LIGHT ELECTRIC FREIGHT VEHICLES IN LAST-MILE DELIVERY

by

Ronald Veldman

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Signature redacted

Author ....
Department of Supply Chain Management
May 10, 2019

Signature redacted

Certified by ....
Dr. Matthias Winkenbach
Director, MIT Megacity Logistics Lab
Thesis Advisor

Signature redacted

Accepted by ....
Dr. Yossi Sheffi
Director, Center for Transportation and Logistics
Elisha Gray II Professor of Engineering Systems
Professor, Civil and Environmental Engineering

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Abstract

In previous decades the postal sector experienced drastic changes. Liberalization and digitization resulted in a continuous mail market decline. Simultaneously the rise of Internet resulted in a booming e-commerce parcel delivery market. To cope with these ongoing market developments Postal Operators (POs) need to rigorously restructure their delivery networks frequently in order to reduce distribution cost. Moreover, POs are searching for synergy opportunities between the mail and parcel delivery network. A recent development in the postal sector is the use of light electric freight vehicles (LEFV) in urban and suburban areas as a sustainable and cheaper solution for last-mile delivery. Limited research has been performed regarding the impact of LEFV on distribution cost and network design. This thesis introduces a two echelon location routing model for POs to determine the optimal network configuration for mail and parcel delivery in order to minimize total distribution costs using LEFV in their vehicle portfolio. A mixed integer linear programming model (MILP) is proposed including a multi-depot VRP for the first tier and continuous approximation techniques (CA) for the second tier. Using a real-world application at the Dutch PO - PostNL - the impact of merging the mail and parcel network as well as the impact of introducing LEFV was established. Results suggest that adding LEFV to the vehicle fleet leads to a distribution cost saving of 3% in the separate mail and parcel network. LEFV are a worthy alternative to vans in dense city areas, due to their high speed on short distances and their manoeuvrability in city areas. While merging the parcel and mail network with the current vehicle fleet leads to a distribution cost reduction of 1%, the inclusion of LEFV in a merger scenario leads to a saving of 5%. Therefore, adding LEFV to the vehicle fleet enables POs to seize synergy opportunities between the distribution networks.

Thesis Advisor: Dr. Matthias Winkenbach
Title: Director, MIT Megacity Logistics Lab

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Chapter 1

Introduction

1.1 Developments in the Postal Market

The rise of commercial Internet had a significant impact on the postal industry and brought postal operators (PO) into a turbulent market situation. The usage of electronic communication methods (e.g., email) caused high substitution levels in PO's letter segment resulting in a continuous volume decline (Copenhagen Economics, 2018). At the same time online transactions were showing solid growth rates worldwide, leading to a flourishing e-commerce market (International Post Corporation, 2017). POs are typically large players in their country's domestic e-commerce market, due to their early presence in the market as well as their established distribution networks. However, margins in the e-commerce market are significantly smaller in comparison to the traditional cash cow letters, as a consequence of fierce competition.

In addition to severe changes in demand, the regulatory framework also went through a major shift. Historically, POs always had a government protected monopoly status in their domestic mail market, but in 2010 the introduction of the international Postal Directive (97/67/EC) liberalized the market. Governments decreased their share of ownership and POs transitioned into (semi-)independent companies. New entrants tried to take over the most profitable regions of a country leading to intensified competition and pressure on margins. The introduction of a Universal

Service Obligation (USO) ensured by law that each inhabitant had access to mail 5 days a week within a 24 hour delivery window. Total delivery cost and transportation cost in the postal industry account for more than 50% of the total cost base, making an efficient logistical infrastructure the key driver for a competitive advantage in the e-commerce market (Nera, 2004). To cope with the ongoing market developments and defend their dominant position in the last-mile delivery market, POs need to overcome several logistical challenges. POs have to scale down their distribution network for mail on a continuous basis, while at the same time being severely limited by the USO. Moreover, fast growth in the e-commerce sector requires POs to quickly expand their sorting and distribution network in order to match capacity with the rapid growth of demand for parcel delivery.

1.2 The Postal Industry: Products and Processes

Postal services include a wide variety of services, but from a delivery point of view, these can be categorized into three major product and service types (van der Lijn et al, 2005). First, *letter mail*, which corresponds to items that are dropped in the mailbox, with a maximum weight of 2 kg. Letter mail can be distinguished into priority mail with a delivery window of 24 hours and non priority mail with a delivery window longer than 24 hours. Second, *parcels* are in general at least 3 inches high, 6 inches long, and 1/4 inch thick, and are delivered in person to the customer or dropped in a parcel locker box. Parcels often include additional services like track and trace functionality as well as time-slot indication during the delivery process. Third, *express and courier mail* represent high added value services often demanding personal reception. These mail services are typically time critical items (e.g., contracts). This research will be restricted to letter mail and parcels, since express services require a separate courier network to meet the required time windows.

In general, the operational process of POs is built around four process steps (WIK Consult, 2016; Nera, 2004):

1. *Collection.* Collecting mail and parcel items from post boxes and post offices throughout the country and optionally from customer facilities.

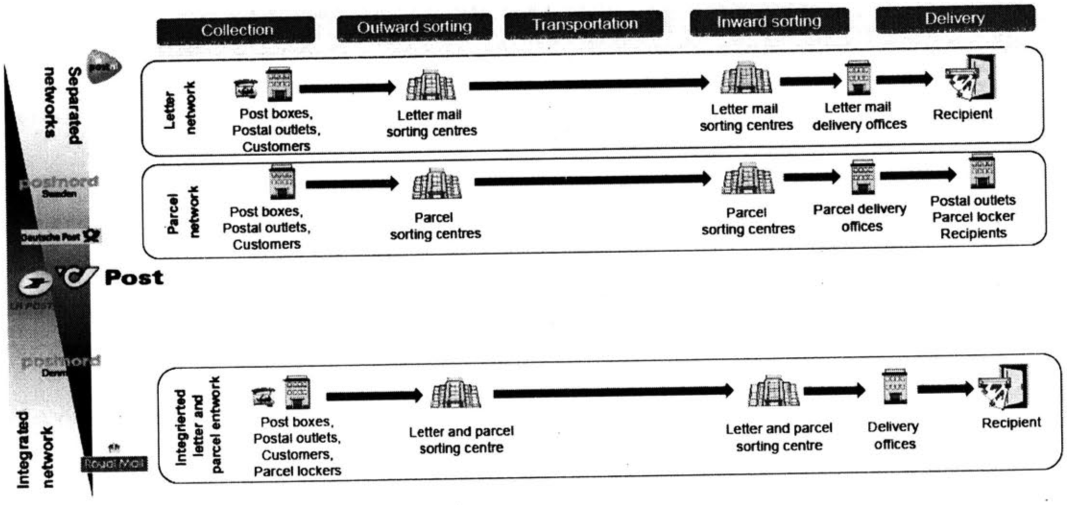
2. *Sorting.* Mail and parcel items have to be organized in the correct sequence for efficient distribution. Sorting machinery is limited to a specific stream of letters or parcels depending on the dimensions and weight of the products.

3. *Transportation.* The majority of the postal operators sort their products in waves (i.e. from region to street sequence) necessitating intermediate transport between sorting centers.

4. *Delivery.* Parcel and mail items are delivered to different households (i.e., demand nodes) using routes with the appropriate vehicles for the area. Pickups of return parcels during the delivery tours are rare. The vast majority of the pickups takes place from pickup points where customers can return their parcels. Dedicated collection tours with larger trucks are collecting these parcel items. These tours will not be included in this research.

Distribution networks underlying mail and parcel operations are similar. Differences occur at the collection process where parcels are often supplied by e-retailers or directly from the order fulfillment center. Moreover, parcel delivery is often executed by vehicles with a larger payload, typically vans. The amount of cooperation between the two divisions varies widely in the industry. Some companies have combined facilities for sorting mail and parcels while others have fully separated operations. Figure 1-1 presents a schematic view of the production flow including the level of network integration of some postal operators. Postal operators that lie in between the two extremes often find themselves using joint delivery in urban areas whereas in rural areas, segregated networks are maintained (Bender, 2016). Bradley (2018) emphasizes that under flexible operations, the postal operator should make letter routes with enough spare capacity to meet the demand for parcel delivery. A turning point will be reached when there is enough parcel volume to seize economies of scale in the parcel delivery routes, surpassing the benefits of joint delivery.

Figure 1-1: Postal Production Process (from WIK Consult, 2016)



In practice, many companies struggle with the decision whether to integrate or maintain separate network structures for parcels and mail. Two major reasons underlie the decision of POs that maintain separate networks. First, sorting of letters and parcels requires different machinery. Although new machinery can sort combinations of both, these machines are still costly. Second, letters are typically delivered by foot or bicycle starting from postal preparation centers or post offices, while parcels are delivered using motorized vans (Copenhagen Economics, 2018). Different modalities frequently correspond to different wage levels (i.e., license requirements result in a higher wage level), and hurdles with regard to security and time windows of parcel delivery have to be overcome in the letter network in order to integrate the networks.

Several trends are developing in the postal industry to cope with the changing market circumstances (WIK Consult, 2013):

1. *Centralization of letter sorting activities.* The number of intermediate hubs as well as the number of sorting centers is decreased severely, following the volume decline of letters. This also means that postal operators have to redesign their hub and spokes structure very frequently.

2. *Automated sorting.* Sorting by means of new machinery that is able to process

a wider range of letter types, thereby reducing the amount of required manual labor. Machinery that combines sorting of parcels and letters is still very costly and does not match the same productivity standards as separate sorting of the product streams.

3. *Unique identification.* The introduction of a unique identifier (i.e., code) for each mail item enables sorting without local human knowledge of the addresses in a geographic area.
4. *Sequence sorting.* In previous decades the last sorting wave was often executed manually at decentralized locations within each region. The combination of sequence sorting with automated sorting enables full centralization.
5. *Optimization of delivery.* Frequent redesign of the routes is required in order to match the volume decline of letters as well as the growth of parcel volumes. Periodically the number of routes has to be reduced to save on headcount and vehicle cost.
6. *Flexibility.* Many POs are trying out new delivery models in order to save delivery costs. This includes decreasing the number of delivery days for all products nationwide or only for specific regions. Moreover, POs are moving towards more temporary and part-time employees, in order to enable flexibility with regards to capacity adjustments.

1.3 The Rise of Light Electric Freight Vehicles in the Postal Sector

Due to recent technological developments, light electric freight vehicles (LEFV) are becoming a viable alternative for conventional forms of transport like cars and bicycles. LEFV assist the driver using an electrical driven motor and are designed for the distribution of freight with a limited speed (van Amstel, 2018). LEFV are available in different types: bike, moped or compact vehicle.

There is a growing interest among logistic service providers (LSP) to use LEFV for urban logistics (van Amstel, 2018). In 2012 the Danish Post won a postal innovation award within the postal and parcel industry for their newly developed e-cargobike suited for last-mile delivery. Multiple national postal operators quickly followed the initiative by setting up pilots with a variety of LEFV (e.g., Scandinavia, Germany, France, US, Netherlands). In particular e-cargobikes - electrically supported bicycle with a higher payload to transport freight - came forward as a common solution.

Gruber (2013) states that 19-48% of the total distances driven by logistics providers with combustion engine vehicles could be substituted by electric cargobikes. Several factors contribute to the rise of LEFV in the postal industry:

1. Logistics operators are responsible for approximately 20% of the total CO2 emission in urban areas (Schoemaker et al, 2006). Transitioning from fossil fueled vans towards electrical vehicles has great potential to reduce this negative impact (Schliwa, 2015).
2. The growing population in combination with urbanization leading to congestion in city areas (Taniguchi, 2015). Moreover, some governments are introducing access restrictions for cities.
3. Technological developments. Contemporary LEFV have a large range and a high payload. Moreover, LEFV can use bicycle lanes, which makes it a suitable alternative for car delivery in dense areas. Another advantage is the opportunity for deliverers - historically using bikes in (sub)urban areas - to deliver mail items together with small parcels seizing synergy opportunities between the parcel and mail network.
4. As a consequence of better affordability, LEFV are becoming a viable alternative for bicycles, since LEFV offer a higher average speed and less physical strain on the deliverers enabling longer tour lengths.

However, the introduction of a new vehicle type in the fleet of POs also leads to new challenges. These vehicles have to be stored and charged, which does not always match with the pick-up point locations that POs are often using as a starting point for their delivery routes. LEFV will require hubs in closer proximity to the delivery area. Additionally, LEFV tend to be more demanding with regards to maintenance compared to bicycles and even though the amount of safety incidents does not seem to increase the severity of traffic incidents does (Popovich et al, 2014). A recent survey in the Netherlands revealed that the interest in LEFV is primarily the result of the pursuit of sustainable business models and innovative ambitions and less of financial objectives (LEVV-NL, 2017). Giuliano et al. (2013) and Browne (2011) mention specifically the use of electric vehicles for urban freight as a sustainable and efficient method for last-mile delivery.

1.4 Research Motivation and Research Goal

A large number of real-world applications have shown that the use of computational models for location and transport optimization can produce substantial savings in transportation costs (Toth & Vigo, 2011). The use of such operations research models can support POs in finding the optimal logistical network design for delivery and give more insights into factors that play an important role regarding the synergy choices. The postal sector is a popular industry for actual applications of these models. Examples include determining postbox locations (Labbe and Laporte, 1986), optimizing parcel delivery (Bruns et al. 2000; Wasner and Zapfel, 2004; Lischak and Triesch, 2007), and optimizing mail delivery networks (Grunert, 2000; Lin, 2004; 2010). Winkenbach et al. (2016) developed a MILP model in cooperation with the French postal operator *La Poste* focused on urban logistics (pickup and delivery). However, the introduction of LEFV in a model and determining the specific impact of adding this vehicle type on the actual network design in combination with synergy opportunities between mail and parcels is an interesting extension. The addition of LEFV to the fleet could enhance synergy between the mail (often including bicycle routes with low payload) and the parcel network (often executed with vans), since the mix of its payload and average speed seems highly suited for dense areas.

This research will include a case study at PostNL (the Dutch PO) with real-world data of their delivery process. PostNL with a fully separated parcel and mail network, faces the same challenge as described in the previous sections. Their choice of a separated network was mainly driven by the different wage levels for the delivery of parcels and mail. Historically, the preferred mode of transportation for mail delivery in the Netherlands is a bicycle operated by low-cost mailmen. However, parcel delivery is executed by vans with a high loading capacity, requiring drivers with higher wages (due to license requirements). The introduction of LEFV without accompanied license requirements could allow PostNL to overcome the high wage barrier for parcel delivery, making an integrated mail and parcel network a viable option in dense areas. Using LEFV and merging the networks will require a redesign of the hub-and-spokes structure. A redesign of the mail hub structure would be required since PostNL makes use of 2,000 pickup points without storage capacity. The parcel division makes use of direct shipping with vans, LEFV would require local hubs and requires indirect shipping. Finally, the introduction of LEFV can bring additional benefits to PostNL contributing to the sustainability goals and resolving the city related problems like congestion.

Consequently, the aim of this research is *the development of a location routing model for postal operators to determine the optimal network configuration for integrated mail and parcel delivery in order to minimize total distribution cost using Light Electric Freight Vehicles in their vehicle portfolio.* The hypothesis is that the introduction of LEFV in the vehicle fleet will lead to a more efficient standalone mail or parcel delivery network, but combining small parcels with mail delivery could significantly increase the benefits of LEFV. A 2-echelon location routing problem (2E-LRP) will be modeled using continuous approximation (CA) techniques.

1.5 Thesis Outline

The remainder of this thesis is structured as follows. In Chapter 2, a literature overview will be presented, identifying the gaps in literature and the contribution of this research. Chapter 3 will state the proposed mathematical model to solve the LRP with the accompanied model assumptions. In Chapter 4, the 2E-LRP will be applied to the industry case of PostNL and the results and discussion of the results will be presented. In Chapter 5, the conclusion and suggestions for future research are stated.

Chapter 2

Literature Review

The primary aim of logistics is improving the transportation of freight between suppliers and customers. This involves decisions on different levels according to their time span (Xia, 2013). At an *operational level*, the actual routing of the tours/vehicles has to be optimized in order to minimize the distance travelled. At a *tactical level*, the optimal number and type combinations of vehicles have to be set as well as the allocation of customers to a certain facility. On a *strategic level*, typical decisions include determining the optimal number of production sites, distribution centers and freight terminals. The application of optimization models deriving from operations research is a useful tool to support decision makers with these kinds of network design decisions. A lot of real-world applications can be found in literature varying from postal distribution to grocery distribution (Feliu & Perboli, 2007).

In this section the main academic contributions in operations research (OR) literature related to transportation systems are presented. The vehicle routing problem and the location routing problem will be covered, followed by a brief overview of the different solution techniques. Finally, an overview of the present status of LEFV, in a logistics context is presented.

2.1 The Vehicle Routing Problem

The vehicle routing problem (VRP) as formulated by Dantzig and Ramer (1959) is an extension of the travelling salesman problem. The VRP assumes a set of vehicles located at a depot that must be routed in order to serve a set of geographically distributed customers. The aim of the VRP is to minimize the vehicle cost and the total routing cost under a given set of constraints (Toth and Vigo, 2002; Torres et al., 2013). Since the introduction of VRP many variants have been applied to real world situations, extensive surveys are available in literature (Laporte, 1992; Min et al., 1998; Zirour, 2008; Kumar, 2012; Caceres-Cruz et al., 2014; Braekers et al., 2016; Koc et al., 2016; Ritzinger et al., 2017; Cao and Yang, 2017; Adewumi, 2018; Sharma et al., 2018). For this brief overview the framework of Min et al. (1998) is presented in Table 2.1.

Table 2.1: VRP Classification (from Min et al, 1998)

Standard of classification	**Types of problems**	
Direction of goods	One direction	Bi-direction
Demand type	Deterministic	Dynamic
Number of facility	Single	Multiple
Number & Typle of vehicles	Single	Multiple
Capacity of vehicle	Determinate	Undetermined
Capacity of depot	Determinate	Undetermined
Number of echelon	Single	Multiple
Time windows	Hard & Soft	None
Objective function	Single	Multiple

Variations exist regarding the number of echelons, the type of demand, and the direction of the goods. Multi-depot VRPs (MDVRPs) consider tours starting from multiple depots to serve all the customers. In most cases, customers have to be assigned to a specific depot (Salhi and Sari,1997; Vidal, 2014). Capacitated VRPs (CVRPs) with a heterogeneous fleet ensure that the tours are respecting the maximum allowed payload for a specific vehicle type, by adding additional capacity constraints (Lima, Goldbarg and Goldbarg, 2004; Vidal et al., 2013; Koc et al., 2016). VRPs with time windows (VRPTWs) ensure that all customers are served within a specific timeframe (Bramel and Sinchi-Levi, 1996; Solomon, 1995; Cuda et al., 2015).

2.2 The Location Routing Problem

The determination of the number and geographic location of facilities dates from the 1960s, known as the traditional p-median problem (Hakimi, 1964; Cooper, 1963). Campbell (1996) expands this model by introducing the option to allocate a destination to multiple hubs and presented two heuristics to solve this problem. Various authors discuss the interdependence between the transportation and facility cost, where the facility location problem and the VRP have to be solved simultaneously (Balakrishan et al, 1987; Nagy and Salhi, 2007, Tuzun & Burke, 1999). The location routing problem consists of three decisions (Min, 1998):

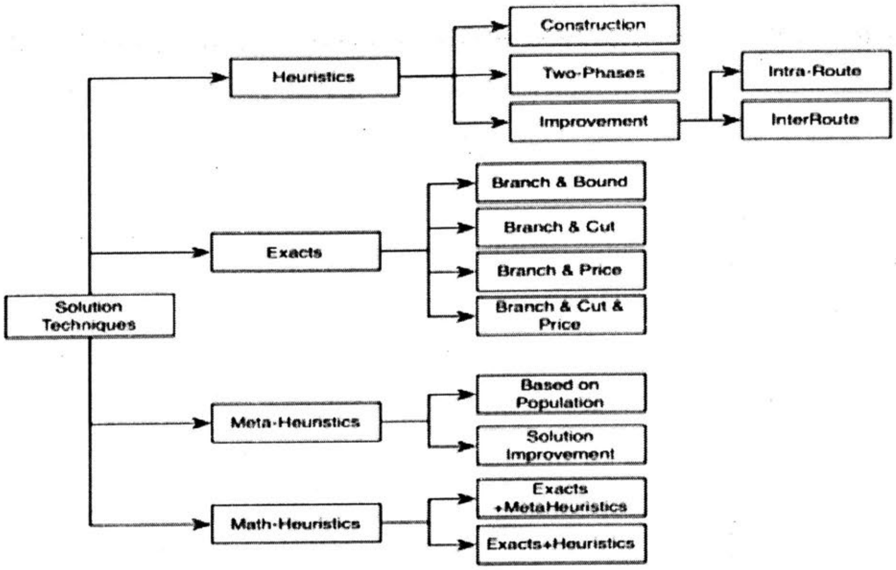
1. The *location decision*: determine the optimal number and locations of facilities.
2. The *allocation decision*: assign the customer nodes to the facilities.
3. *Routing decision*: determine the optimal number of routes and the actual vehicle routes throughout the geographical area.

Various surveys are available in location routing literature, among them Madsen (1983), Balakrishan et al (1987), Laporte (2000), List et al (1991), Min et al. (1998) and Nagy and Salhi (2007), Prodhorn and Prins (2014), Drexl and Schneider (2015, 2017). Min et al (1998) present a detailed taxonomy including problem variations regarding demand types, time windows, capacity constraints, multiple depots, multiple vehicles and in addition a breakdown in solution methods (exact algorithm and heuristics). An overview of the specific VRP extensions has already been stated in the previous section which can also be applied to a LRP model. However, there are some additional extensions possible. In dynamic problems the planning horizon can be divided into multiple periods adding uncertainty to some parameters like customer demand (Pillac, 2011). This is an important aspect, since the LRP tries to tackle the facility location problem which is a strategic decision and the tactical and operational routing. The VRP is applied to routes which are updated more frequently than location structures. Nagy and Salhi (2007) emphasize that using a shorter planning interval for routing planning therefore seems to match better with real-life location routing problem sets, examples solution methods are shown by Laporte (1988, 1989) and Salhi and Nagy (1999). Other extensions include the addition of inter-depot routes and inter-satellite routes, which is addressed in many-to-many LRPs. Three papers are addressed to parcel delivery operations and focus on this specific problem. Bruns (2000) assumes a problem in the parcel industry where the location of delivery bases and the allocation of the customers is determined. They also include a route length estimation formula as an approximation technique, reducing the LRP to a simple location problem assuming routing cost based on the formula as assignment cost. Wasner and Zapfel (2004) solve a many-to-many LRP including deliveries and pick-ups in the routes as well as their satellite locations. A similar problem is addressed by Lischak and Treisch (2007) who include direct shipping from the depot to the customer as well as determining the throughput capacity of the depots. Finally, satellite synchronization is sometimes added to the model considering time constraints at the satellites as well (Perboli, 2011).

2.3 Solution Methods

The location routing problem as well as the vehicle routing problem are NP-hard problems, where only for small instances exact algorithms suffice. However, due to computational limitations, larger instances must be solved by means of (meta-)heuristics or a combination of approximation techniques with an exact method. Even though meta-heuristics or continuous approximation (CA) methods are significantly faster than exact methods, there is no guarantee that the optimal global solution is obtained. In general, capacitated problems without distance constraints are often solved using exact methods, while heuristic methods consider distance constraints and the number of routes as a decision variable (Toth & Vigo, 2002). A variety of solution methods is

Figure 2-1: Solution Methods LRP (from Escobar, 2016)



proposed in literature to find solutions for the vehicle routing problem and the location routing problem. An overview of the possible solution methods is presented in Figure 2-1 following the classification scheme of Toro and Escobar (2016). Heuristics can be divided in 3 different classes. *Construction heuristics* start with an empty solution that is filled with a feasible alternative, the most famous being the Clark and Wright savings algorithm (1964) and insertion heuristics (Mole and Jameson, 1976; Laporte, 1992). *Improvement heuristics* aim to improve the existing routes by using methods like swaps and the famous 2-opt method. 2-opt was introduced by Croes (1958) and improves the route by relinking edges to prevent cross-overs within a route. Subramanian (2012) gives a detailed overview of the different improvements that can be applied to a route. *Two phase heuristics* make use of two stages to solve the problem: first an initial solution is created including customer allocation and routing sequences, followed by the application of improvement heuristics. Ultimately, it is a combination of the two aforementioned heuristics.

Originally, VRPs were solved using exact methods, a thorough overview is presented by Laporte and Nobert (1987) and later actualized by Toth and Vigo (2002).

Branch and Bound (Laporte and Norbert, 1987; Fischtti, Toth and Vigo, 1994; Baldacci, 2004), *Branch and Cut algorithms* (Cordeau, 2006) and *Branch and Cut Price* (Baldacci, 2010) are the most well-known methods. Essentially the method branches the initial solution into several subproblems and creates better lower bounds for each tour. By doing this iteratively the total feasible solution space becomes smaller until the global lower bound is found.

A different set of methods to solve LRPs and VRPs consists in *meta-heuristics.* A meta-heuristic is a problem-independent algorithmic framework that provides a set of guidelines or strategies to develop heuristic optimization algorithms (Sorensen and Glover, 2013). Meta-heuristics are more efficient in searching the solution space than the conventional approaches by using different strategies. A meta-heuristic has to check a large enough search space to pass by the local optimum and find another (local) optimum. Several types of meta-heuristics have been applied to solve VRPs: Tabu Search (TS) and Simulated Annealing (SA) were among the first solution methods (Prins 2007), but nowadays more cutting-edge methods like genetic algorithm (GA) (Lacomme, 2001), ant colony optimization (Donati, 2008) and variable neighbourhood search are applied (Hemmelmays and Doerner, 2009). *Tabu Search* is an iterative based approach where during each iteration the best solution in the neighborhood is selected as the new current solution, even when this leads to an increased level of total cost. A tabu list (hence the name) is used to store recent visits that cannot be visited again. *Simulated Annealing* originates from the process of physical annealing. The current state (like metal annealing) is represented by a temporary solution of routes. During each iteration the solution is altered by randomness. In case the new solution is better than the current one, it will become the current solution. In case the new solution is worse than the current one, it will be accepted based on a probability distribution (i.e., chances for acceptance increase when the temperature is high and the cost increment is minimal). *Genetic Algorithm* uses metaphors founded in nature like survival of the fittest, genetic crossovers and mutation. The idea is that only the best solutions will procreate (selection of the fittest) by combining the best features of each solution.

The metaheuristic *Ant Colony Optimization* is based on the patterns ants in nature walk in order to find the shortest path to their nest. Each ant spreads pheromones on the ground as a communication device, exposing the path it has passed. When the number of ants that is following the same path becomes higher, the quantity of pheromones spread out on the path increases which in turn leads to more ants being attracted to follow the same path. In a routing context this metaphor is applied artificially to construct a solution including a heuristic evaluation of the elements and the amount of pheromones (Yang et al, 2008). Mladenovc and Hansen (2010) propose *Variable Neighbourhood Search* which uses small neighbourhood steps (i.e. called the shaking process) when the heuristic enters a local optimum. These shaking steps will be increased to find multiple possible solutions. An initial solution is generated using the cheapest insertion method that adds a customer to any route in any position with the lowest additional cost. Then the solution is improved due to the use of the shaking methods by moving customers from one route to another. *Large Neighbourhood Search* is highly comparable, but destroys parts of the incumbent solution which can lead to temporary infeasible solutions that are repaired afterwards (Shaw, 1998).

The final category of solution methods encompasses matheuristics which entail *hybrid strategies* that combine heuristic, metaheuristic and exact methods. The problem is broken down into different subproblems and then solved using exact methods, sometimes supported by Lagrangean relaxation or dynamic programming (Prins, 2007; Escobar, 2013; Pessoa, 2008).

2.4 Continuous Approximation

The use of exact methods is often accompanied by CA methods when applied to real-world LRP to overcome computational limitations and limited data availability (Langevin et al., 1996; Franceschetti, Jabali, Laporte, 2017). Comparable to metaheuristics. the solution will normally not match with the global actual optimum, but for larger instances CA methods perform quite well.

CA methods applied to LRP enable the estimation of the expected distance of a delivery route, without determining the actual routing sequence throughout the points of delivery (POD). Since the aim of the LRP is strategic by nature, the actual routing sequence can be ignored. Customer aggregation groups customers (i.e., POD) together in different regions representing customer segments. Customer aggregation to a cluster can be done based on distance between the POD with methods like nearest neighborhood algorithm, minimum spanning tree or by using a grid-based approach in which the geographical area is split into a uniform distribution with equally sized segments (Gendreau, 2008).

To determine the travel distance within a customer segment, the CA method uses a closed form expression (e.g., route length estimation formula) based on the surface area of the customer segment and the spatial density of the served points of delivery (Daganzo, 1984, 1999; Shen and Qi, 2007; Laporte and Dejax, 1989, Chien, 1993, Nagy and Salhi, 1996; Bruns, 2000). In some cases, a rectilinear norm (i.e., L1 norm) is used assuming that the road network has a homogeneous rectangular design. Though typically road works are not homogeneously designed and moreover include obstacles (e.g. vehicle restrictions, one-way streets). Therefore, the application of Euclidian distances (i.e., L2 norm) in combination with a detour or circuity factor is used to closer match the actual situation in an empirical setting (Love and Morris, 1972; Ballou, 2002 Merchan and Winkenbach, 2019). The circuity factor is the ratio between the shortest path network distance on the road network and the Euclidian distance (Barthlemy, 2011). Circuity factors values depend strongly on the actual road network density and the presence of geographic obstacles (Ballou, 2002).

Smilowitz and Daganzo (2007) developed a CA method to determine the routing cost for a parcel delivery company. This model was extended by Winkenbach (2016a,b) and applied to the postal network of the French PO *La Poste*, this augmented routing cost estimation formula (ARCE) will form the basis for this research.

2.5 Light Electric Freight Vehicles

In the previous decade urban logistics gained attention as a major research topic, as a consequence of urbanization and strong growth of the e-commerce market (Taniguchi et al, 2015; Savelsbergh and Van Woensel, 2016). Subsequently this leads to more focus on possible applications of LEFV. LEFV offer major benefits in comparison to fossil fueled vans in dense areas that are often used for parcel delivery. LEFV are a sustainable alternative and can overcome congestion in urban areas (Balm et al, 2017). Other advantages that are mentioned are lower purchasing cost and limited driver training requirements (Gruber, 2013). However, LEFV have a small payload, a limited operational range and safety risks (Merchan and Blanco, 2015).

Research regarding the use of electrical vehicles is centered around the technical design of the vehicle or in a logistics context determining the impact of adding the recharging requirement as additional constraints to the VRP, the so called Electrical VRP (Paz et al, 2018). Typical examples include the addition of battery swapping, partial recharging at specific locations during the tour, or minimizing total energy consumption. Reporting in scientific literature regarding the use of LEFV in urban logistics is however limited (Schliwa et al, 2015) and mainly focused on specific pilots where LEFV were used in a city with positive results (Navarro, 2016; Gruber, 2013, Melo, 2014, Nocerino, 2016). Balm et al (2017) state that the use of LEFV could be a promising alternative to LTL deliveries in congested areas, specifically the delivery of time critical smaller freights. LEFV are still in the development phase with limited user practices. Therefore LEFV can be considered a technological niche product with the potential to scale up in the future (Hyvonen, 2016).

Van Amstel (2018) emphasizes the importance of adjusting the logistics concept in conjunction with the introduction of LEFV. LEFVs are very suitable in areas where the vehicle speed or access to the area is limited as a result of congestion or government regulations. Moreover, additional benefits come forward when delivery nodes are in close proximity and finding parking spots is difficult, as a LEFV will be faster in all of the aforementioned cases. However, to benefit from these time advantages additional transshipment points have to be added in close proximity to the delivery routes within the supply chain network with their accompanied cost.

2.6 Literature Gaps and Research Contribution

Several gaps can be identified in literature. First, research regarding the actual cost benefits of LEFV on a large scale is severely limited. Research is primarily focused on pilots and qualitative benefits. This thesis will present a 2E-LRP model including LEFV, to determine the benefits of LEFV within last-mile delivery networks. Second, the CA method is a critical component in order to apply exact methods to LRP models to support the strategic decisions regarding network design. Research is being done in the field, but extensions are useful to validate the CA method in a real-world setting. The industry case at PostNL presented in Chapter 4, will give more insights in the practical applicability of LRP models in the real world and specifically the performance of using approximation methods within LRP. Third, integration of different networks in the postal sector is a critical topic as a consequence of market developments. Winkenbach et al. (2016b) applied a full integration scenario to the French PO *La Poste*. However, the extension in this thesis will aim to find the geographical characteristics that drive the decision for combined delivery of parcel and mail.

Chapter 3

Methodology

In this chapter, we present the mathematical formulation for a 2E-LRP aiming to minimize the total distribution cost in the postal network. The supply chain network includes three types of nodes: *depots* (i.e. postal sorting centers), *satellites* (i.e., postal pickup points) and *customer segments* (i.e., set of customers in a region). The mixed multi-tier delivery system distinguishes between a tier for the delivery of mail directly from the depot to the customer segments and a tier enabling indirect delivery through the satellites to the customer segments. The delivery network model allows tours to deliver mail or parcels separately or perform combined delivery of mail and parcels to a customer segment. This enables the model to determine in which customer segments it is feasible to integrate the parcel and mail delivery network.

The proposed mixed integer linear programming model (MILP) is based on the formulation by Winkenbach (2016) and extended with a MDVRP (Wu, Low, Bai; 2002). The tier feeding satellites with mail and parcels from the depots is modeled by a MDVRP. A set of binary decision variables show respectively the actual tours of the trucks feeding the satellites from the depot, satellites allocated to a specific depot, and the active depot locations. The tier performing the delivery from depots or satellites directly to the final customer segments is modeled using the ARCE CA-method as proposed by Winkenbach (2016a,b) in order to estimate the cost of serving a customer segment. A second set of binary decision variables show which satellites to activate and which customer segments to serve from which satellite or depot. Moreover, it shows the optimal vehicle for the tour and the optimal network type (i.e. separate or combined delivery).

3.1 Model Assumptions

The following model choices are underlying the mathematical model (based on Min et al, 1998):

- The *hierarchical structure* is one-directed. The model includes direct as well as indirect shipping to the customer segments.
- *Demand* is deterministic and there is a single planning period (i.e. static problem). Variations in mail and parcel demand will be simulated using sensitivity analysis in subsequent chapters.
- The *number of facilities* is multiple, using a discrete solution set of *capacitated satellites.* The capacitated depot locations are predetermined and all in use (i.e. parcel and mail sorting centers have to remain open).
- The *vehicle fleet is heterogeneous.* Tours between depots and satellites are performed using trucks, but customers are served using a mixed vehicle fleet comprised of bicycles, LEFV, scooters, cars and vans. Each *capacitated vehicle* has its according payload, speed profile and maximum tour duration. All vehicles return to their origin location.
- There are *two echelons.* Direct delivery is possible directly from the depot to the customer segments. Indirect delivery through the satellites to the customers is performed through a tier feeding the satellites from the depot and a tier between the satellites and the customers.
- A *single cost objective function* minimizing the daily distribution cost.
- *Time windows* are not included in the model.

3.2 Notation

Table 3.1: Cost Function Notation

K	Daily total delivery cost
K^F	Daily facility cost of the depots and satellites
K^H	Daily handling cost at the depot and satellites
$K^{T,S}$	Daily transportation cost for the truck tours between depots and satellites
$K^{T,D}$	Daily distribution cost the total network
$K^{T,D,n}$	Daily distribution cost for mail delivery M, parcel delivery P or combined delivery C. $n \in \{M, P, C\}$ representing the network type
K^U	Daily cost of space capacity utilization in the facilities

Table 3.2: Sets and Indices

D	$\{0,1,...,i\}$: set of depot locations
S	$\{0,1,...,j\}$: set of satellite locations
C	$\{(0,1,...,k\}$: set of customer locations
R	$\{0,1,...,r\}$: set of trucks
V	$(0,1,...,v\})$: set of vehicle types used for delivery to customers
N	$n \in \{M, P, C\}$: set representing the network type setting: separate mail delivery M, separate parcel delivery P, or combined delivery C

Table 3.3: Decision Variables

$X_{i,j,r}$	Binary variable to indicate whether depot i immediately precedes satellite j on route r
$W_{i,j}$	Binary variable to indicate whether satellite j is served by depot i
$U_{l,r}$	Auxiliary variable showing the position in which node j is visited on route r. Used for subtour elimination, $l \in S$
Y_i^D	Binary variable defining whether depot i is open or not
Y_j^S	Binary variable defining whether satellite j is open or not
$Z_{i,k,v}^{1E,M}$	Binary variable defining whether depot i serves customer segment k directly with vehicle v with network type mail ($n = M$).
$Z_{i,j,k,v}^{2E,M}$	Binary variable defining whether satellite j serves customer segment k with vehicle v originating from depot i with network type mail ($n = M$).
$Z_{i,k,v}^{1E,P}$	Binary variable defining whether depot i serves customer segment k directly with vehicle v with network type parcels ($n = P$).
$Z_{i,j,k,v}^{2E,P}$	Binary variable defining whether satellite j serves customer segment k with vehicle v originating from depot i with network type parcels ($n = P$).
$Z_{i,k,v}^{1E,C}$	Binary variable defining whether depot i serves customer segment k directly with vehicle v with combined parcel and mail delivery ($n = C$).
$Z_{i,j,k,v}^{2E,C}$	Binary variable defining whether satellite j serves customer segment k with vehicle v originating from depot i with combined parcel and mail delivery ($n = C$).

Table 3.4: General Parameters

c_i^F	Daily facility cost incurred when opening a depot i
c_j^F	Daily facility cost incurred when opening a satellite j
γ_k^n	Customer stop density for the delivery of network type n in city segment k
Ω_v	Physical space utilization requirement for vehicle type v
Ω_v^R	Physical space requirement for storing the tour' payload for vehicle type v
c^{Ω}	Cost of physical space at satellite and depot locations per sqm.
ω_i	Total physical capacity available at depot i
ω_j	Total physical capacity available at satellite j
A_k	Surface area of segment k
$c^{H,M}$	Handling cost of a mail item per day at a depot or satellite
$c^{H,P}$	Handling cost of a parcel item per day at depot or satellite
α	Factor for converting the capacity and throughput characteristics of mail items to parcel items

Table 3.5: Parameters for Truck Tours from Depot to Satellites

w^T	Wage per hour for a truck driver
$r_{i,j}$	Euclidean distance from depot i to satellite j
σ^S	Truck speed
ϑ^T	Detour factor to estimate Manhattan distance
$c^{O,T}$	Operating cost per hour for a truck
$c^{F,T}$	Fixed cost per day for a truck
τ^L	Total loading time for a full truck tour
N	Number of trucks available
$c_{i,j}$	Cost to travel from depot i to satellite j
V_i	Maximum throughput at depot i in parcel items
d_j^M	Demand of satellite j for mail items
d_j^P	Demand of satellite j for parcels items
Q_r	Capacity of the truck r expressed in parcel items

Table 3.6: Delivery Parameters

w_v	Wage per hour for a driver of vehicle type v
$r_{i,k}$	Euclidian distance from depot i to the centroid of customer segment k
$r_{j,k}$	Euclidian distance from satellite j to the centroid of customer segment k
σ_v	Linehaul speed from satellites and depots to customer segments for vehicle type v
κ_v	Road circuity factor for vehicle type v between households in a customer segment
ϑ_v	Detour factor for the Euclidean distance using vehicle v
$Tmax_v$	Maximum service time for vehicle v
$c^{1E,n}_{i,k,v}$	Daily distribution cost to serve segment k with vehicle v directly from depot i for network type n
$c^{2E,n}_{i,j,k,v}$	Daily distribution cost to serve segment k with vehicle v through satellite j originating from depot i for network type n
$m^{1E,n}_{i,k,v}$	Average number of tours from depot i with vehicle v to serve customer k for network type n
$m^{2E,n}_{i,j,k,v}$	Average number of tours from satellite j with vehicle v to serve customer k originating from depot i for network type n
$n^{1E,n}_{i,k,v}$	Average number of customers stops in segment k with vehicle v per tour starting from depot i for for network type n
$n^{2E,n}_{i,j,k,v}$	Average number of customers stops in segment k with vehicle v per tour starting from satellite j originating from depot i for network type n
$\delta^{1E,n}_{i,k,v}$	Average number of full load tours a vehicle v can complete within the $Tmax^B_v$ for network type n when serving segment k from depot i
$\delta^{2E,n}_{i,j,k,v}$	Average number of full load tours a vehicle v can complete within the $Tmax^B_v$ for network type n when serving segment k from satellite j originating from depot i
ξ^n_v	Maximum number of customers that can be served using vehicle v for network type n
$q^{1E,n}_{i,k,v}$	Number of vehicles of type v to serve segment k from depot i for network type n
$q^{2E,n}_{i,j,k,v}$	Number of vehicles of type v to serve segment k from satellite j originating from depot i for network type n
$\tau^{L,n}_v$	Loading time per tour using vehicle v for network type n
$\tau^{S,n}_v$	Service time per household using vehicle v for network type n
$\tau^{R,n}_{k,v}$	Tour time of vehicle v in segment k for network type n
τ^P_v	Parking time to serve a household using vehicle v
c^O_v	Operating cost per hour for a vehicle v
c^F_v	Fixed cost per day for a vehicle v

3.3 Mathematical Model

The cost model for the total network is:

$$K = K^F + K^H + K^{T,S} + K^{T,D} + K^U, \tag{3.1}$$

with

$$K^F = \sum_{i \in D} c_i^F Y_i^D + \sum_{j \in S} c_j^F Y_j^S, \tag{3.2}$$

$$K^H = c^{H,M} \sum_{k \in C} \gamma_k^M A_k + c^{H,P} \sum_{k \in C} \gamma_k^P A_k, \tag{3.3}$$

$$K^{T,S} = \sum_{i \in D \cup S} \sum_{j \in D \cup S} \sum_{r \in R} c_{i,j} X_{i,j,r} + N^R \tau^L w^T + N c^{F,T}, \tag{3.4}$$

$$K^{T,D} = \sum_{n \in N} K^{T,D,n}, \tag{3.5}$$

$$\begin{aligned} K^U = {} & c^{\Omega}[\sum_{i \in D} \sum_{k \in C} \sum_{v \in V} Z_{i,k,v}^{1E,n} (q_{i,k,v}^{1E,n} \ \Omega_v + m_{i,k,v}^{1E,n} \ \Omega_v^R)] \\ & + c^{\Omega}[\sum_{i \in D} \sum_{j \in S} \sum_{k \in C} \sum_{v \in V} Z_{i,j,k,v}^{2E,n} (q_{i,j,k,v}^{2E,n} \ \Omega_v + m_{i,j,k,v}^{2E,n} \ \Omega_v^R)], \qquad \forall n \in N \end{aligned} \tag{3.6}$$

$$c_{i,j} = [\frac{r_{i,j} * \vartheta^T}{\sigma^S} (w^T + c^{O,T})]. \tag{3.7}$$

Here,

$$K^{T,D,n} = \sum_{i \in D} \sum_{k \in C} \sum_{v \in V} (Z_{i,k,v}^{1E,n} \ c_{i,k,v}^{1E,n} + \sum_{j \in S} Z_{i,j,k,v}^{2E,n} \ c_{i,j,k,v}^{2E,n}), \qquad \forall n \in N, \tag{3.8}$$

$$
\begin{aligned}
c_{i,k,v}^{1E,n} = \quad & q_{i,k,v}^{1E,n}\ m_{i,k,v}^{1E,n}\ \tau_v^{L,n}(w_v + C_v^O) \\
& + q_{i,k,v}^{1E,n}\ m_{i,k,v}^{1E,n}\ n_{i,k,v}^{1E,n} \tau_v^{S,n}(w_v + C_v^O) \\
& + q_{i,k,v}^{1E,n}\ m_{i,k,v}^{1E,n}\ n_{i,k,v}^{1E,n}\ \tau_v^P (w_v + C_v^O) \\
& + q_{i,k,v}^{1E,n}\ m_{i,k,v}^{1E,n}\ [2\frac{\vartheta_v r_{i,k}}{\sigma_v}(w_v + C_v^O)] \\
& + q_{i,k,v}^{1E,n}\ m_{i,k,v}^{1E,n}\ [n_{i,k,v}^{1E,n}\ (\frac{\kappa_v \vartheta_v}{\sigma_v \sqrt{\gamma_k^n}} + (w_v + C_v^O)] \\
& + q_{i,k,v}^{1E,n}\ C_v^F, \qquad\qquad \forall n \in N,
\end{aligned}
\tag{3.9}
$$

$$
\begin{aligned}
c_{i,j,k,v}^{2E,n} = \quad & q_{i,j,k,v}^{2E,n}\ m_{i,j,k,v}^{2E,n}\ \tau_v^{L,n}(w_v + C_v^O) \\
& + q_{i,j,k,v}^{2E,n}\ m_{i,j,k,v}^{2E,n}\ n_{i,j,k,v}^{2E,n}\ \tau_v^{S,n}(w_v + C_v^O) \\
& + q_{i,j,k,v}^{2E,n}\ m_{i,j,k,v}^{2E,n}\ n_{i,j,k,v}^{2E,n}\ \tau_v^P (w_v + C_v^O) \\
& + q_{i,j,k,v}^{2E,n}\ m_{i,j,k,v}^{2E,n}\ [2\frac{\vartheta_v r_{j,k}}{\sigma_v}(w_v + C_v^O)] \\
& + q_{i,j,k,v}^{2E,n}\ m_{i,j,k,v}^{2E,n}\ [n_{i,j,k,v}^{2E,n}\ (\frac{\kappa_v \vartheta_v}{\sigma_v \sqrt{\gamma_k^M}} + (w_v + C_v^O)] \\
& + q_{i,j,k,v}^{2E,n}\ C_v^F, \qquad\qquad \forall n \in N,
\end{aligned}
\tag{3.10}
$$

$$\tau_{k,v}^{R,n} = \xi_v((\frac{\kappa_v \vartheta_v}{\sigma_v \sqrt{\gamma_k^n}}) + \tau_v^P + \tau_v^{S,n}), \qquad \forall n \in N, \tag{3.11}$$

$$\tag{3.12}$$

$$\delta_{i,k,v}^{1E,n} = \frac{Tmax_v}{\tau_{k,v}^{R,n} + \tau_v^{L,n} + 2(\frac{\vartheta_v r_{i,k}}{\sigma_v})}, \qquad \forall n \in N, \tag{3.13}$$

$$\delta_{i,j,k,v}^{2E,n} = \frac{Tmax_v}{\tau_{k,v}^{R,n} + \tau_v^{L,n} + 2(\frac{\vartheta_v r_{j,k}}{\sigma_v})}, \qquad \forall n \in N, \tag{3.14}$$

$$m_{i,k,v}^{1E,n} = max[1, \delta_{i,k,v}^{1E,n}], \qquad \forall n \in N, \tag{3.15}$$

$$m_{i,j,k,v}^{2E,n} = max[1, \delta_{i,j,k,v}^{2E,n}], \qquad \forall n \in N, \tag{3.16}$$

$$n^{1E,n}_{i,k,v} = \xi^n_v min[1, \delta^{2E,n}_{i,k,v}], \qquad \forall n \in N, \qquad (3.17)$$

$$n^{2E,n}_{i,j,k,v} = \xi^n_v min[1, \delta^{2E,n}_{i,j,k,v}], \qquad \forall n \in N, \qquad (3.18)$$

$$q^{1E,n}_{i,k,v} = \frac{\gamma^n_k A_k}{\xi^n_v \delta^{1E,n}_{i,k,v}}, \qquad \forall n \in N, \qquad (3.19)$$

$$q^{2E,n}_{i,j,k,v} = \frac{\gamma^n_k A_k}{\xi^n_v \delta^{2E,n}_{i,j,k,v}}. \qquad \forall n \in N. \qquad (3.20)$$

Here, the total distribution cost (3.1) are comprised of the total facility cost (3.2), the total handling cost (3.3), the total transportation cost of the tours feeding the satellites (3.4), the total delivery cost for all the network types (3.5) and the total cost of space utilisation (3.6). Total facility cost (3.2) consist of the fixed facility cost for depot locations active due to direct shipping and the active satellites. Each item has a handling fee in order to be processed in their starting location resulting in the handling cost (3.3). Total cost for feeding the satellites (3.4) include the transportation cost between the depots and the satellites and additionally the loading time of the truck as well as the fixed cost of a truck.

Total transportation cost in the delivery network are comprised of the distribution cost to serve each city segment in a tour with either mail, parcels or combined delivery (3.5). The total cost for each network type are given by equations (3.8). The distribution cost consist of the following activities: loading the vehicle, serving the households, parking the vehicle, the line haul, intra-stop time between the delivery nodes and finally the fixed vehicle cost (3.9 and 3.10). Equations (3.10 - 3.20) represent the ARCE function. The ARCE function has to be created for the direct and the indirect delivery tier, due to the fact that the linehaul distance differs between the direct delivery tier and the indirect delivery tier. The ARCE function includes the total number of tours (3.15 and 3.16), the number of customers per tour (3.17 and 3.18) and the number of vehicles (3.19 and 3.20). Tour time (3.11) is determined based on the total time required to serve the customers (parking, serving and intra-stop times). Consequently, the average number of full load tours within the maximum service time can be derived (3.13 and 3.14). Equations (3.6) determine the total cost for the required capacity in the facilities to store the vehicles as well as a store the payloads for each tour. This leads to the following network optimization model:

$$\min_{X_{i,j},W_{i,j},U_{l,r},Y_i^D,Y_j^S,Z_{i,k,v}^{1En},Z_{i,j,k,v}^{2En}} \quad K = K^F + K^H + K^{T,S} + K^{T,D} + K^U \tag{3.21}$$

subject to

$$\sum_{r\in R}\sum_{i\in D\cup S} X_{i,j,r} = 1, \qquad \forall j \in S, \tag{3.22}$$

$$\alpha\sum_{j\in S} d_j^M \sum_{i\in D\cup S} X_{i,j,r} + \sum_{j\in S} d_j^P \sum_{i\in D\cup S} X_{i,j,r} \leq Q_r, \qquad \forall r \in R, \tag{3.23}$$

$$U_{l,r} - U_{j,r} + NX_{i,j,r} \leq N - 1 \qquad \forall l,j \in S, r \in R, \tag{3.24}$$

$$\sum_{j\in S\cup D} X_{i,j,r} - \sum_{j\in S\cup D} X_{j,i,r} = 0, \qquad \forall i \in D\cup S, r \in R, \tag{3.25}$$

$$\sum_{i\in D}\sum_{j\in S} X_{i,j,r} \leq 1, \qquad \forall r \in R, \tag{3.26}$$

$$\alpha\sum_{j\in S} d_i^M W_{i,j} + \sum_{j\in S} d_i^P W_{i,j} \leq V_i, \qquad \forall i \in D, \tag{3.27}$$

$$-W_{i,j} + \sum_{u\in D\cup S} (X_{i,u,r} + X_{u,j,r}) \leq 1, \qquad \forall i \in D, j \in S, r \in R, \tag{3.28}$$

$$\sum_{i\in D}\sum_{v\in V}\sum_{n\in N, n\neq P} (Z_{i,k,v}^{1E,n} + \sum_{j\in S} Z_{i,j,k,v}^{2E,n}) = 1, \qquad \forall k \in C, \tag{3.29}$$

$$\sum_{i\in D}\sum_{v\in V}\sum_{n\in N, n\neq M} (Z_{i,k,v}^{1E,n} + \sum_{j\in S} Z_{i,j,k,v}^{2E,n}) = 1, \qquad \forall k \in C, \tag{3.30}$$

$$\sum_{v\in V} Z_{i,k,v}^{1E,n} \leq Y_i^D, \qquad \forall i \in D, k \in C, n \in N, \tag{3.31}$$

$$\sum_{v\in V} Z_{i,j,k,v}^{2E,n} \leq Y_i^D, \qquad \forall i \in D, j \in S, k \in C, n \in N, \tag{3.32}$$

$$\sum_{i\in D}\sum_{v\in V} Z_{i,j,k,v}^{2E,n} \leq Y_j^S, \qquad \forall j \in S, k \in C, n \in N, \tag{3.33}$$

$$\sum_{k\in C}\sum_{v\in V}\sum_{n\in N} Z_{i,k,v}^{1E,n}(q_{i,k,v}^{1E,n}\ \Omega_v + m_{i,k,v}^{1E,n}\ \Omega_v^R) \le \omega_i Y_i^D, \qquad \forall i \in D, \tag{3.34}$$

$$\sum_{i\in D}\sum_{k\in C}\sum_{v\in V}\sum_{n\in N} Z_{i,j,k,v}^{2E,n}(q_{i,j,k,v}^{2E,n}\ \Omega_v + m_{i,j,k,v}^{2E,n}\ \Omega_v^R) \le \omega_j Y_j^S, \qquad \forall j \in S, \tag{3.35}$$

$$X_{i,j,r} \in \{0,1\}, \qquad \forall i \in D, j \in S, r \in R, \tag{3.36}$$

$$W_{i,j} \in \{0,1\}, \qquad \forall i \in D, j \in S, \tag{3.37}$$

$$U_{l,r} \ge 0, \qquad \forall l \in S, r \in R, \tag{3.38}$$

$$Y_i^D \in \{0,1\}, Y_j^S \in \{0,1\}, \qquad \forall i \in D, j \in S, \tag{3.39}$$

$$Z_{i,k,v}^{1E,n} \in \{0,1\}, Z_{i,j,k,v}^{2E,n} \in \{0,1\}, \qquad \forall i \in D, j \in S, k \in C, v \in V, n \in N, \tag{3.40}$$

Objective function (3.21) aims to minimize the total distribution cost of the system. Constraints (3.22) ensure that each customer is assigned to a route exactly once. Equations (3.23) are the vehicle capacity constraints which provide the total demand of the customers not exceeding the vehicle capacity. Constraints (3.24) provides sub-tour elimination. Equations (3.25) represent flow conversation constraints. Constraints (3.26) ensures that a vehicle can exit from at most one depot. Equations (3.27) are the depot capacity constraints, according to which the total demand of the customers assigned to a depot can not exceed the depot capacity. Equations (3.28) enable a satellite to only be assigned to a depot if there is a route from that depot going through that satellite. Constraints (3.29) ensure that all customer segments are served with mail by exactly one vehicle from the integrated or the separate network. Constraints (3.30) ensure that all customers are served with parcels by exactly one vehicle from the separate parcel or integrated network. Constraints (3.31), (3.32) and (3.33) force customer segments only to be served by an open satellite location. Constraints (3.34) and (3.35) make sure the physical storage capacity for storing the vehicles is respected. Constraints (3.36) through (3.40) define the domains of all decision variables.

Chapter 4

A Case Study at PostNL

4.1 Company Overview PostNL

The Dutch PO, PostNL, is divided into three business divisions (PostNL, 2018):

- *Mail* is the largest division with 30,753 employees and a revenue of 1.678 billion euro in 2018. The total yearly delivery volume is 1.781 billion mail items. The sorting process is executed in five sorting centers and 38 preparation centers, after which the product is transported to nearly 2,000 pickup points throughout the Netherlands. The employee workforce consists primarily of part-time employees (i.e., on average 9 working hours per week). Delivery tours have an average duration of 3 hours. The vehicle fleet consists of a variety of bicycles, scooters and cars. Bicycles are the preferred mode of transportation and represent 91% of the vehicle fleet. The remaining routes are performed by scooters and cars, representing respectively 7% and 2% of the vehicle fleet. Bicycles are privately owned by the deliverers, who bring their bicycle for the delivery route directly from home. All other vehicles are company owned. All bicycles and scooters depart from a pickup point location (i.e., satellite), resulting in a two echelon mail network operating five days per week.
- In 2018 the *parcel division* distributed 251 million parcels with 5,722 employees resulting in a revenue of 1.33 billion euros. There are 22 locations available

for sorting and distribution. The sorting process is done in two steps. In step one parcels are sorted to regions. During the second step, parcels are sorted to zipcode level. After the second sorting step, parcels are directly loaded into vans at the sorting center using rolling conveyors. Distribution is executed seven days a week and the vehicle fleet consist of vans. The majority of routes is performed by subcontractors who bring their own vans. Parcels involve typically more complex services than mail, like track and trace and second attempt delivery on the next day.

- The *international* mail and parcel division which focuses on the delivery of parcels and mail throughout the world. This division is out of scope for this research.

4.2 Strategic Relevance for PostNL

PostNL is facing market developments similar to those of other POs in the world and is therefore highly representative of the whole postal sector. At PostNL mail volume decreased 10.7% in 2018 while parcel volumes increased by 21.5%. PostNL is continuously adjusting its network to the shifting market dynamics in the Netherlands, in order to maintain a sustainable cash flow. Keeping the mail network profitable by a further reduction of the distribution cost is essential, since cutting out delivery days is not feasible due to the USO.

The possible introduction of LEFV can strongly influence the operations strategy. In the mail division, LEFV will enable the introduction of longer routes up to 5,5 hours due to the reduced physical strain on the deliverer. This will allow the company to reduce the number of headcounts, enabling a reduction in staff personnel assuming a similar span of control. Moreover, the implementation of LEFV in the distribution process could support a further reduction of the number of pickup points. The higher speeds of LEFV on the linehaul could compensate disadvantages due to positioning mail locations further away from the starting point of the routes. Replacing bicycles with LEFV will necessitate deliverers to return to the satellite locations to store and charge the LEFV after finishing the route. Currently the pickup points are typically garage boxes without electricity facilities. In order to store the LEFV in the new situation a transition towards larger satellite locations is required.

In the parcel division the focus is on expanding the capacity of the network. In previous years two sorting centers were built annually to match the volume growth. The introduction of satellites in local proximity of dense areas with high demand could be beneficial since the linehauls could be consolidated to the satellite, preventing numerous linehauls from the sorting center to the customer zone. The use of LEFV could also be more efficient in congested areas, since they can manoeuvre faster through traffic, which has been shown in different pilots by PostNL in Amsterdam.

A possible future scenario where the delivery networks are completely or partially merged could reduce delivery costs. A merger could also bring additional benefits from an organizational point of view, since scaling down the mail network could be compensated by the growing parcel division. First, deliverers in the mail network could be transferred to the parcel division which is in great need of personnel. Second, assets like satellite locations could be shared. Third, the LEFV could be shared reducing the total capital expenditure in case of investing in LEFV.

The proposed 2E-LRP will support PostNL in the decision making process regarding the operations strategy. Previous studies regarding network merger and LEFV usage were done within the company and by external consulting firms on a strategic level. However, the 2E-LRP offers much more granularity and insights on a tactical level, offering a more detailed estimation of operational and cost effects.

4.3 Geographic Scope

This research focuses on the delivery area of Utrecht located in the center of the Netherlands. The geographical area has a high variety of densities including city centers, suburban areas and rural areas. In order to ensure that the impact of LEFV in the different density areas is considered, the model is applied to two specific areas:

1. A city area with an average density of 7,269 points of delivery (POD) per km2, which is quite dense for the Netherlands (i.e. average density of the total Netherlands is 413 inhabitants per km^2). The area consists primarily of flats and has a very dense road network with high accessibility for bikes and LEFV, but lower accessibility for cars and vans.
2. A suburban and partial rural area, with an average density of 198 POD per km^2. The landscape can be typified as a small village surrounded by farms with a limited road network.

Table 4.1 presents a summary of the key figures of these zones (see appendix for a map).

Table 4.1: Characteristics Customer Zones

Zipcode 4	Nb of Customer Segments (Zipcode 6)	Number of points of delivery	Density (POD per km2)	Daily Mail Volume	Daily Parcel Volume
3417	239	4,582	198	4,260	481
3532	163	3,294	7,265	2,331	328

4.4 Model Parameters

The current distribution cost for the separate mail and parcel distribution network are modeled first, in order to establish a baseline case for comparison with the LEFV and synergy scenario's. The following assumptions are applied:

1. The locations of the parcel and mail sorting centers (i.e., depots) are set as fixed positions and forced to remain open. In total one mail and three parcel sorting centers in the surrounding area are included. A discrete set of 10 satellite locations is used, placed at the centroids of the zipcode 5 segments. The satellite set is duplicated with identical positioning but with varying space capacity (50 m^2, 100 m^2, 150 m^2). Cost per m^2 is set at 100 euro, a fixed cost of 5,000-15,000 Euro is used for opening a satellite, depending on the satellite size.

2. A set of 5 trucks is used for this case. Loading parameters and transportation cost are retrieved from the cost database of PostNL and will remain confidential.

3. The vehicle fleet for the mail network is composed of bicycles (payload 144 liters), scooters (payload 144 liters) and cars (payload 3,7 m^3). The parcel network solely uses vans, with a payload of 14 m^3, but the payload is limited due to weight restrictions to 200 parcels per load. Pedestrian routes with trolleys are rare and make up less than 1% of all routes in the Netherlands, therefore trolleys are not included in the model. LEFV are set with a payload of 2 m^3.

4. Maximum service times differ per vehicle type and are based on the current agreements within PostNL: bicycles (3.5 hours), scooters (4.0 hours), LEFV (5.5 hours), cars (8 hours), vans (8.0 hours). The maximum service time varies for the different vehicle types as a result of the physical strain a specific vehicle puts on the deliverer.

5. The volumes and parcel sizes are derived from the sorting and track and trace systems of PostNL over 2018. Total daily volume included 6,591 letters per day and 809 parcels for this region.

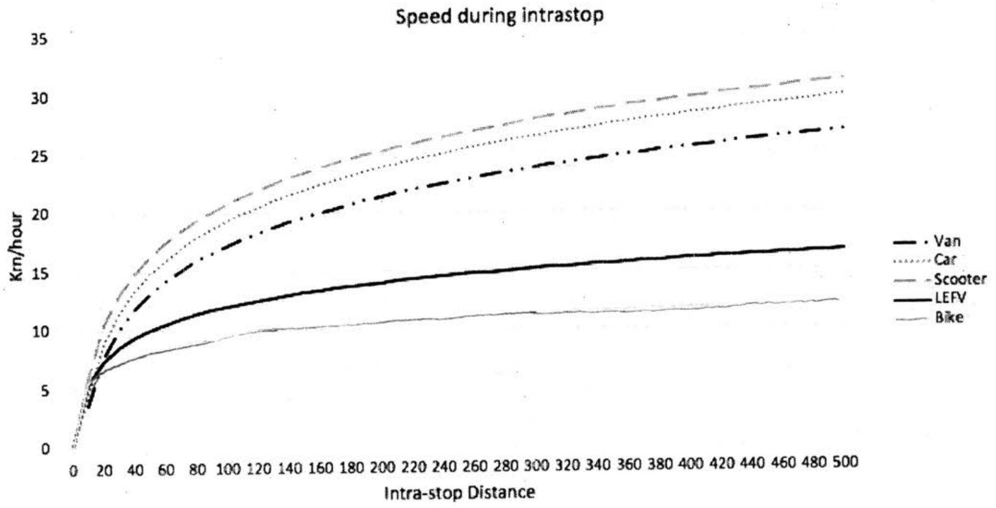
6. All operational parameters for handling, (un)loading, serving a customer and parking time for vehicles as well as the current wage levels are retrieved from the cost price models and will remain confidential. These operational parameters are determined in previous decades by field measurements during the execution of the routes by deliverers.

7. The circuity and detour factors are determined by comparing the Euclidean straight line distances of the current route sequences with the actual distances generated over the road network in the Utrecht area. The circuity factor averages 1.215 for bicyles, LEFV, and scooters and 1.751 for cars and vans (see appendix A).

8. Speed distribution profiles play a critical role in determining the actual time required to deliver all the items in a customer segment. The average intra-stop

distance will affect the average speed a specific vehicle can reach between the stops. The longer the intra-stop distance the more the vehicle can accelerate, favouring faster vehicles on longer distances. In PostNL, the different speed profiles were determined using field measurements over several months taking into account the actual travel disturbances (e.g., traffic lights, driver behavior). Using regression the intra-stop times for all distances for the entire vehicle fleet could be retrieved. The speed profiles for the intrastop distances are presented in Figure 4-1 (see appendix B).

Figure 4-1: Intra-stop Speed



4.5 Model Implementation

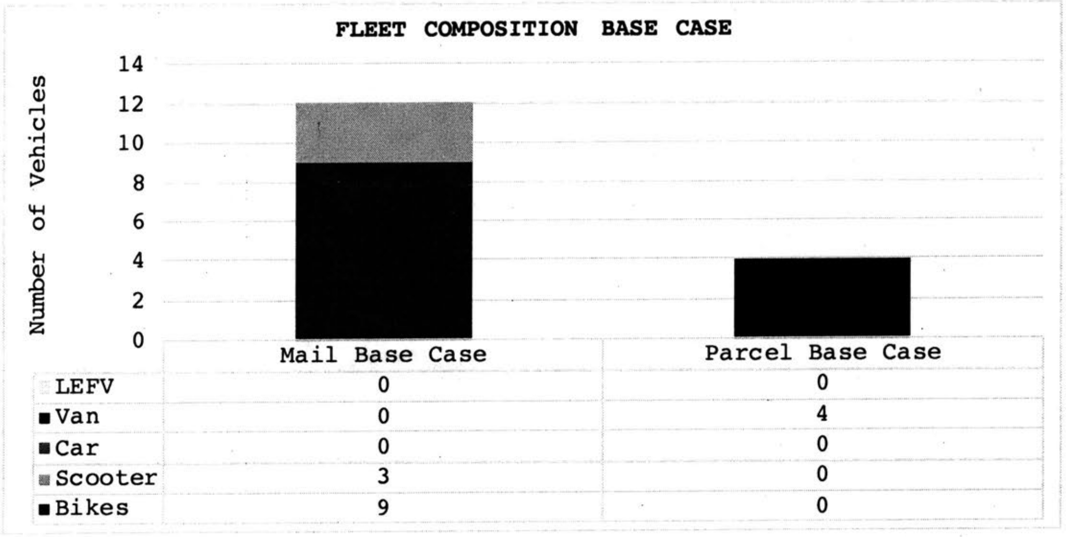
The 2E-LRP was implemented in PYTHON 3.6 and solved using GUROBI 8.0 on an Apple macbook air with a 1,8 GHz Intel Core i5 processor and 8 GB RAM running macOS Sierra in 64-bit mode.

4.6 Model Results

4.6.1 Baseline Scenario: Mail and Parcel Network

The baseline model has been validated using the current distribution cost prices for mail and parcel delivery. Figures 4-2, 4-3 and 4-4 show that the mail network is primarily served by scooters and bikes through two satellite locations where these vehicles are stored. However, one route departs directly from the depot due to the favorable location of the sorting center and the faster linehaul speed of scooters. The parcel customer base is exclusively served by vans departing directly from the depot location, which is matching the current situation at PostNL.

Figure 4-2: Vehicle Composition, Base Case



	Mail Base Case	Parcel Base Case
□ LEFV	0	0
■ Van	0	4
■ Car	0	0
▨ Scooter	3	0
■ Bikes	9	0

Figure 4-3: Number of Drops Served by Direct and Indirect Delivery

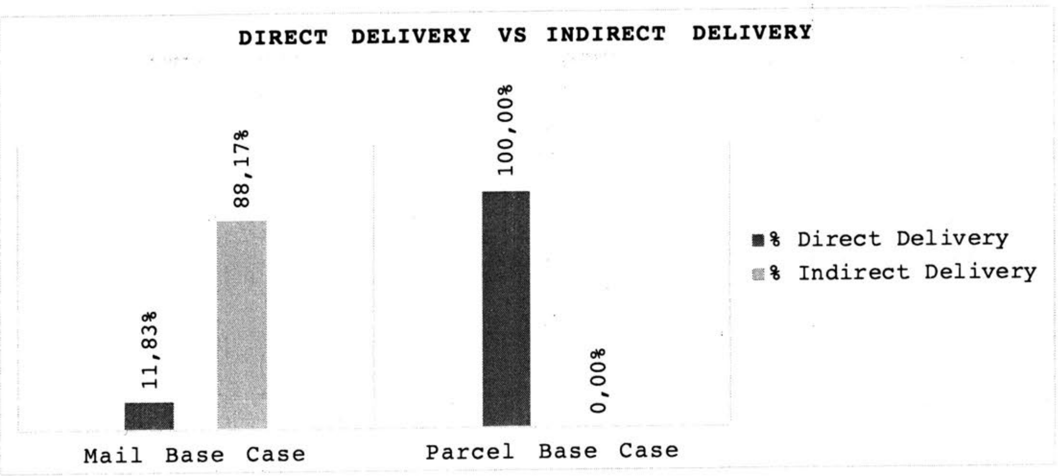
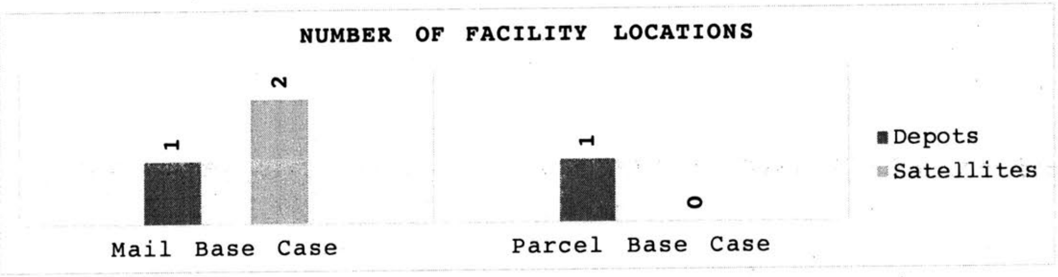


Figure 4-4: Active Locations, Base Case



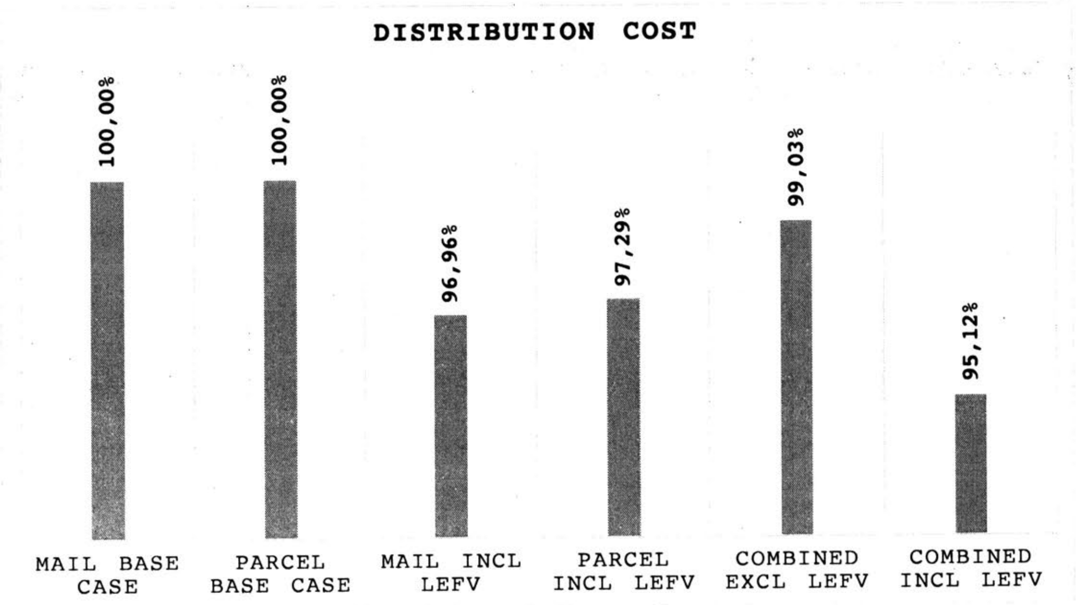
For the purpose of comparing the base case with the scenarios, the total daily distribution cost of the mail and parcel network is set to an index of 100%. The combined network is compared to the sum of the two standalone networks.

4.6.2 Scenario Analysis

The first scenario is based on the sole introduction of the LEFV in the separate mail and parcel network. The introduction of LEFV in the vehicle fleet leads to a reduction of approximately 3% in the mail as well as in the parcel network (see Figure 4-5). From Figures 4-6, 4-7, and 4-8 the following can be derived:

1. In the mail network, bikes are substituted by LEFV. These LEFV have a higher

Figure 4-5: Distribution Cost Scenarios



linehaul speed than bicycles, resulting in the closure of one satellite location and an increased level of direct delivery.

2. In the parcel network a second echelon is created due to the fact that two vans are substituted by LEFV. This also results in opening three satellite locations. These LEFV are used in the dense city segments, while the rural/suburban area is still served by vans.

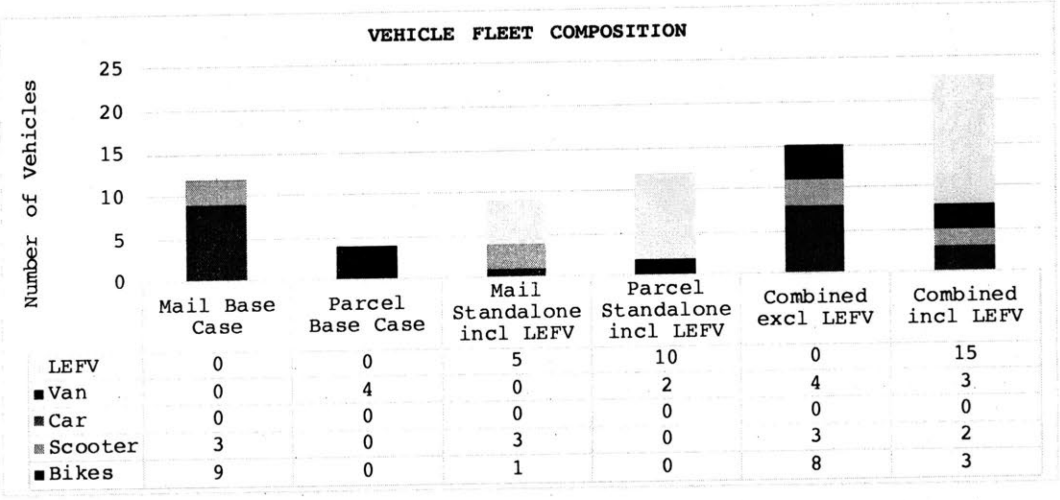
The second scenario allows each customer segment to be served by a combined delivery for parcels and mail items. Figure 4-5 shows that allowing combined delivery by the current vehicle fleet leads to a delivery cost reduction of 1%. However, the introduction of LEFV combined with the option of combined delivery leads to a distribution cost reduction of 4.9%. Furthermore Figures 4-6, 4-7, and 4-8 show that:

1. In the combined delivery scenario excluding LEFV only three customer segments substitute to van delivery in the rural area, resulting in a limited change of cost. The number of locations does not change as a result of the merger: two depots

are required (i.e. one for mail and one for parcels) and two satellites are opened. Moreover, direct delivery remains the case for the parcel network. The payload requirement for parcels requires the usage of vans which due to the high linehaul speed can depart directly from the depot. On the opposite, transitioning mail from a bicycle to a higher cost van leads to higher delivery cost.

2. The combined delivery scenario including LEFV shows a similar movement as the introduction of LEFV in the parcel network: substitution of vans to LEFV and activating more satellites in local proximity (two vs five). However, more synergies arise by using LEFV. The LEFV is more suited for dense areas to deliver both parcels and mail, due to the fact that the vehicle is cheaper than a van, has a higher payload than a bicycle, but in a dense area with small intra-stop distances can still reach a speed comparable to a van.

Figure 4-6: Fleet Composition Scenarios



	Mail Base Case	Parcel Base Case	Mail Standalone incl LEFV	Parcel Standalone incl LEFV	Combined excl LEFV	Combined incl LEFV
LEFV	0	0	5	10	0	15
■ Van	0	4	0	2	4	3
■ Car	0	0	0	0	0	0
▨ Scooter	3	0	3	0	3	2
■ Bikes	9	0	1	0	8	3

Figure 4-7: Number of Drops: Direct vs Indirect Delivery LEFV Case

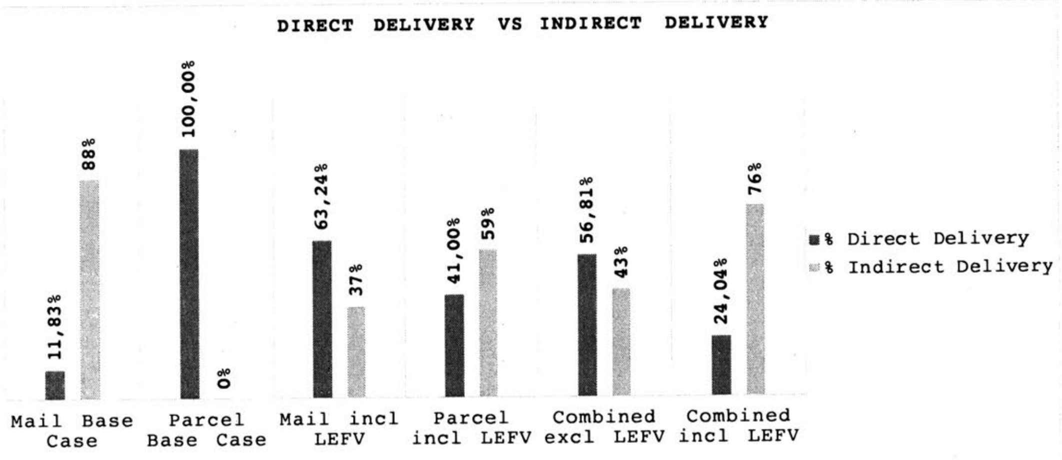
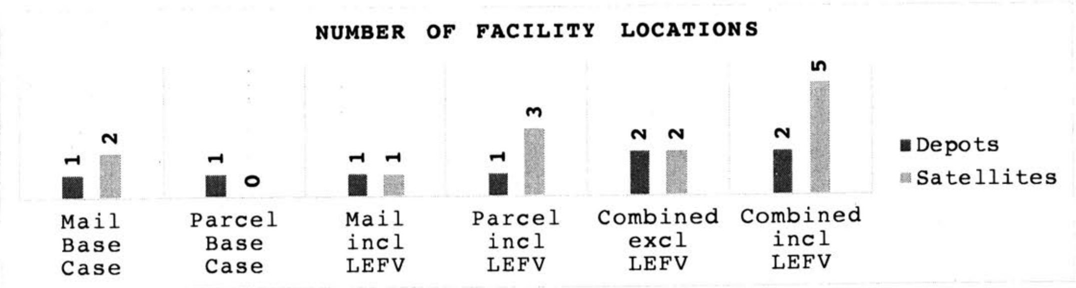


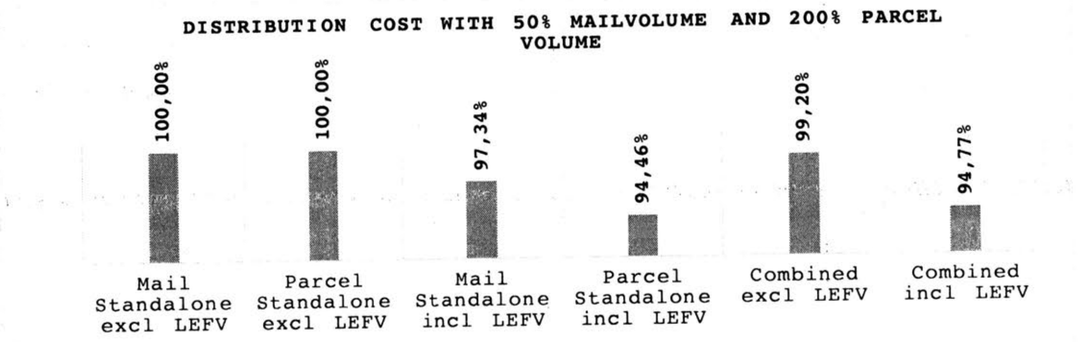
Figure 4-8: Active Locations Scenarios



4.6.3 Sensitivity Analysis

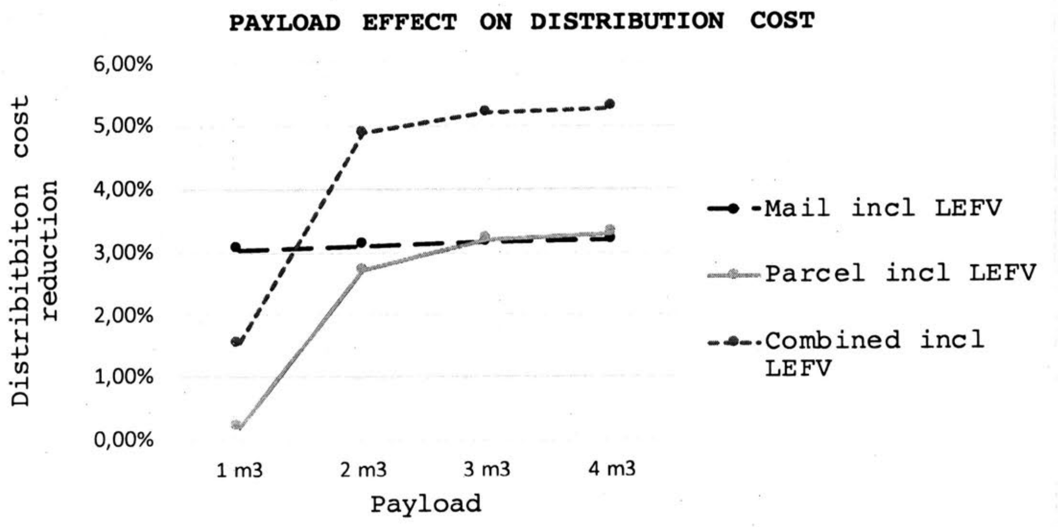
A sensitivity analysis was performed with regards to three parameters: First, we varied volume. The mail volume was decreased by 50% while the parcel volume was increased by 100%. This represents the volume forecast for 2023. Figure 4-9 shows that the distribution cost development is similar to the base scenario. In this volume scenario with LEFV distribution cost decrease with 5,5% in the parcel network, mail decreases with 3% and combined delivery with 5,2%. The trends with regard to vehicle substitution and the opening of a second echelon are similar to the base case scenario.

Figure 4-9: Effect of Volume on Distribution Cost



Second, we varied the LEFV payload. In the base case a payload of two m^3 was used for the LEFV, this matches the payload of the current e-cargobikes being used in the parcel delivery market. From figure 4-10 it is clear that even though a small payload of one m^3 is acceptable for mail delivery, the payload is too small to make it an efficient mode of transportation in the parcel network. Increasing the payload up to three m^3 has a further beneficial effect, after which the effect diminishes. A payload between two and three m^3 seems to be optimal. Effect of higher payloads than four m^3 would also require an adaption of the intra-stop speed distribution, since larger vehicles seem unlikely to be able to use the bicycle lanes and are more difficult to manoeuvre.

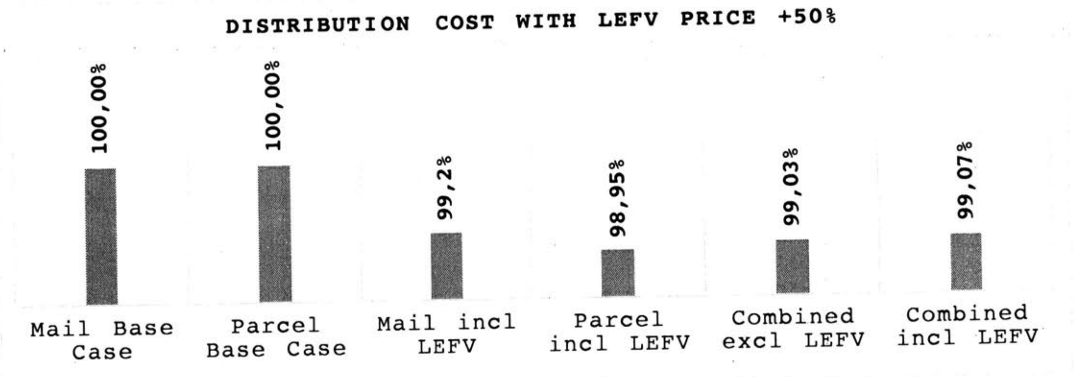
Figure 4-10: Payload LEFV vs Distribution Cost



Third, we varied the price of the LEFV. In the base case the LEFV price was set at 5,000 euro. Since LEFV are still in a development stage in the market, prices are varying. Therefore a price increase 50% was applied to the base model. Figure 4-11 shows that total distribution cost savings reduce to approximately 1% in all the network configurations. However, the substitution in the mail and parcel network from respectively bikes and vans to LEFV is similar to the base case scenario, as well as the creation of the second echelon.

The sensitivity analysis shows that the introduction of LEFV in the distribution networks leads to robust results. Following the market trends, the distribution cost savings would increase over time. Since LEFV tend to be more suited for dense areas the benefits of introducing LEFV in the vehicle fleet in the parcel segment increase as the customer density increases. Moreover, the design of the LEFV payload plays an important role in order to gain enough benefits, since a minimum size of two m^3 is required to gain significant savings. Finally, based on the price variation of the LEFV we estimate that the price of the LEFV has to be set to a maximum of 7,500

Figure 4-11: Distribution Cost with LEFV Price + 50%



euro in order to result in significant savings.

4.7 Discussion

Our findings show that the introduction of LEFV in the mail distribution network leads to significant cost savings. The advantages of a longer maximum service time and the faster intra-stop and linehaul speed, result in a 3% reduction of distribution cost. There is substitution of bicycles with LEFV, while scooters remain at a constant level. Even when the market volumes will drop according to the forecast, investing in LEFV still results in a significant cost saving. A reduction of volume leads to longer intra-stop distances resulting in more benefits as a result of the LEFV's higher intrastop speed in comparison to bicycles. Payload does not play a major role in the mail network, since the maximum service time is the limiting factor.

In the separate parcel network the introduction of LEFV also leads to a reduction of +/- 3%. Vans in dense customer areas are substituted by LEFV which have a lower operating cost, while still reaching a similar intra-stop speed as a consequence of the high customer density. A second echelon is created with satellite locations in close proximity to the LEFV served customer areas, minimizing the linehaul distance to compensate for the slower linehaul speed of LEFV compared to vans. Selecting a LEFV with a payload between two and three m^3 is essential in order to use these vehicles efficiently. Smaller payloads do not lead to a substitution of vans. An increase in volume, resulting in higher customer density will lead to even more cost savings when LEFV are used, bringing the total distribution cost saving to 5.5%, making it a robust model for the future.

While benefits of combined delivery of parcels and mail with the current fleet seem severely limited (i.e., cost saving less than 1%), the merger of networks with LEFV in the vehicle fleet does lead to additional savings. Cheaper vehicles with similar speed characteristics on short intra-stop distances in dense areas are favorable over vans. The increase of indirect delivery and the opening of multiple satellites ensures that linehaul distances are minimized.

Chapter 5

Conclusion and Future Work

In this research an extension of the 2E-LRP model by Winkenbach (2016b) was developed to determine the efficiency gains of using LEFV. The model extension included a MDVRP for the first echelon as well the option to combine separate distribution networks only in specific geographical regions. The model was applied to the case of the Dutch postal operator PostNL. PostNL is the dominant player in the Netherlands in the mail and e-commerce last-mile market. The proposed model and findings in this research can support PostNL in its decision making process regarding a possible merger of the distribution networks in the future. Our research shows that the introduction of LEFV in last-mile delivery results in significant distribution cost savings between 3-5% in this specific area.

LEFV are a worthy alternative to vans in dense city areas, due to their high speed on short distances and their manoeuvrability in city areas. Moreover, they offer a longer maximum service time (MST) due to less physical strain on the deliverer and higher payloads than bicycles. Our model suggests that traditional bicycle routes in the mail network can be substituted by LEFV. The additional operating and storage cost are more than compensated by the faster speeds on the intra-stop and line haul distances. Moreover, in the parcel network LEFV with a minimum payload of 2 m^3 will substitute traditional vans. LEFV reach similar speeds as vans in dense city areas. To overcome the lower linehaul speed, the model suggests creating a second echelon network opening satellite locations in close proximity to dense city areas. A combination of the mail and parcel network seems infeasible with the current fleet mix due to limited savings. Bicycles and scooters are not suited for delivery of parcels due to their limited payload, while at the same time migrating letters to the parcel network served with vans would lead to higher operational and labour cost. The inclusion of LEFV in the fleet would allow PostNL to start combining delivery with distribution cost savings up to 5.5%. Sensitivity analysis following the market volume developments show that the cost benefits remain for the coming years.

This research can be extended in several ways. First, the model can be applied to a larger data set measuring the effects on an entire delivery region. Second, even though the implementation of LEFV results in a significant reduction of distribution cost, the actual implementation will require a further development of the distribution process designs within the company. The production processes are currently not aligned for combining mail and parcel product flows. Third, this model focuses on the strategic and tactical level, but parcel delivery requires time window estimates on an operational level. Developing a VRP with time windows to validate the actual behaviour of combined mail and parcel routes with LEFV is a useful addition. Finally, an optimal LEFV has to be designed or purchased, since the results depend highly on the final configuration of the vehicle. Implementing the LEFV on a small scale could support our analysis to validate the results. Moreover it could also give more insights in maintenance cost and other assumed parameters.

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Appendix A

Determining the Circuity Factor

In this research the k-value used in the ARCE formula to derive the real intra-stop distance is determined based on the method proposed by Merchán and Winkenbach (2019). The circuity factor c is defined as the ratio between the shortest path network distance d_c and the Euclidean distance d_{L2}. Subsequently, the k_c-value (i.e. referred to as k-value in Equations 3.9-3.10) can be derived by multiplying the circuity factor for the region by the Euclidean (i.e., L_2 norm) upper bound value of 0.9 as proposed by Daganzo (1984).

$$c = \frac{d_c}{d_{L2}} \tag{A.1}$$

$$k_c = ck_{L2} \tag{A.2}$$

For the case of PostNL, determination of the k_c-value for the different vehicle type was done in four steps. First, the data set with the current tours of PostNL with their accompanied routing sequence for this specific customer region was collected. Second, the coordinates of the points of delivery (POD) were plotted to the closest accessible road using PostNL's GIS software. The POD database of PostNL includes field measurements of the distances from each household (i.e., POD) in the Netherlands to the road network, this ensured a high accuracy on this plotting procedure. Third, for the tour sequences in the data set, Euclidean distances between the POD were calculated. The actual distances over the road network were determined using the Open Street Map Routing (OSRM) engine with different vehicle profiles. Fourth, the k-values were determined for different vehicle types by Equations A.1 and A.2.

Additionaly, an approach that is less dependent on the actual tour sequences of PostNL was tested. In this case for each customer segment a Nearest Neighbourhood Search (NNS) was applied to each customer segment, where the first POD was set to the lowest house number (i.e., address). This seems to fit well with the practical execution of delivery where a deliverer tries to park-and-loop within each customer segment. Park and loop is a delivery method in which the carrier parks the vehicle and walks out and back over one or more streets, delivering mail away from and looping back to the vehicle. For each customer segment this delivery sequence was used to determine the circuity factor and k-values.

The PostNL tour sequence resulted in an average k-value for bikes, LEFV and scooters (same road network) of 1.215, cars and vans have a k-value of 1.751. The NNS method resulted in a k-value for bikes, LEFV and scooters of 1.312 and cars and vans have a k-value of 1.912. The higher k-values for the NNS sequence can be explained by the fact that the tour routing sequences of PostNL sometimes deviate from the park-and-loop system, specifically for car delivery (i.e., street crossovers) when this results in a shorter distance. For this research the actual tour routing sequence of PostNL is used to set the k-values as an input parameter, but the NNS-method seems to be an acceptable solution with a gap of 7-9% in case a company creates a greenfield delivery network.

Appendix B

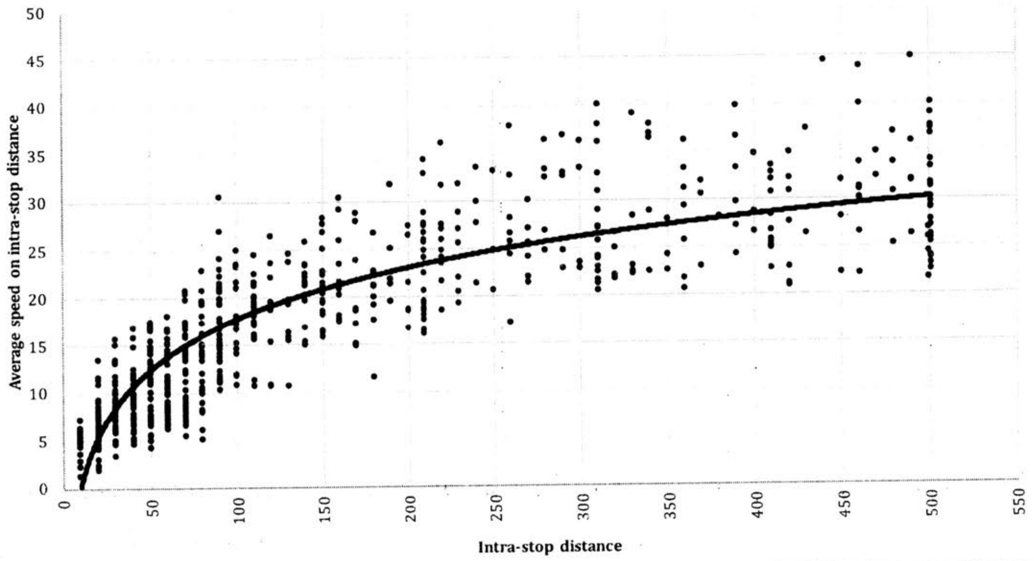
Determining Vehicle Speed Profiles

The CA method used for determining the cost of serving a customers segment is depending on the time required for driving the total intra-stop distance. Besides the physical vehicle characteristics, the time a vehicle requires to overcome the intra-stop distance is dependent on driver behaviour (i.e., does he or she (de-)accelerates quickly) and the road disturbances (e.g., traffic, traffic lights) along the route. We refer to these respectively as the *driver factor* and *road disturbance factor.* In cooperation with PostNL, extensive field measurements were performed to determine the actual time it takes a driver to overcome the intra-stop distance.

The method involved three steps. First, on an empty road without any disturbances all vehicles types drove a variety of intra-stop distances. A driver had to drive the entire pre-specified distance and stop in front of the simulated POD. The test was performed with five different drivers for all vehicle types used by PostNL. These results were used to set the initial speed profiles in combination with the driver factor. Second, in order to determine the road disturbance factor the drivers were followed and measured for a week during their delivery tours. For each intra-stop distance the actual time required was registered, leading to almost 1,000 measurements per vehicle type. Third, linear regression was applied on the data set (including the effects of driver behaviour and road disturbances) to determine the speed profile for each vehicle. The R^2 value varied for the different vehicle types between 75% and 85%. In

Figure B-1 an example of the measurements for car delivery leading to the intra-stop speed profile is presented.

Figure B-1: Regression Average Speed Car



Appendix C

Figures

Figure C-1: City Area Utrecht

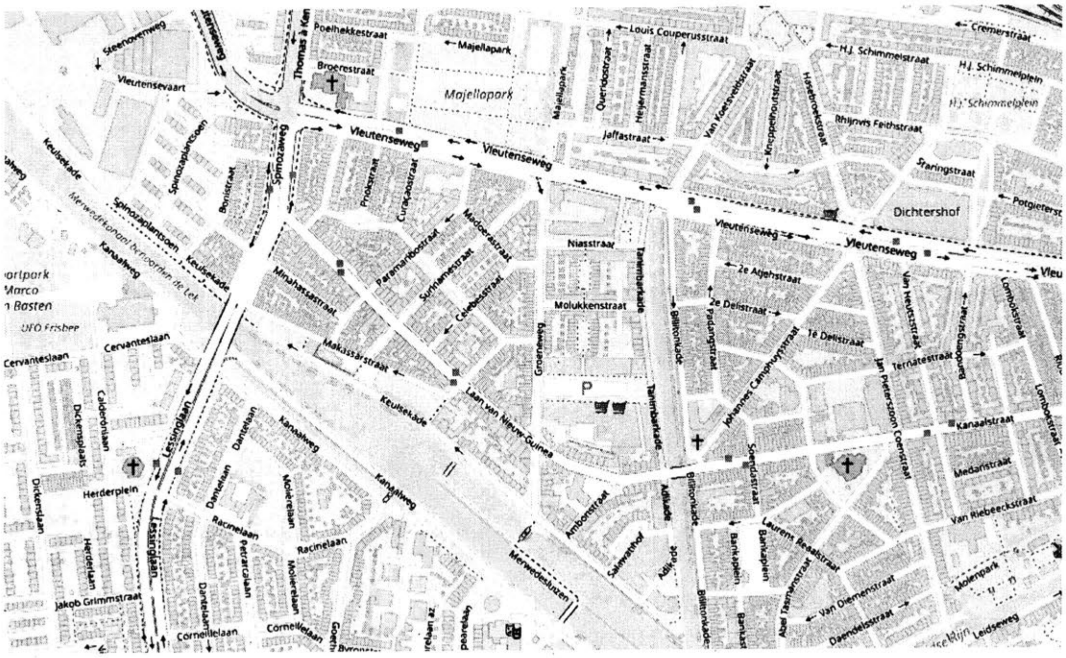


Figure C-2: Suburban and Rural Area Utrecht