograms of CO_2 in Eindhoven alone. This is a estimated reduction of more than 63% relative to the current system.

All packages being sent through Wuunder is not expected to happen overnight and probably not within a small time frame. As can be deducted from Table 5.9, the coexisting of the Wuunder platform along the current system is not necessarily more efficient for every case.

With all three sub-questions answered, the main question asked in this report is examined:

How can Wuunder arrange the parcel delivery system in a city in the most efficient way by using Wuunder points and couriers?

From this report we gather that sending parcels via the Wuunder platform has the potential to make the parcel delivery system more efficient. A model has been developed that calculates optimal configurations in terms of the number of Wuunder points and required trips per vehicle type. It is shown that costs and configurations depend heavily on the tightness of the time windows that clients specify as well as the proportion of clients that does so. The number of customers within a region greatly affect the costs as well. Efficiencies are more easily exploited for a greater number of customers and thus, costs per parcel are reduced.

In this report, the assumptions made tend to be favorable towards the existing system. For instance, no time windows and unattended deliveries are assumed for the current system to assess the environmental impact, while the Wuunder system does have time windows. These failed deliveries result in repeated delivery journeys as well as consumer's trips to retrieve their packages. Time windows should logically decrease the number of unattended deliveries, but this effect is not taken into account in the comparison.

7.1 Future research and recommendations

Dedicated Wuunder points

The biggest impact on the performance of the model is the capacity of a Wuunder point. Currently, a limit of 240 packages is used, as the points are not necessarily dedicated parcel hubs. Wuunder simply uses otherwise unused space in locations and pays a fee per package. For some cases, the costs are 18.86% higher compared to when the capacity of a Wuunder point is not restricted. The use of dedicated Wuunder points should be considered as the current limited capacity has a considerable impact on the costs and configurations of the system. Research into an acceptable price for the use of such points could therefore prove valuable.

Data on time window impact

The most important aspect that requires a more thorough understanding concerns the impact of time windows. The estimate for distance penalty should be estimated by analyzing case-specific data. Furthermore, the estimate for time window distance penalties is likely dependent on the type of vehicle being used. For a bike with only 3 packages, a time window is very likely to cause the need for an entirely new additional route. For a van with a capacity of 200 packages, a route is more easily adapted to incorporate the package into the route without violating the time window. Therefore, future research should focus on this relation. This means storing data on specified time windows and the tour lengths which are to be compared with optimal tour lengths.

Negotiating contracts

If contracts with partners can be renegotiated or new vehicles with different characteristics are considered, attention should be paid to the effect of these characteristics. Especially the characteristics of the cargo bike should be considered carefully, as these impact the costs and configurations severely. Lower variable costs should have priority over fixed costs, as in the model the proportion of variable costs is higher than the proportion of the fixed costs.

Ecological comparison

Secondly, the ecological effects of the Wuunder concept should be more extensively researched. To assess this effect better, more information is needed for the pollution associated with the current system. The current evaluation is based on assumptions to fit the current system into the model. If accurate data is available, this evaluation would be more sensible.

Failed deliveries

Related to the environmental aspect is the number of driven kilometers due to failed deliveries. The amount of failed deliveries, as well as their effect on the costs incurred, is currently unclear but likely considerable. The inefficient routing due to time windows could be (partially) offset by a decreased amount of failed deliveries and therefore deserves further investigation.

Load sharing

In this report, the effect of load sharing between districts is not incorporated. This is a very interesting topic that could further increase the efficiency of the system. Jabali et al. (2012) already identify this as an interesting topic for further research. Arguably, it is even more relevant for this research, as districts within a region overlap in reality.

Topology

This report only considers a ring-radial network. The model of (Nourinejad and Roorda, 2017) could also be applied to this case to derive an even further understanding of the system and its workings. Additionally, the inner ring capacity constraints should be reviewed for the model. Currently, the radius of the inner ring is determined for optimality if a single district is considered, but proves to be suboptimal if a region is partitioned into multiple districts. Further adaptation of the model to incorporate for this effect is therefore required.

Multiple packages per customer

In this report, it is assumed that every customer orders a single package. However, especially for pickups this number may be much higher, meaning a significant decrease in costs per package. Furthermore, chiefly for vans, the problem can also be described as a pickup-and-delivery problem instead of a capacitated VRP. For (cargo) bikes, the odds of having a pickup and a delivery in the same zone allowed by the time windows are much smaller due to the limited capacities of these vehicles. Still, this chance exists. A capacity dependent chance of this happening should be included in the model as it changes the amount of customers a vehicle is able to visit in a single trip.

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Appendix A

Solution methods in literature

Type	Solution technique	Mentions	Sources
Metaeuristic	Simulated annealing	3	(Sajjadi et al., 2010; Wu et al., 2002; Yu et al., 2010)
Metaheuristic	GRASP	2	(Contardo et al., 2014; Prins et al., 2007)
Metaheuristic	Tabu search	2	(Baumung et al., 2015; Escuín et al., 2012)
Metaheuristic	GRASP+ILP	1	(Contardo et al., 2014)
Metaheuristic	VNS-TS	1	(Escuín et al., 2012)
Heuristic	VNS	3	(Escuín et al., 2012; Gansterer et al., 2016; Stenger et al., 2013)
Heuristic	Continuous Approximation	3	(Lin et al., 2016; Jabali et al., 2012; Ouyang and Daganzo, 2006)
Heuristic	Lagrangian relaxation	2	(Nikbakhsh and Zegordi, 2010; Prins et al., 2007)
Heuristic	Ant Colony System	2	(Nadizadeh et al., 2011; Sajjadi et al., 2010)
Heuristic	Minimum spanning forest problem	1	(Nikbakhsh and Zegordi, 2010)
Heuristic	ILP with Lagrangean relaxation	1	(Mahmoudi and Zhou, 2016)
Heuristic	Local Improvement Heuristic	1	(Contardo et al., 2014)
Heuristic	Approximation Algorithm	1	(Harks et al., 2013)
Heuristic	Hybrid Algorithm	1	(Männel and Bortfeldt, 2016)
Heuristic	Greedy Clustering	1	(Nadizadeh et al., 2011)
Heuristic	Neighbourhood search	1	(Nikbakhsh and Zegordi, 2010)
Heuristic	Or-opt	1	(Nikbakhsh and Zegordi, 2010)
Heuristic	Granular Tabu Search	1	(Prins et al., 2007)
Heuristic	Fix-and-optimize	1	(Rieck et al., 2014)
Heuristic	Genetic algorithm	1	(Rieck et al., 2014)
Heuristic	Decomposition Approach	1	(Sebastian, 2012)
Exact	Branch-and-Cut Algorithm	2	(Belenguer et al., 2011; Jepsen et al., 2013)
Exact	LMIP	1	(Alumur et al., 2012)
Exact	Benders decomposition algorithm	1	(Contreras et al., 2011)
Exact	ILP	1	(Laporte et al., 1986)

Table A.1: Solution methods for the location-routing problem used in literature

Appendix B

Parameters

For delivery vans, it is known that a driver receives 35 € per hour and makes 8 stops in that time. Furthermore, it is known that sending a single package costs 20 €. Using the assumption that a single stop requires a service time of 5 minutes and knowing that the speed of a van is approximately 40 km/h, one can calculate that a courier drives 20 minutes at 40 kilometers an hour. That would mean 8 stops equal $\frac{40}{3}$ km and one stop therefore $\frac{40/3}{8} = \frac{5}{3}$ km. Since two points, dependent on distance have been established, a fixed and variable cost can be determined as can be seen in Equations B.1.

$$\begin{array}{rcl rcl} Price & = & f_1 + d_1 * Distance & 15 & = & d_3 * \frac{35}{3} \\ 20 & = & f_1 + d_1 * \frac{5}{3} & d_1 & \approx & 1.29 \\ 35 & = & f_1 + d_1 * \frac{40}{3} & f_1 & \approx & 17.86 \end{array} \tag{B.1}$$

The fixed and variable costs for cargo bikes are derived differently than above, because other information was known about the rates. The tariffs as depicted below in Table B.1 were supplied by the partner for (cargo) bikes:

Tariff (€)	Destinations	Max distance (km)
6.50 €	Within the ring	4.4
10.50 €	Woensel, Airport, Acht, Ekkersrijt	6.5
14.50 €	Geldrop, Waalre, Best, Nuenen, Son, Gerwe	11.0
18.00 €	Valkenswaard, Mierlo, Oirschot	14.0

Table B.1: Tariffs handeld by a bicycle courier in Eindhoven

$$\begin{array}{rcl rcl rcl} Price & = & f_3 + d_3 * Distance & 11.5 & = & d_3 * 10.3 & d_2 & \approx & 1.12 \\ 6.5 & = & f_3 + d_3 * 2.2 & d_3 & \approx & 1.12 & f_2 & = & f_3 + 2.50 \\ 18 & = & f_3 + d_3 * 12.5 & f_3 & \approx & 4.04 & f_2 & \approx & 6.54 \end{array} \tag{B.2}$$

$$\begin{aligned} AUC_{exact} &= 6.5 * 4.4 + 10.5 * (6.5 - 4.4) + 14.5 * (11 - 6.5) + 18 * (14 - 11) \\ &= 169.9 \\ AUC_{approx} &= \int_0^{14} 1.12x + 4.04dx \\ &= \left[\frac{1}{2}1.12x^2 + 4.04x\right]_0^{14} \\ &\approx 166.03 \end{aligned} \tag{B.3}$$

Appendix C

Maximum number of Wuunder points

Let $x_{11} = 1$ and $p_t, k_t, r \geq 0$, Then if $l_{11} \geq r$, it must hold that:

$$
\begin{array}{rclrcl}
 & & & \delta\gamma l_{i1} * \left(1 + p_t k_t \frac{r}{2}\right) & \geq & c_i x_{i1} \\
 & & & r + p_t k_t \frac{r}{2} & = & \frac{c_1}{\delta\gamma} \\
p_t k_t & = & 0, & r & = & \frac{c_1}{\delta\gamma} \\
p_t k_t & \neq & 0, & \frac{p_t k_t}{2} r^2 + r - \frac{c_1}{\delta\gamma} & = & 0, \\
 & & & r & = & \frac{\sqrt{1 - 2 p_t k_t \frac{c_1}{\delta\gamma}} - 1}{p_t k_t}
\end{array}
\tag{C.1}
$$

If a maximum value for radius r of a district is obtained, one can easily deduct the corresponding maximum number of Wuunder points in the region. Let r_r denote the radius of the entire region and r_{min} the minimal radius of a single district. Then for the maximum number of Wuunder points (or districts) in a region, denoted by the integer p_{max} it holds that:

$$
\begin{array}{rcl}
r_{min} & \geq & \frac{r_r}{\sqrt{p_{max}}} \\
\sqrt{p_{max}} & \leq & \frac{r_r}{r_{min}} \\
p_{max} & = & \left\lfloor \left(\frac{r_r}{r_{min}}\right)^2 \right\rfloor
\end{array}
\tag{C.2}
$$

Appendix D

Time window fleet compositions

W points	Costs (€) L_{TW}	Costs (€) U_{TW}	Van	Cargo	Bike	l_{i1}	$\sum_{i=1}^{q} l_{i2}$	l_{i3}	Gap (%) L_{TW}-U_{TW}	Gap (%) L- L_{TW}
1	4024.94	4070.16	47		7	1.37	16.63		1.12	79.57
2	3924.40	4000.93	60		14	1.59	11.14		1.95	52.05
3	4037.58	4134.07	72		21	1.71	8.68		2.39	40.32
4	4155.85	4266.89	80		28	1.79	7.21		2.67	32.51
5	4343.20	4465.44	90		35	1.85	6.20		2.81	34.92
6	4587.55	4712.67	102		42	1.91	5.44		2.73	46.10
7	4587.92	4774.75		196	49	1.95	1.77	3.08	4.07	43.68
8	4589.88	4780.27		208	56	1.97	1.27	3.12	4.15	62.43
9	4347.81	4525.00		135	135	2.00	4.00		4.08	48.19
10	4377.06	4539.21		140	150	2.03	3.67		3.70	41.44
11	4361.79	4487.21		143	154	2.06	3.37		2.88	34.00
12	3728.71	3865.59		144	84	2.07	3.13		3.67	11.84
13	3877.10	4007.14		156	91	2.09	2.90		3.35	11.14
14	3928.09	4067.37		154	98	2.10	2.71		3.55	7.97
15	4075.69	4207.04		165	105	2.12	2.53		3.22	7.43
16	4211.02	4351.05		176	112	2.13	2.37		3.33	6.84
17	4359.92	4490.98		187	119	2.15	2.22		3.01	9.41
18	4388.41	4519.29		180	126	2.16	2.09		2.98	6.24
19	4525.74	4655.84		190	133	2.17	1.96		2.87	5.87
20	4661.15	4799.73		200	140	2.17	1.86		2.97	5.51
21	4803.34	4931.46		210	147	2.19	1.74		2.67	5.27
[1]22	4935.94	5464.12		220	154	2.19	1.64		10.70	17.26
23	4925.26	5058.84		207	161	2.20	1.55		2.71	13.73
24	5065.17	5188.91		216	168	2.22	1.46		2.44	16.25
25	5196.53	5327.48		225	175	2.20	1.40		2.52	16.17
26	5327.53	5455.15		234	182	2.22	1.31		2.40	16.08
27	5464.87	5591.42		243	189	2.22	1.25		2.32	16.10
28	5601.49	5717.49		252	196	2.25	1.16		2.07	16.13
29	5731.96	5852.03		261	203	2.24	1.10		2.09	16.01
30	5192.97	5310.82			480	2.25	1.04		2.27	2.68

[1] Model U_{TW} uses an additional 22 vans in this scenario.

W points: Number of Wuunder points. This can also be seen as the number of districts in a region. U_{TW}: The model for the upper bound with time windows, L_{TW}: The model for the lower bound with time windows.

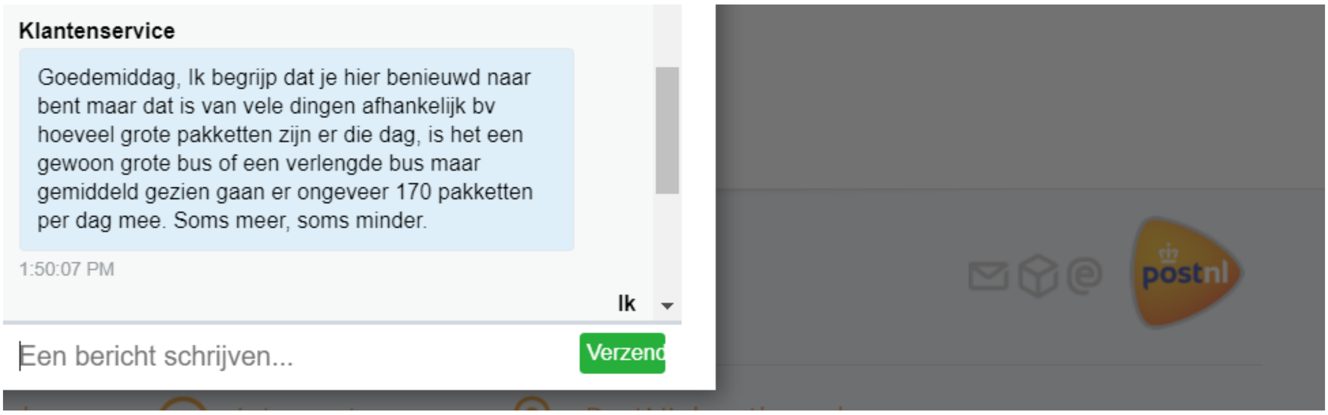
Distance penalty per time window = $0.2\bar{r}$ km, Proportion of customers with time windows = 50%.

Table D.1: Resulting fleet compositions and costs for base case scenarios with time windows

Appendix E

Van Capacity PostNL

Below in Figure E.1 a conversation (in Dutch) is shown with the customer service of PostNL. The message translates into: *"Good day. I understand that you are interested, but that [van capacity] is dependent on many factors. For instance, how many big packages there are that day, whether it is a regular big van or an extended van. On average, around 170 packages are taken daily. Sometimes more, sometimes less."*



Klantenservice

Goedemiddag, Ik begrijp dat je hier benieuwd naar bent maar dat is van vele dingen afhankelijk bv hoeveel grote pakketten zijn er die dag, is het een gewoon grote bus of een verlengde bus maar gemiddeld gezien gaan er ongeveer 170 pakketten per dag mee. Soms meer, soms minder.

1:50:07 PM

Figure E.1: Estimation of van capacity for PostNL by customer service

Appendix F

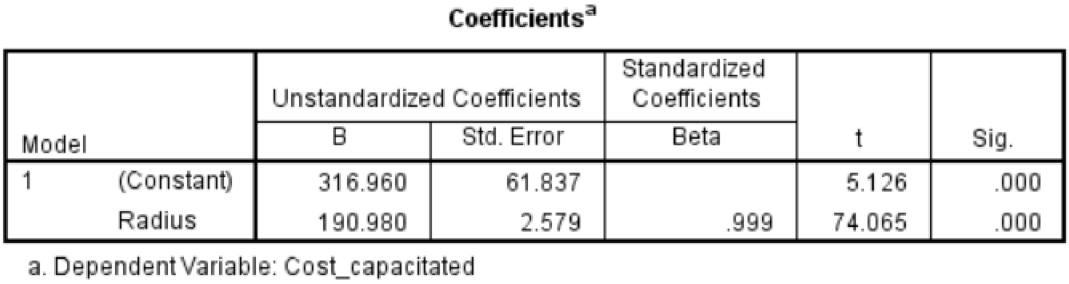
Implementation distances

Via Wuunder (%)	Costs	Points	Vans	Cargo	Bikes
5	2349.1	0	1218.2	307.22	6
10	3310.5	0	1618.6	383.98	10
15	4149.6	0	1916.6	453.96	14
20	4920.3	2681.2	0	42.576	2
25	5454.7	2988.6	0	38.081	2
30	5916.7	3266.5	0	34.763	2
35	6350.6	3522.1	0	32.185	2
40	6799.5	3761.1	0	30.097	2
45	7157.2	3984.5	0	28.376	2
50	7535.3	4195.7	0	26.921	2
55	7891.6	4105.2	0	41.467	3
60	8218.2	4588.7	0	24.576	2
65	8553.4	4454.9	0	38.141	3
70	8860.9	4950.1	0	22.754	2
75	9128.8	4778.7	0	35.505	3
80	9432.4	4931.9	0	34.381	3
85	9714.6	5447.6	0	20.647	2
90	9969.8	5225.6	0	32.413	3
95	10252	5754.6	0	19.53	2
100	10487	5503.4	0	30.748	3

Table F.1: Distances driven (km) per vehicle types in different stages of Wuunder adaptation ($e = 8125$)

Appendix G

Statistical analysis of the radius impact

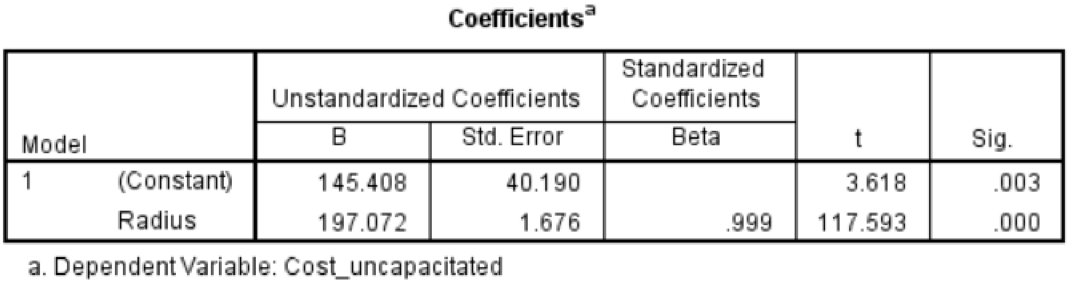


Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	316.960	61.837		5.126	.000
	Radius	190.980	2.579	.999	74.065	.000

a. Dependent Variable: Cost_capacitated

Figure G.1: Statistical analysis of the impact of radius on costs if Wuunder points are uncapacitated



Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	145.408	40.190		3.618	.003
	Radius	197.072	1.676	.999	117.593	.000

a. Dependent Variable: Cost_uncapacitated

Figure G.2: Statistical analysis of the impact of radius on costs if Wuunder points are capacitated