MASTER

Network design for crowd-delivery
towards a crowdsourced delivery network for ecommerce

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Network design for Crowd-delivery: Towards a crowdsourced delivery network for ecommerce

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Management summary

In recent years, e-commerce sales within the Netherlands have been rapidly increasing, resulting in a growing parcel delivery market. Due to this growing market, the number of transport movements and delivery vans within the residential areas has been increasing. To counter these effects city logistical solutions might be required. One of these solutions is the use of crowd-delivery, which Trunkrs aims to introduce in the Netherlands. In crowd-delivery, non-professional drivers are used to perform the transport of parcels within their existing traffic movements. In this way, the number of traffic movements could decrease while also reducing the delivery costs.

To implement crowd-delivery, the current delivery network needs a redesign to accommodate the non-professional drivers (occasional drivers). These occasional drivers require a transfer point where the assigned parcels are collected and the current locations are not suitable to perform this operation. Therefore, new locations (crowd-hubs) that are suitable need to be introduced within the network. Furthermore, in the current situation, it is unknown where crowd-delivery could be a profitable option. By identifying where crowd-hubs could be profitable, a sustainable delivery network can be designed. Therefore, this research aims to answer the research question:

*How should the delivery network of Trunkrs be designed, such that crowdsourced delivery can be implemented?*

To answer this research question, multiple scenarios have been analysed with the use of an optimization based on the hub location problem. This optimisation aims to find the network design under minimal total network costs, which should identify the profitable crowd-hubs. To be profitable, the crowd-hubs require the savings of crowd-delivery to be bigger than the location costs. The optimisation model is constraint by, the requirement that all demand needs to be delivered, a crowd-hub capacity, and that only a part of the assigned parcels are accepted by occasional drivers. Finally, to reduce the complexity of the analysis and to assure that crowd-hubs have a logical set of destinations assigned, only a crowd-hub that is local to the destination can be used. Under these constraints and with the goal to minimize the network costs the model decides how destinations are connected to the network (professionally or via a crowd-hub) and which crowd-hubs are used.

With the use of this cost minimization the analysis was performed, which showed that crowd-hubs can be a profitable addition to the delivery network and can be used throughout the Netherlands. For a location to be profitable it is important to have a cost difference between crowd-delivery and professional delivery of at least €0.75 per package. When this cost difference is sufficient, the number of crowd-hubs and the use of crowd-delivery will increase with demand. However, when crowd-delivery costs and professional delivery costs become similar crowd-delivery is not feasible. Therefore, it will be important to reduce the crowd-delivery costs as demand increases and the professional delivery efficiency improves due to economies of scale. Obtaining a similar reduction in costs for crowd-delivery might be difficult as the capacity of an occasional driver is limited and the compensation paid will probably influence the parcel acceptance rate. Therefore, managing the crowd-delivery costs will be important for a profitable crowd-delivery network. This management of the costs includes monitoring the cost difference with professional delivery and optimizing the assignment of parcels to occasional drivers. With the assignment of parcels to occasional drivers, the compensation required per parcel could be minimized, which will increase the profitability of crowd-hubs. Additionally, monitoring the cost difference can assure that the paid crowd-delivery compensation still provides sufficient savings. In conclusion, managing the crowd-delivery costs will be crucial for crowd-hub profitability.
When the compensation paid to an occasional driver is lowered, the acceptance of parcels might reduce. As a result, the network costs might increase because a costly professional repair delivery is required. Therefore, when reducing the crowd-delivery costs it is important to account for the effects on parcel acceptance, as this could influence the savings made.

In addition to the crowd-delivery costs, the demand has a significant influence on crowd-hub profitability. As demand increases, the costs per parcel and the use of crowd-delivery will increase because more crowd-hubs will become profitable. Furthermore, for the network design to be stable the demand assigned to a crowd-hub needs to be relatively certain. As a result, the network will stabilize when demand increases. To assure that crowd-hubs are feasible and the network is stable the possible network connections need to be maximized. In addition, increasing the service area of a crowd-hub will reduce costs because fewer crowd-hubs are needed or more crowd-hubs will be feasible. Increasing the service area is most important in rural areas because it is the only way to have sufficient demand for feasible crowd-hubs. In conclusion, the crowd-hubs require sufficient demand to be feasible, which can be reached by extending the service area of a crowd-hub or increasing the number of parcels in the network.

Other important factors to consider within the network design are the crowd-hub capacity and location costs. When the cost difference between professional- and crowd-delivery is decreasing, the capacity becomes a limiting factor for the feasibility of crowd-hubs. Therefore, increasing the crowd-hub capacity reduces the total network costs and can make crowd-delivery a profitable option. For a crowd-hub to be feasible, the use of crowd-delivery should reduce the delivery costs with more than the location costs. Therefore, a decrease in location costs will increase the number of crowd-hubs used as crowd-delivery will become a more profitable option.

A successful implementation of occasional drivers and crowd-hubs into the delivery network can lead to significant savings in the total network costs. As with the inclusion of crowd-delivery, the total costs per package could be reduced with at least €0,20 for the high demand scenarios. Even higher savings per parcel can be obtained for the lower demand scenarios and with an increase of the service area

In conclusion, to implement crowd-delivery in the existing delivery network the profitable crowd-hubs can be identified using a variation on the hub location problem. These locations should be able to serve a stable and sufficient number of parcels on a daily basis, with a crowd-delivery cost that is sufficiently lower than the professional costs. The locations that currently seem to best fit this description are locations on the border of cities that can deliver both in and around the city. By placing them in cities a daily demand amount is guaranteed and by servicing around the city more significant savings can be obtained.
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References
1 Introduction

In the last couple of years, online sales have been rapidly increasing, resulting in a growth of parcel delivery and traffic movements within residential areas. Using crowd-delivery the traffic movements and delivery costs could be reduced. To include crowd-delivery, within an existing delivery network new locations might be required. At these locations, packages can be transferred between the existing network and crowd-delivery. This research introduces the concept of network design in crowd-delivery, to research the potential of these new locations.

This chapter introduces the research by, first, providing some background information on the e-commerce market and the concept of crowd-delivery. Secondly, the company at which the research has been performed is discussed, with a description of the current and desired situation. Thirdly, the research is described with the problem description, research questions, and relevant stakeholders. To conclude this introduction, an outline of the thesis is provided.

1.1 Background

This thesis research has been performed within the Dutch e-commerce market. Therefore, the first part introduces the current developments in the Dutch e-commerce market and its effects on parcel delivery. Second, some background information on crowd-delivery is given to further introduce the topic of this thesis. Within this part, the definition of crowd-delivery is discussed.

1.1.1 E-commerce and parcel delivery

The last couple of years online sales have been increasing, as is shown in Figure 1.1. Within three years (2013-2016), the online revenue has increased with over 60 percent. As a result, the online revenue of 2016 was over 20 billion euros in 2016 (Thuiswinkel.org, 2017). The e-commerce market is still growing rapidly because between 2015 and 2016 a growth of 23% was recorded. In addition, there is an increasing number of people ordering online as well as an increase in orders per online customer (thuiswinkel.org, 2015). Therefore, the current growth rate is not likely to decline.

As a result of the rapidly growing e-commerce market, the parcel deliveries have been rapidly increasing since 2003 (Post-NL, 2016). This effect is shown in Figure 1.2, which shows the number of parcels delivered by the Dutch market leader. A growth in parcel delivery occurs because the increase in online shopping results in a shift in traffic movements. Instead of people having their personal shopping trips to different stores a delivery movement has to be made, which shifts traffic movements to the residential area (Esser & Kurte, 2006). As a result, the number of delivery vans within the residential area has been increasing, because more delivery companies need to enter a specific residential area. This leads to, a current rate of twelve to fifteen delivery vans a day entering specific
areas in Amsterdam (te Pas, 2016), which with the current growth rate could in a couple of years increase to 60 vans a day (Vervest, 2017). These additional traffic movements, within the residential area, will increase the traffic intensity and could decrease road safety (Braimaister, 2002).

1.1.2 Crowd-delivery

One solution to counter the negative effects of a growing e-commerce market is Crowd-delivery. With crowd-delivery, parcels are delivered by non-professionals who collect and deliver the parcels on their route, for example: their daily commute. This idea is similar to ridesharing, where a passenger is taken on (part of) a trip that the driver was already planning to take (Amey, 2010). To perform crowd-delivery a group of people needs to be mobilized to perform the task (Howe, 2006) (Estellés-Arolas & González-Ladrón-de Guevara, 2012), which defines it as a type of crowd-sourcing. Combining these definitions of ridesharing and crowdsourcing results in the following definition of crowd-delivery, as used within this research.

*Transporting packages by the use of a group of people, who are not professional drivers (occasional drivers) and deliver these packages for a small compensation on or close to their already planned route.*

Crowd-delivery is one of the solutions under research as an option for city-logistics. Within city-logistics, the aim is to reduce the transport movements in cities (Savelsbergh & Van Woensel, 2016). In the case of crowd-delivery, this transport movement reduction is done by combining freight delivery with private traffic movements. Other solutions where transport movements are combined are ‘using urban distribution centres’ and ‘combining freight with public transport’. City-logistics also includes other solutions, such as the use of smart lockers or pickup points. When using pickup points or smart lockers, the parcels are delivered to a pick-up point or smart locker instead of the home address and the recipient collects it from there. This eliminates the probability of a recipient not being home, which reduces the number of revisits and the transport movements required. In addition, the pick-up points concentrate the deliveries into one address, improving the delivery efficiency. In conclusion, this research is focused on the combination of freight with existing private traffic movements but other city logistical solutions with the same goal of reducing transport movements within cities exist.
1.2 Trunkrs
A company that wants to use crowd-delivery within their delivery network is Trunkrs, which is where this research has been performed. Trunkrs is a start-up based in Utrecht, the Netherlands, that provides a same-day delivery service for online stores. Trunkrs is a young company (founded in 2015) and currently has around 10 employees. These employees are used to manage and construct the delivery network.

1.2.1 Current situation
Currently, Trunkrs uses a professional delivery network, which is shown in Figure 1.3. Within this network professional partners are mobilized to perform all transport movements and deliveries. The network consists of a central hub and multiple local hubs, where the central hub also functions as a local hub. The central hub has an important function within the network because here most of the parcels are sorted by destination. The local hubs, mainly, function as a starting point for the delivery routes but some sorting occurs to have the right parcels on a delivery route.

![Figure 1.3 Professional network Trunkrs](image)

With the use of this delivery network Trunkrs, currently, delivers around 1,500 parcels per day throughout the Netherlands. Most of these parcels have a destination within Amsterdam because Trunkrs only recently extended to countrywide coverage. Therewith, an increasing number of parcels needs to be delivered in other parts of the Netherlands because the nationwide network increases the number of online stores that are willing to use Trunkrs for their delivery.

The parcels flow through the professional network with the following process. When the e-commerce companies (online stores) make a sale, they prepare the order for shipment and create a transport request at Trunkrs. This transport request is sent to Trunkrs before a pre-determined cut-off time. After this cut-off time, Trunkrs arranges the collection of parcels at the different e-commerce companies. The professional partners deliver the collected parcels to a hub within the network. Within the local hubs, multiple collection routes are combined into one transport movement towards the central hub, where the parcels are sorted by destination and transported to the local hubs. From there, the professional delivery routes will depart, resulting in the process to end with the consumer receiving its order.
The transport demand at Trunkrs originates from online sales and is created by online stores. The e-commerce companies are the customers of Trunkrs and decide if Trunkrs is used for a delivery. Some e-commerce companies, however, let this choice be influenced by the consumer, by providing the option to select a delivery time. As a result, only part of their online sales is transported by Trunkrs, as not all consumers are willing to pay extra for same-day delivery. However, no matter if a consumer has had the option to select same day delivery all packages handled by Trunkrs have to be delivered within this time frame. Given the short time frame and the extra costs for some consumers, the quality of the delivery service is important.

1.2.2 Desired situation

The delivery network of Trunkrs is still undergoing significant changes since Trunkrs is still a relatively young company. For example, the professional delivery network is still extending to increase the service level and the capacity. Additionally, Trunkrs is actively extending the customer base to increase the transport demand. Most of the growth at Trunkrs, currently, results from adding new customers to the network. These new customers are important to Trunkrs because according to their most recent break-even calculations a daily demand of roughly 3.00 parcels is required to break-even. Nevertheless, more parcels are required to maintain a sustainable profit.

In addition to including an increasing number of parcels in the delivery network, Trunkrs aims to implement crowd-delivery. The crowd-delivery service will use a combination of occasional drivers and professional partners to operate the delivery network. To successfully implement crowd-delivery, Trunkrs would like to open new transfer points (crowd-hubs), where occasional drivers collect the packages for delivery and the parcels transfer from the professional delivery network to occasional drivers. The crowd-hubs are required because Trunkrs does not have any locations that are suitable for crowd-delivery.

In conclusion, the desired situation by Trunkrs is an efficient delivery network that provides a sustainable profit with the use of crowd-delivery. The network should, therefore, include locations where occasional drivers can collect their assigned parcels. In addition, the delivery network should handle a sufficient number of parcels.

1.3 Research

To move towards the desired situation, this research focuses on the network design of Trunkrs. Specifically, the extension of the current network with locations that are suitable as transfer points to occasional drivers.

1.3.1 Problem description

Currently, there are no suitable locations to transfer parcels to occasional drivers and there is no method in place to identify where these locations need to be placed. For a successful and sustainable implementation of crowd-delivery, these locations are required and need to be placed in profitable areas. Therefore, a method is required to identify profitable crowd-hubs within the delivery network.

In this research, the extension of the current delivery network of Trunkrs is investigated. With this extension, crowd-hubs are added to the existing professional network to find interesting areas for crowd-delivery. These areas should provide sufficient savings for Trunkrs to open a new location. At these locations, the packages are stored between the drop-off and the collection by occasional drivers, such that professional delivery and crowd-delivery are able to support each other.
1.3.2 Research question

This research is summarized in the following research questions, where the main question is:

*How should the delivery network of Trunkrs be designed, such that crowdsourced delivery can be implemented?*

Sub-questions:

1. How should the network design model for the network extension with crowd-hub locations be constructed?
   a. What should be the goal of this model?
   b. Which variables are important to consider within this model?
   c. What cost are relevant within this model?
2. Where should the crowd-hubs be located?
3. When are crowd-hubs profitable for Trunkrs?
4. How does the use of crowd-hub locations respond to demand?

The first sub-question is used to make a considered choice on how the model should be constructed, and what should be considered within the network design extension. The second until fourth question are used to determine which locations should be used by Trunkrs in the current and future situation.

1.3.3 Stakeholders

The network extension within this research is influenced by multiple stakeholders, who have their desires with respect to the delivery network. To obtain insight into these desires, this section discusses the following stakeholders and their desires:

- Trunkrs
- E-commerce companies and consumers
- Professional deliver companies
- Occasional drivers
- Crowd-hubs

1.3.3 (a) Trunkrs

The extended delivery network will be coordinated by Trunkrs, who aims to use this delivery network to perform their same-day delivery service and therewith maximize its profit. A maximum profit is obtained by having a maximum number of parcels at minimal costs. Therefore, the network should be able to handle multiple demand scenarios and flexible enough to deal with demand growths. With a minimization of the costs, the network design should be found where the sum of location costs and transportation costs are the lowest. The location costs are the costs associated with the network design, such as opening a facility or recruiting occasional drivers. The transportation costs are the costs that result from using the network and having parcels flow through the network. In conclusion, Trunkrs aims to have a delivery network that performs under minimal costs and maximizes their profit by effectively delivering the transport demand.
1.3.3 (b)  **E-commerce companies and consumers**
The delivery service of Trunkrs will be sold to e-commerce companies. The e-commerce companies use the same-day delivery service to be competitive with local stores and to sell to consumers who want their products as fast as possible. Therefore, the cut-off time needs to be as late as possible, requiring short delivery times. However, most of all, these stakeholders require the delivery to be in good quality and on time. In addition, the e-commerce companies aim to reduce their cost per parcel and the number of collections because this will have a direct effect on their profit margin. In conclusion, the customers and the online stores want a delivery service with short delivery times where orders are delivered in good condition for minimal costs.

1.3.3 (c)  **Professional delivery companies**
The delivery network largely depends on the professional delivery partners. These delivery partners will execute most of the transport movements and guarantee that deliveries are made. The professional delivery partners are needed to repair deliveries, which are left behind by occasional drivers, and to assure that packages arrive at a crowd-hub. With the inclusion of crowd-delivery, their total amount of transport movements might decrease and their role will shift to a backbone function. However, their aim remains transporting as many parcels as possible, since this maximizes their profit. Therefore, the professional delivery will probably not be a limiting factor to the network design.

1.3.3 (d)  **Occasional drivers**
The extension of the delivery network introduces new stakeholders, the occasional drivers, and the crowd-hubs. The occasional drivers are the people who will perform the crowd-delivery part of the delivery network. These occasional drivers collect and deliver the parcels during their already planned route, which means that they will perform the delivery within their existing traffic movements. As a result, the number of packages that can be delivered by the occasional drivers is unsure and limited. Where professional drivers accept all transport movements assigned, the occasional drivers will only accept deliveries that do not interfere with their planned route and that can be performed within the little extra time they have available. The profit for the occasional driver will be the small financial compensation they will receive for performing the delivery.

1.3.3 (e)  **Crowd-hubs**
The crowd-hubs are, also, a stakeholder in the network design as they will be placed in existing businesses. These businesses aim to maximize their profit, which could potentially benefit from the occasional drivers visiting their locations to collect the packages. In addition, they might receive some compensation to handle the packages. Because the crowd-hubs are located in existing businesses they provide some constraints to the network design. For example, the number of packages that are transferred at a crowd-hub is limited because they can only reserve a limited space for the packages to be stored, otherwise, it would limit the existing business. Furthermore, the crowd-hubs are restricted by opening hours because the crowd-hubs might not be willing or able to extend their current opening hours. The selection of possible crowd-hubs will, therefore, be crucial to the usability of a solution. Another example of this is the reachability of a crowd-hub, which will influence the availability of occasional drivers.
1.4 Thesis outline

The remainder of this thesis elaborates on the related literature, methodology, results and conclusions of this research. In this section an overview on the different chapters that follow is given, to provide insight into the structure of the thesis.

Chapter 2 discusses some of the literature related to this research. Within this chapter, the focus is on two parts, first an introduction to previous studies into crowd-delivery is provided. In the second part, some network design studies are discussed, with the goal to identify a model that could be used in the analysis.

Chapter 3 discusses the methodology used during this research, which consists of model building, data collection, and analysis. In the discussion of these research steps, the assumptions and decisions are explained.

In chapter 4, the model for the analysis is explained, by discussing the goal, constraints, variables, and parameters. In the conclusion of this chapter, the model is shown in a mathematical formulation. Building on chapter 4, Chapter 5 describes the data used in the analysis. For different parameters, the data settings used is explained, which results in an overview of the base case.

The results of the analysis are discussed in chapter 6, where the effect of different parameters is shown. These effects are discussed and visualized with the use of graphs. Building on these results chapter 7 formulates the conclusions of this research, such that chapter 8 can provide the recommendations.

2 Related literature

This master thesis is related to research into crowd-delivery and network design. Within this chapter, a short introduction of previous studies in these fields is provided. For a more extensive description, I refer to the literature review made as preparation for this research (Bos, 2017). This chapter first introduces papers about crowd-delivery, which is divided into business research and routing research. Second, some network design papers are discussed, to identify models that could be used in the analysis.

2.1 Crowd-delivery

Crowdsourced delivery is under increasing interest of businesses and academics. For example, Walmart (Barr & Whol, 2013) and Amazon (Bensinger, 2015) have already shown interest or started testing with crowd-delivery. In addition, multiple start-ups that provide a crowd-delivery service have been founded (such as Rideships, MyWays (DHL) and PiggyBaggy) (Rougès & Montreuil, 2014). That these companies are interested in crowd-delivery indicates that there might be an opportunity. As a result, the academics have also started to become interested in crowd-delivery (Savelsbergh & Van Woensel, 2016), which started multiple studies into crowd-delivery.
The current state of crowd-delivery research can be divided into two groups. First the business research, where the concept of crowd-delivery is studied. Second, the routing papers who focus on the routing problem of crowd-delivery. Examples of the business research are the papers of Rougès & Montreuil (2014) and Mldenow et al. (2016), who compare the business models of different crowd-delivery companies. In these papers, the implementation of crowd-delivery at these companies is discussed, to identify the possibilities of crowd-delivery. A second example of business research is the work of Verheyen (2016), who focussed on the legal implications of crowd-delivery. A third example is the case study performed by Paloheimo et al. (2016), which investigated the motivation of occasional drivers to perform crowd-delivery. In this study, it was shown that crowd-delivery participants are influenced by the compensation structure but the monetary compensation is not their only motivator to join. In addition, this case study showed that an assignment algorithm or routing solution is important for an efficient implementation of crowd-delivery.

To solve the assignment of parcels to occasional drivers the routing research for crowd-delivery has been introduced, which can be divided into two approaches. These two approaches are routing with only crowd-delivery and routing with a professional backbone. The research into routing with only occasional drivers has been building on ridesharing studies. Ridesharing studies use shortest path based algorithms to find the optimal assignment of passengers to drivers (Furuhata, et al, 2013). For the crowd-delivery cases, a similar approach is used to assign parcels to taxi movements, which created the share-a-ride problem (Li, et al, 2014). Wang, et al. (2016) had a different approach to the routing and introduced a network of pick-up points from where people had the option of crowd-delivery or collect the parcels themselves. In this problem, a shift to include a professional network is shown, as the problem only uses crowd-delivery for the last mile. Further, the studies into routing with only crowd-delivery showed that the parcels might accumulate waiting times at transfer points, which will significantly increase the delivery times (Chen, et al. 2016a). These waiting times are induced when a parcel is waiting for the following connection and the intensity of movements between two transfer points is low. Therefore, the inclusion of a professional delivery network might be necessary to guarantee delivery times.

The routing problem with the inclusion of professional delivery has been introduced as an extension to the vehicle routing problem (VRP), which is a problem where the assignment of parcels to vehicles is optimized (Dantzig & Ramser, 1959)(Laporte, et al, 1985). The extension with crowd-delivery has been introduced by Archetti, et al. (2016), who introduced the vehicle routing problem with occasional drivers. In this research, they formulated a mixed integer programming model, which is solved with the use of a multi-start heuristic. The vehicle routing problem with occasional drivers has been further extended by Chen, et al (2016b), Qi, et al. (2016), and van Cooten (2016) who adapted the routing problem to include multiple locations. Mayer, et al. (2016) and Arslan, et al. (2016) are working on ways to include the uncertainty in the network by either the use of simulation or dynamic routing.

To concluded, the research into crowd-delivery has been focusing on defining crowd-delivery and solving practical problems. Most of the research is focused on the routing of parcels and to optimize this operational problem. However, little research has been done into the network design for a crowd-delivery network.
2.2 Network design

This research deals with a network design question; therefore, it is important to identify related network design papers. The research into network design has a significantly larger history and amount of papers than the crowd-delivery research. Therefore, only selection of the published papers are discussed. In this section, two types of network design papers are discussed a hub selection approach and a coverage approach.

The hub selection type of network design originates from the hub location problem, which is an optimization problem introduced by O’Kelly & Morton (1986). In this problem, the optimal hub location needs to be selected from a set of candidate nodes while minimizing the network costs. During these studies, the approach is to formulate the problem as a linear mixed integer problem, which is then optimized using heuristics or CPLEX (Farahani, et al., 2013), (Alumur, et al., 2012a) (Topcuoglu, et al., 2005). In this type of optimisations, the locations are chosen such that transport movements can be combined and the total costs are reduced. This problem has been extended in multiple ways, for example with the location routing problem (Laporte, 1988) (Prins et al, 2007) (Winkelbach et al, 2016). The location routing problem is a combined routing and network design problem, which is often solved with a two-phase heuristic that uses the routing solution to improve the network design. Another extension is the inclusion of time constraints by Cardona-Valdés, et al. (2011) and Campbell, et al. (2007), whom investigated the placement of crowd-hubs with a minimization of the delivery time or under time constraints. A third extension of the hub location problem is the inclusion of uncertainty (Alumur, et al., 2012a) (Santoso, et al., 2005), which was done by including multiple scenarios and the probability into the optimisation.

A different approach to the network design are the coverage models. Coverage models optimize the network over the areas served, which is done by either minimizing the number of locations or maximizing the service area for a fixed number of locations. (Kao & Lin, 2002) (Murray, 2003) (Yu, et al., 2013). This kind of problems are mostly used to determine the optimal location of a service point and to find the optimal spread of locations over an area. The profitability and costs of the network design are of less importance in this kind of problems.

For this research, a hub location problem approach seems to be the most suitable because the designed network should only use profitable crowd-hubs. With a coverage model, the goal would be to have crowd-hubs throughout the delivery network but a hub location problem allows for professional delivery to be used when it is efficient. Therefore, a hub location problem will be better to identify profitable crowd-hubs, whereas a coverage model is better to identify the optimal location within a certain area.

3 Methodology

The network design research was done in three phases: model building, data collection, and analysis. The following sections discuss these three phases of the research and the decisions made during these phases, which combined provides an overview of the methodology used.

3.1 Model building

During the first phase of the research, the network design problem was described in more detail, to identify its core. The research goal was to find the network design were crowd-delivery can be implemented in a sustainable way. Therefore, the crowd-hubs implemented in the network should be profitable, used effectively, and able to handle demand fluctuations. Furthermore, the network design should account for the stakeholder desires, which are described in section 1.3.3.
To build an optimal delivery network the analysis should provide the crowd-hubs locations that reduce the total network costs. Therefore, the network design should be optimised in such a way that only profitable crowd-hubs are included. Furthermore, these profitable crowd-hubs should be linked to the destinations that could be interesting for crowd-delivery. The network design is a strategic decision and the operation of the network is influenced by daily fluctuations. Therefore, the network connections might change on a daily basis and are only an indication of possibly interesting areas.

This optimisation of the crowd-delivery network can be modelled as a variation on the hub location problem. The hub location problem aims to minimize the network costs, which results in only efficient crowd-hubs being used. Therefore, a hub location problem approach is the best way to identify profitable crowd-hubs. For this research, the choice has been made to analyse the hub location problem for crowd-delivery as a static and deterministic problem because it drastically reduces the complexity of the analysis. However, in reality the problem is stochastic and has many unknowns. Therefore, it is important to analyse different scenarios and how they influence the network, to have a sustainable network design.

3.1.1 Modelling assumptions

The variation on the hub location problem used within this research required some modelling assumptions, which are summarized below. These assumptions have been made to limit the complexity of the problem and the reasoning behind these assumptions is discussed per assumption.

- **Demand is aggregated by four digit postal code**

  The transport demand considered in this case originates from online sales. The online stores will have different customers and different orders every day. As a result, the destinations and amount of parcels to transport is unknown. To have a reasonable location and amount for the demand as input for the analysis, the demand is aggregated over the four digit postal code. The four digit postal codes are viewed as one destination where demand of that area is all assumed to be in the centre.

- **Inter-hub costs are constant and excluded**

  The crowd-hubs need to be connected to the existing professional delivery network. When these crowd-hubs are close to multiple local hubs, the connection could be made with either of these local hubs. This could have an effect on the inter-hub costs. However, by assuming that demand via crowd-hubs eventually uses the existing network in the exact same way, these costs can be assumed to be constant and excluded from the analysis.

- **Crowd-hubs accept all packages assigned**

  The possible crowd-hubs that are included in the analysis have not been contacted and their willingness to function as a crowd-hub is unknown. However, the assumption is made that they are willing to become crowd-hubs. The recruitment of the crowd-hubs is part of the implementation and out of scope for this research.
• **The professional network has unlimited capacity**

The delivery network will be required to collect and deliver all transport demand. Therefore, the model requires a possible connection for all demand to obtain a feasible result. As the current professional network is already in place, the capacity of professional delivery is assumed to be sufficient to handle the transport demand. In addition, the capacity of professional delivery can relatively easily be extended in a strategic problem because additional delivery partners or delivery vans can be added to the network. The capacity for crowd-hubs and occasional drivers will be a limiting factor as increasing their capacity will not always be possible.

• **Time constraints are part of the operational problem**

The extension with crowd-hubs creates extra steps in the delivery process, which might increase the delivery time, while same-day delivery requires short delivery times. However, this extra delivery time can be countered in other ways. For example, the cut-off times or the routing of parcels might change. Nevertheless, the routing of parcels is an operational decision, which are excluded from this strategic problem. Therefore, the time constraint should also be part of the operational decision and excluded from this analysis.

• **Parcel acceptance by occasional drivers is constant and known**

The inclusion of occasional drivers in the network will introduce an uncertainty of parcel acceptance and delivery. Occasional drivers might not be able to collect the parcels they were assigned. As a result, packages might not be delivered by the crowd but a professional driver might have to repair this delivery. To analyse the effect of this process an acceptance rate is included in the network design, which analyses the effects of this uncertainty.

### 3.2 Data collection

The analysis on network design for crowd-delivery required a wide selection of data, which needed to be collected. The collection of data was the second phase of the methodology and this section explains the assumptions made to obtain this data.

#### 3.2.1 Demand

The crowd-delivery network should collect and deliver demand throughout the Netherlands on a daily basis. This daily demand fluctuates, as the amount and destination of these parcels depend on online sales. As a result, the exact demand amounts and locations are unknown. To analyse the network design of Trunkrs, demand scenarios were created that should represent an average day. The timeframe of a day is used because it models the capacity in a more sensible way. The network is used for same-day delivery and the capacity is, therefore, the number of parcels that can be handled on a daily basis. Any spare capacity on days that demand is low cannot be used on other days. As a result, modelling over a longer time span is not useful. Therefore, the network design needs to be done based on a daily demand. The demand average has been used because the problem is strategic and the hubs will be used over multiple time periods. The downside of using an average is that on days with high demand, the hubs might have insufficient capacity. This can partially be countered by underestimating the crowd-hub capacity. The alternative of using the maximum demand will overestimate the demand and results in crowd-hubs being placed in areas that are not yet feasible.
The estimates of this daily demand have been created with the use of market shares of the four digit postal codes within the Netherlands. This method provides fixed demand locations that are relatively precise and useful for analysis. In this research, three market shares were created. The first market share is the percentage of packages within a four digit postal code that Trunkrs has delivered within the last two years. The disadvantage of using the historic demand of Trunkrs is that demand is focussed into certain areas because Trunkrs only recently extended to a nationwide delivery network. Therefore, the other two market shares were created, which assume a nationwide demand. The second market share is similar to the first market share but the percentages are calculated with a yearlong demand of Trunkrs biggest customer. This online store sells general purpose products throughout the Netherlands and has a nationwide demand. This nationwide demand could be a good predictor for the demand spread in future scenarios because these products are required by all sorts of people in all areas. The third market share is the percentage of the Dutch population that lives within the four digit postal codes. This population percentage has been calculated based on the most recent data (2005), that could be found at the central bureau of statistics.

To create a specific demand scenario the number of parcels is multiplied by the percentages of a market share and rounded to an integer value. Rounded values were used because delivery is done in packages and partial packages do not exist. In addition, the model has an integer constraint for the number of parcels. Due to this rounding, there is a slight fluctuation in the number of parcels between the different market shares.

3.2.2 Possible crowd-hub locations

The model selects profitable crowd-hubs that can be included in the delivery network. For this research, two sets of possible crowd-hubs were created: Highway-locations and City-locations. To create these sets, point of interest (POI) files with GPS information for navigation systems were used. The used POI files were from the four biggest gas station brands and the two largest supermarket chains in the Netherlands and contained GPS information on all the locations of these companies. In addition to this information, the company websites were used to collect the address information and opening hours.

The address information was used to split the possible locations in the two sets. The locations directly on a highway were marked as highway-locations and all other locations as city-locations. This resulted in the first set of possible locations the Highway-locations.

For the City-locations some additional selection was required, as it contained some locations that are not suitable as a crowd-hub. For the gas stations within this data set, the locations without a shop that is at least open until 21.00 were excluded. The shop is required to have a place where packages can be stored between drop off and collection. Additionally, the opening hours are required to enable a professional repair for the not collected parcels. For the supermarket locations, the locations without a parking space next to the shop were excluded. This was checked by satellite imagery of Google maps. The excluded locations are locations that are less reachable by car and are mostly located within shopping areas. As a result, these locations are mostly focussed on pedestrian and bike traffic, making them less interesting as crowd-hubs.
3.2.3 Network connections

A crowd-hub can only be used to deliver to destinations that are relatively close to the crowd-hub. Therefore, the model only allows destinations to select a crowd-hub connection via a crowd-hub that is close. This limitation is also used to assure that crowd-hubs are placed in interesting areas and to reduce the size of the problem. In this research four sets of possible network connections have been made and used in the analysis.

The first two sets of possible network connections are the 2.5KM and the 5KM cases. For these cases, the four digit postal codes within a 2.5 or 5 kilometre range from the city-locations have been identified using a tool of freemaptools.com. For the destinations within the radius, the possible network connection via that crowd-hub has been included in the analysis. Using a radius assumes that traffic to all areas around a possible crowd-hub exists. However, the availability of occasional drivers to certain areas within the radius might be lower as the traffic flows might be lower towards these areas. In addition, crowd-hub locations towards the city centre might be preferred by the model because of a higher population density. In practice the locations to the edge of a city might be preferred as these locations might enable the flow into the city better then city centre locations enable the flow out of the city. To partially counter for this effect the crowd-hubs were assumed to be in the centre of their four digit postal codes when determining the service area. While in fact the locations are located more to the edge of a four digit postal code and therefore compensating for this effect.

By using the 2.5km and 5km cases, the crowd-delivery scenario is that packages are delivered to the edge of a residential area for an occasional driver to conclude the delivery. However, it might also be possible to have a parcel collected earlier in the route of an occasional driver. To analyse this scenario a third set of network connections, the highway connections case has been made. In this case, the highway-locations can be used to deliver destinations that are near the highway on which the crowd-hub is located. Based on how traffic to and from the nearest city might flow over the local highways the delivery area of a crowd-hub is assumed.

Finally, the fourth case of network connections combines the 2.5 km and the highway connection cases into the combination case. This case was made to compare the two scenarios and was used to identify the preferred type of location to use within the delivery network.

3.2.4 Costs

The use of the delivery network has different costs that need to be considered. To include the costs into the analysis, cost assumptions were made based on the existing cost expectations of Trunkrs. The professional delivery costs were obtained from a previously made break-even calculation, where delivery costs were specified per demand amount. For this research, the cost assumption with the most similar amount of parcels has been applied to a scenario. This might underestimate the professional delivery costs as using crowd-delivery will reduce the number of professionally delivered packages, reducing the efficiency of the professional delivery and increasing the costs per package. For the location costs, a cost per day was assumed based on a yearly cost assumption for the fixed costs plus the costs to connect the hub to the professional network.
3.3 Analysis

During the third phase, the analysis, the mathematical formulation has been implemented using Gurobi (version 7) for Java. Gurobi is a solver for Mixed Integer Problems, like the problem formulated in this research. In this implementation, the goal and the constraints are formulated for the analysis. To specify the parameters of the different cases an Excel file has been created. This excel file is read by java at the start of a run to define the parameter values for the optimisation. Next, the application uses Gurobi to solve the problem to optimality. Finally, the application generates a results file, which reports the following values:

- Objective value (total cost)
- Number of crowd-hubs used
- The crowd-hubs used and the connected destinations
- Number of packages assigned to a specific crowd-hub
- Total demand served professionally
- Destinations with professional connection with their demand

In this research, multiple scenarios were created, by changing the parameters in the input file. To analyse the effect of these parameter changes, the result files were used to calculate the following performance indicators:

- Total cost
- Number of crowd-hubs used
- Costs per parcel
- Percentage of parcels via a crowd-hub
- Average number of destinations per used crowd-hub

These performance indicators were used because they show the important effects of a parameter change. The total cost was only used to analyse effects within a demand scenario. In the comparison of cases with different demands, the cost per parcel is used to more clearly show the effects. The “average number of destinations per used crowd-hub” is used to analyse where a decrease in “percentage of parcels via a crowd-hub” might originate.

In addition to investigating the effects of parameter changes, the stability has been analysed. In this sensitivity analysis, the reported crowd-hubs and connected destinations were subjected to other demand scenarios. By applying these connections to the demand scenarios, the costs per parcel were calculated and compared to the optimal solutions. To calculate these costs per parcel, the demand has been multiplied by the cost of the assigned network connection. However, when the capacity of a hub has been exceeded the extra parcels were multiplied with the professional delivery costs.
4 Model
For the analysis, a MIP (mixed integer problem) has been formulated. This MIP is a variation on the hub location problem. This chapter describes the model by first discussing the goal, constraints, variables, and parameters and concludes with the mathematical formulation of the optimisation.

4.1 Goal
The optimal network design is the network where the total network costs are minimized because this maximizes the profits obtained. By transporting the maximum number of parcels for minimum costs, the network will be the most profitable. However, the demand cannot be influenced as all demand needs to be delivered, resulting in a minimization of the costs as the goal for this optimisation. The option to maximize the profit does not provide additional benefits but requires more input. For a maximisation of the profit, the income per delivery needs to be known but given that there is no option to select which packages to transport the problem will be equal to a minimization of the costs.

4.2 Constraints
The network design is bound by multiple constraints, to assure that the solution is useful. The first constraint is that all demand needs to be collected and delivered. Therefore, a connection needs to be made between the existing network and the demand locations (origins and destinations).

Second, the network design is restricted by a capacity for the crowd-hubs. The occasional drivers and crowd-hubs have a maximum number of parcels they are able to handle. This limit results from the limited space crowd-hubs have available for packages or the number of occasional drivers available. The crowd-hubs might have a limited space because they are placed in existing companies that do not want their existing business to be limited. The capacity of the occasional drivers is because they can only take a few parcels and only a few people might be willing to perform crowd-delivery.

Third, the occasional drivers might not accept all assigned packages. Therefore, the number of packages delivered by the crowd is limited to a maximum percentage of demand assigned to a crowd-hub. The remaining parcels are assigned as a professional repair. This constraint is included such that the effect of increasing the uncertainty in delivery can be analysed.

Finally, the network handles parcels which are unique units. The amounts within the network are, therefore, integer values. As the packages cannot be divided over multiple flows, and half packages cannot be ordered.

4.3 Variables
The network extension has multiple decisions to consider during the optimisation. These decisions are included in the variables of the model and can be divided into three groups: network connections, crowd-delivery and hub use.

4.3.1 Network connection
The main decision made by the optimisation is how demand locations (origins and destinations) are connected to the existing delivery network. The demand can either be connected directly via professional delivery or indirectly through a crowd-hub. This decision is visualized in Figure 4.1, where the variables used are shown. These variables are binary and set to 1 if a connection is used.
4.3.2 Crowd-delivery
In the case that demand is connected via a crowd-hub, a second decision needs to be made. In this case, the demand needs to be divided into accepted and non-accepted parcels. The costs of the accepted parcels will be lower, however, due to the acceptance rate constraint, some demand is assigned as non-accepted. The non-accepted parcels have the costs of a professional repair and are used to account for part of the network uncertainty. These variables are included as integer values as they represent the number of packages.

4.3.3 Hub use
The third decision in the optimization is the use of a crowd-hub. For a connection with a crowd-hub to be made the crowd-hub needs to be included in the network. In this way, the location costs can be accounted for. Therefore, the use of a hub has been included as a binary variable, which is set to 1 to represent a used crowd-hub. The use of a crowd-hub is also an important output of the optimisation, as these crowd-hubs might be interesting locations to implement in the delivery network.

4.4 Parameters
The optimisation is also influenced by a set of parameters, which define the values based on which the decisions are made. For this problem, there are four sets of parameters: demand, capacity, acceptance rate, and costs.

The demand is the integer number of parcels to collect at the origins or to deliver to the destinations and are used to define the number of parcels that flow through the network. The capacity parameters define how many parcels can be handled by the crowd-hubs and results from either the number of occasional drivers or the space at a crowd-hub. The acceptance rate is the percentage of parcels that are at most accepted by occasional drivers and is used to shift some of the parcels to the non-accepted variables. The cost parameters are used to account for the network costs. These costs consist of a cost per location for the crowd-hubs and a cost per parcel for professional delivery, crowd-delivery, and the professional repair for non-accepted parcels.
4.5 Mathematical formulation

The goal, constraints, variables, and parameters combined construct the mathematical problem that is used for the analysis. This model is shown and discussed in this section and uses the notation in Table 4-1.

Table 4-1 Model notation

<table>
<thead>
<tr>
<th>Letter</th>
<th>set/parameter/variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>set</td>
<td>Demand destinations</td>
</tr>
<tr>
<td>$K$</td>
<td>set</td>
<td>Demand origin locations</td>
</tr>
<tr>
<td>$H$</td>
<td>set</td>
<td>Possible crowd-hub locations</td>
</tr>
<tr>
<td>$G_k$</td>
<td>sub set of $H$</td>
<td>Possible crowd-hub locations for origin $k$</td>
</tr>
<tr>
<td>$H_j$</td>
<td>sub set of $H$</td>
<td>Possible crowd-hub locations for destination $j$</td>
</tr>
<tr>
<td>$d_k$</td>
<td>parameter</td>
<td>Packages to collect from origin $k$</td>
</tr>
<tr>
<td>$f_j$</td>
<td>parameter</td>
<td>Packages to be delivered to destination $j$</td>
</tr>
<tr>
<td>$q_i$</td>
<td>parameter</td>
<td>Capacity at hub $i$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>parameter</td>
<td>Acceptance rate for crowd-collection (percentage of packages that is at most accepted)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>parameter</td>
<td>Acceptance rate for crowd-delivery (percentage of packages that is at most accepted)</td>
</tr>
<tr>
<td>$p_k$</td>
<td>parameter</td>
<td>Cost of professional collection for origin $k$</td>
</tr>
<tr>
<td>$g_{ki}$</td>
<td>parameter</td>
<td>Cost crowd collection from origin $k$ via hub $i$</td>
</tr>
<tr>
<td>$n_{ki}$</td>
<td>parameter</td>
<td>Cost not collected package from origin $k$ via hub $i$</td>
</tr>
<tr>
<td>$o_j$</td>
<td>parameter</td>
<td>Cost professional delivery to destination $j$</td>
</tr>
<tr>
<td>$c_{ji}$</td>
<td>parameter</td>
<td>Cost crowd delivery to destination $j$ via hub $i$</td>
</tr>
<tr>
<td>$m_{ji}$</td>
<td>parameter</td>
<td>Cost not collected to destination $j$ via hub $i$</td>
</tr>
<tr>
<td>$e_i$</td>
<td>parameter</td>
<td>Cost of opening crowd-hub $i$</td>
</tr>
<tr>
<td>$y_k$</td>
<td>variable</td>
<td>The use of a professional collection connection for origin $k$</td>
</tr>
<tr>
<td>$x_{ki}$</td>
<td>variable</td>
<td>The use of crowd-hub $i$ for the collection from origin $k$</td>
</tr>
<tr>
<td>$z_j$</td>
<td>variable</td>
<td>The use of a professional delivery connection for destination $j$</td>
</tr>
<tr>
<td>$w_{ji}$</td>
<td>variable</td>
<td>The use of crowd-hub $i$ for the delivery of packages designated to destination $j$</td>
</tr>
<tr>
<td>$a_{ki}$</td>
<td>variable</td>
<td>The number of packages that are accepted by occasional drivers for crowd collection from origin $k$ via crowd-hub $i$.</td>
</tr>
<tr>
<td>$b_{ji}$</td>
<td>variable</td>
<td>The number of packages that are accepted by occasional drivers for crowd delivery from crowd-hub $i$ to destination $j$</td>
</tr>
<tr>
<td>$h_i$</td>
<td>variable</td>
<td>The use of crowd-hub $i$</td>
</tr>
<tr>
<td>$l_{ki}$</td>
<td>variable</td>
<td>The number of packages that are not accepted by occasional drivers for crowd collection and need a professional repair from origin $k$ via crowd-hub $i$.</td>
</tr>
<tr>
<td>$r_{ji}$</td>
<td>Variable</td>
<td>The number of packages that are not accepted by occasional drivers for crowd delivery and need a professional repair from crowd-hub $i$ to destination $j$</td>
</tr>
</tbody>
</table>
During the optimisation, the total costs are minimized, which leads to the following objective function.

\[
\min \sum_{k} y_k p_k + \sum_{k \in G_k} a_{ki} g_{ki} + \sum_{k \in H_k} l_{ki} h_{ki} + \sum_{j} z_j o_j f_j + \sum_{j \in H_j} b_{ji} c_{ji} + \sum_{i} r_{ji} m_{ji} + \sum_{i} h_i e_i
\]

The first three terms are the costs for the collection side of the problem, with first the cost of a professional connection, second the cost of crowd-collection and third the cost for professional repair. The fourth until sixth terms of the objective present the same three costs but for the delivery side. Finally, the seventh term is the location costs.

This optimization is subject to the following constraints:

\[
\sum_{i \in G_k} x_{ki} + y_k = 1 \quad \forall k \in K
\]

\[
\sum_{i \in H_j} w_{ji} + z_j = 1 \quad \forall j \in C
\]

These first constraints determine that a destination or origin needs to be connected to the network and that only one of these connections is made. Either a connection via crowd-hub or a direct professional connection is made. A connection via crowd-hub is selected from the set of possible crowd-hubs for that destination.

\[
a_{ki} + l_{ki} = d_k x_{ki} \quad \forall i \in G_k \forall k \in K
\]

\[
b_{ji} + r_{ji} = d_j w_{ji} \quad \forall i \in H_j \forall j \in C
\]

These second constraints are in place for when a crowd-hub is used. When a crowd-hub is used, all demand is either assigned as accepted or as non-accepted. Assuring that all packages via a crowd-hub connection will be assigned their respective costs. For the professional connection, no additional constraint is required as all packages will have the professional cost.

\[
\sum_{k \in K} a_{ki} \leq \alpha \sum_{k \in K} x_{ki} d_k \quad \forall i \in H
\]

\[
\sum_{j \in C} b_{ji} \leq \beta \sum_{j \in C} w_{ji} f_j \quad \forall i \in H
\]

To account for the uncertainty, not all packages via a crowd-hub can be assigned to occasional drivers. This is limited by the acceptance rate. To assign the correct number of parcels as non-accepted these constraints limit the number of packages assigned to crowd-delivery with the acceptance rate.
\[
\sum_{k \in K} a_{ki} + \sum_{k \in K} l_{ki} \leq q_i h_i \quad \forall i \in H
\]
\[
\sum_{j \in C} b_{ji} + \sum_{j \in C} r_{ji} \leq q_i h_i \quad \forall i \in H
\]

The crowd-hubs are bound in the number of packages they can handle. Therefore, these capacity constraints are added, which state that the number of packages transported via the crowd-hub needs to be less than the capacity. Further, in combination with the second set of constraints, it is assured that a crowd-hub is set to active when a crowd-hub connection is used.

Finally, the variables are bound as follows:

\[
x_{ki}, w_{ji}, y_k, z_j, h_i = \{0,1\} \\
a_{ki}, b_{ji}, n_{ki}, n_{ji} = \{0,1,2,\ldots\}
\]

5 Data

In the analysis, multiple scenarios were analysed and a wide set of data was used. The methodology part of this thesis discusses the data collection, which was performed. This chapter provides the result of this data collection and should give an overview of the analysed case.

5.1 Locations

The network design requires three sets of locations as input into the analysis: the origins, destinations, and possible crowd-hubs. The destinations used for this research are the 4,035 four-digit postal codes within the Netherlands. For the origins, the location of the five existing customers has been used, which have not been varied during the analysis as future developments on this side of the problem were relatively unsure.

The possible crowd-hub locations included in the analysis were divided into multiple cases, as described in the methodology chapter. The selection of these locations resulted in the number of locations as shown in Table 5-1, which also shows the total number of locations found.

Table 5-1 Amount of locations

<table>
<thead>
<tr>
<th></th>
<th>Unsorted All Locations</th>
<th>Selected city-locations</th>
<th>Selected Highway-locations</th>
<th>Combination case</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td>334</td>
<td>169</td>
<td>39</td>
<td>209</td>
</tr>
<tr>
<td>Shell</td>
<td>499</td>
<td>316</td>
<td>71</td>
<td>387</td>
</tr>
<tr>
<td>Texaco</td>
<td>420</td>
<td>198</td>
<td>9</td>
<td>207</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>288</strong></td>
<td><strong>173</strong></td>
<td><strong>42</strong></td>
<td><strong>215</strong></td>
</tr>
<tr>
<td>Gas stations</td>
<td>1,541</td>
<td>856</td>
<td>161</td>
<td>1,018</td>
</tr>
<tr>
<td>Albert Heijn</td>
<td>658</td>
<td>511</td>
<td></td>
<td>511</td>
</tr>
<tr>
<td>JUMBO</td>
<td>298</td>
<td>287</td>
<td></td>
<td>287</td>
</tr>
<tr>
<td>Supermarkets</td>
<td>956</td>
<td>798</td>
<td></td>
<td>798</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2,497</strong></td>
<td><strong>1,654</strong></td>
<td><strong>161</strong></td>
<td><strong>1,816</strong></td>
</tr>
</tbody>
</table>
5.2 Demand

In the analysis, a selection of demand scenarios was applied. These scenarios were constructed by multiplying the market shares with different amounts of parcels. Because the demands needed to be rounded for the analysis, the number of parcels used for the analysis is lower than the multiplier. Table 5-2 shows the demand scenarios that have been used. These scenarios range from 500 parcels to 15,000 parcels, which should include current situations and long term growth effects. Most of the analysis has been done with the 1,500, 3,000, 6,000 cases. These amounts have been chosen to represent the current situation, the short term growth, and the long term growth.

Table 5-2 Number of parcels in analysed cases

<table>
<thead>
<tr>
<th>Input</th>
<th>Customer</th>
<th>Current</th>
<th>Population</th>
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</thead>
<tbody>
<tr>
<td>500</td>
<td>79</td>
<td>390</td>
<td>31</td>
</tr>
<tr>
<td>1000</td>
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<tr>
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<tr>
<td>1350</td>
<td>1086</td>
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</tr>
<tr>
<td>1400</td>
<td>1142</td>
<td>1286</td>
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<td>1563</td>
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<td>1551</td>
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<tr>
<td>15000</td>
<td>14940</td>
<td>14839</td>
<td>14891</td>
</tr>
</tbody>
</table>
density is not equal over the Netherlands, the professional delivery costs will be different for specific areas. Therefore, the delivery destinations have been divided in the Randstad area and rest of the Netherlands. The Randstad area is the highest populated area in the Netherlands and includes Amsterdam, The Hague, Rotterdam, and Utrecht. For this research, also the more rural areas between these cities have been included as the Randstad area. In the cost estimation, a difference between the Randstad and the rest of the Netherlands has been assumed as most parcels will be delivered within the Randstad. The estimated costs are shown in Table 5-3 which shows the estimated costs for different demand scenarios.

6 Results
Analysing the network extension generated a broad set of results, as multiple scenarios were analysed. The following sections discuss these results per parameter, by showing the effects on costs, the number of crowd-hubs used, and the percentage of parcels delivered by the crowd. After discussing the effects of different parameter changes this chapter also discusses a possible starting location and the calculation time.

6.1 Network connections
The network design model considers a restriction in possible network connections, by having a set of possible crowd-hubs per destination. This set of possible crowd-hubs has an influence on the feasibility of crowd-delivery. Figure 6.1 shows that increasing the possible network connections will reduce the total network costs. When a hub has a bigger service area (can be used by more destinations), more packages can be assigned to this hub increasing the feasibility. This figure also shows that the costs do not decrease for the case with 5,838 parcels, which is explained in the section on demand (6.2) and cost-difference (6.5).

Table 5-3 cost estimates professional cost

<table>
<thead>
<tr>
<th>Parcels</th>
<th>Randstad</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>€4,11</td>
<td>€8,33</td>
</tr>
<tr>
<td>2000</td>
<td>€3,80</td>
<td>€7,26</td>
</tr>
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<td>2500</td>
<td>€3,45</td>
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<td>€5,77</td>
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<td>€3,48</td>
<td>€5,-</td>
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<td>4000</td>
<td>€3,45</td>
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</tr>
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</tr>
<tr>
<td>15000</td>
<td>€3,13</td>
<td>€3,36</td>
</tr>
</tbody>
</table>

Figure 6.1 Total costs for network connections
The most savings, compared to professional delivery, are obtained in the combined case, which shows a potential for local (2.5km case) and highway (highway case) locations. If the locations can service a bigger area the savings of crowd-delivery will be higher because more locations reach their feasible demand level or fewer locations are required. Figure 6.2 shows the number of hub locations that are used within the solution, which shows that the number of locations used is increasing when the 5KM case is used but decreases for the highway cases. The increase in locations for the 5km case is the result of more locations being feasible because the number of connections per crowd-hub is also increasing, as shown in Figure 6.3. The increase in locations for the 5.838 parcels case shows an increasing number of locations being feasible, which is why only the combination case showed some savings.

Figure 6.2 Crowd-hubs used network connections

Figure 6.3 Destinations per used hub

The combination case, where the 2.5KM and highway case are combined, showed an increase in locations used and savings made compared to the original cases. The savings of the combination case are the most similar with the highway case, indicating that the highway-locations provide the most savings. However, the city-locations do provide some savings. Figure 6.4 shows that in the combination case some city-locations replace the highway-locations, as fewer highway-locations are used. The replacement of highway-locations by city-locations is probably caused by the capacity constraint. The city-locations are able the handle the spare capacity of multiple crowd-hubs because they deliver in a range around the hub reaching deeper into the city than Highway-locations, who can only reach one side of a city.

Figure 6.4 crowd-hubs used by location type
Figure 6.4 shows that the highway-locations are the preferred location type. This preference is logical because they only differ in the possible network connections. Therefore, these locations have a clear benefit over the city-locations. To investigate the extent of this preference, Figure 6.5 shows the effect of increasing the location cost for highway-locations on the number of crowd-hubs used, which shows that the cost increase mainly results in a decrease in locations. Only a part of the decrease in highway-locations is replaced by city-locations, which shows that highway-locations have a clear benefit over the city-locations. This benefit even exists when the highway-locations are 3 times as expensive as city-locations.

The benefit of highway-locations over city-locations is also visualized by Figure 6.6, which shows the effects on the total costs. Although the location costs for highway costs increase significantly, the total network costs remain to be lower than the 2.5KM case. Proving that the highway-locations still provide substantial savings.
The highway-locations with the highest savings are located in the more rural areas of the Netherlands, as is shown in Figure 6.7. This figure shows the locations used plotted to a map, which shows that city-locations (red dots) are used mostly within the Randstad. However, the highway-locations (green dots) are continued to be used in the rest of the Netherlands.

Further, Figure 6.7 clearly shows the decrease in locations, which results in a more concentrated spread of locations. An effect that is also shown in Figure 6.8, which shows the decreasing percentage of crowd-delivery resulting from the increase in location costs for highway-locations. These effects of increasing the location costs for highway-locations show that in the 2.813 parcel case the highway-locations are preferred because the profitability is significantly higher.
In addition to highway-locations having a higher location cost, the city-locations might have a lower crowd-delivery cost. The crowd-delivery costs might be lower because the shorter delivery distances might require a lower compensation for occasional drivers to accept a parcel. This affects the network design and slightly reduce the total costs, as can be seen in Figure 6.9.

The total costs are only slightly decreasing because shifting to a city-location will require multiple city-hubs to perform the same deliveries, which is shown in Figure 6.10. As crowd-delivery costs are decreasing in city-locations, an increasing number city-locations are used. This increase in city-locations is bigger as the decrease in highway-locations because more city-locations are needed to perform the same amount of deliveries. That the increase in locations originates from the shift in location type can be seen in Figure 6.11, because this percentage only increases slightly as it was already high.
This shift in locations mainly occurs in the highly populated areas, such as the Randstad. Figure 6.12 shows that the new city-locations are mostly appearing in the urban areas, whereas the more rural areas remain unchanged. This proves that the city-locations could be interesting additions to the network in urban areas when they reduce the crowd-delivery costs.

Figure 6.12 Location spread changes after reducing crowd delivery cost from €3,- to €2,50 for city-locations

In conclusion, the possible network connections have an important influence on the network design. An increased service area reduces the total costs and increases the profitability of a crowd-hub. Even when the increased service area has higher crowd-delivery costs or location costs the savings of an increased service area could be substantial.

6.2 Demand

The network design is, also, influenced by the number of parcels that flow through the network on a daily basis. Figure 6.13 shows that only increasing the demand reduces the costs per parcel but eventually the costs per parcel will stabilize. The reduction in costs results from an increasing number of crowd-hubs reaching a feasible demand level, which increases the percentage of crowd-delivery. When these hubs reach their capacity additional crowd-hubs are added to the network, which has location costs, resulting in stabilization of the cost per parcel. This effect is also shown in Figure 6.14, where the percentage of packages via the crowd is shown. This shows that eventually the percentage of packages via a crowd-hub is stabilizing or decreasing, resulting in a stabilization of the costs. The decrease in crowd-delivery occurs because crowd-hubs are at capacity and no other possible crowd-hubs are near.

Figure 6.13 Total cost per package with increasing demand (no economies of scale)  
Figure 6.14 percentage of demand via crowd-hub with increasing demand (no economies of scale)
The effect of a demand increase on the network design is most clearly visible in the number of crowd-hubs used. When the demand is increasing the number of crowd-hubs required also increases. The increase in locations is relatively stable as shown in Figure 6.15. This growth in locations used is because an increasing number of locations is required to perform the delivery and more crowd-hubs reach a feasible demand level.

![Number of hubs for increasing demand (equal costs)](image)

Figure 6.15 also shows that the number of locations in the current demand cases is stabilizing. This is the result from a more concentrated demand scenario. In the current demand scenarios almost all demand is located in Amsterdam, therefore fewer locations can be used in these scenarios. The percentage of parcels by crowd-delivery is, also, decreasing for these scenarios because the locations that are in range of demand are filled to capacity and no more feasible locations can be found.

The lower number of locations in the current demand scenarios shows that the demand location also influences the network design. This can also be seen in Figure 6.16, which shows the locations of different demand scenarios plotted to a map. This figure shows that the used crowd-hubs are located near the destinations with a higher demand, as most of the locations are located in and around the cities or on main corridors. Further, the focus of locations around Amsterdam in the current case is clearly shown. In addition, Figure 6.16 shows some more rural locations for the population case, where the customer case has a few more city-locations.
The demand scenarios discussed above have assumed that the professional delivery does not obtain economies of scale, to show the effect of only an increase in demand. However, an increase in demand provides economies of scale. Therefore, the effects of an increase in demand should include the change in professional delivery costs. When the economies of scale are applied in the analysis, an interesting effect can be seen. When demand increases, the cost of professional delivery (existing network) becomes equal to the costs of crowd-delivery (extended network). This shows that including crowd-delivery might not be feasible when demand continues to increase, which is also the reason why Figure 6.1 showed little to no savings for the biggest case.

![Figure 6.16 Location spread for the different demand deviations with 1800 parcels (from left to right: customer, current, population)](image1)

![Figure 6.17 cost per parcel with increasing demand (with economies of scale)](image2)
The infeasibility of crowd-delivery in these bigger cases can also be seen in Figure 6.18, where the number of crowd-hubs used are shown. With the increase of demand, the number of locations used starts to drop around 4300 parcels. At this point, the cost difference between crowd-delivery and delivery within the Randstad is €0.40. This means that 37 parcels are needed for a crowd-hub with location costs €15,- and a capacity of 30 to be feasible, which is not possible. As a result, the number of locations drops. The slight increase after this drop is because in rest of the Netherlands there are still some feasible hubs due to higher professional delivery costs. This idea is further discussed in section 6.5.

For crowd-delivery to be feasible and crowd-delivery to be used the crowd-delivery costs might have to decrease as well. This effect is shown in Figure 6.19 and Figure 6.20, which show that the lower crowd-delivery cases remain to have a lower cost per parcel than professional delivery. As a result, having crowd-delivery cost of €2,50 will result in a difference in total cost of around €0,20 per parcel for the high demand cases.
Figure 6.19 shows an increase in cost for the crowd-delivery cases with high demand, which results from having an insufficient number of possible crowd-hubs. In these cases, the crowd-hubs within the analysis can no longer provide the required capacity to perform crowd-delivery. As a result, the percentage of packages in Figure 6.21 is decreasing for all cases. In the case of Figure 6.22, a sufficient number of locations is available and this shows the crowd delivery percentage increasing for the cheaper cases. In the €3,- case crowd-delivery proves to be infeasible as the use of crowd-delivery decreases.

That the decrease in crowd-delivery results from having an insufficient number of crowd-hubs can be seen in Figure 6.23, which shows that the number of crowd-hubs is stabilizing for the larger cases. However, in the 2.5KM case of Figure 6.24, a clear continuation of the growth in locations required is shown. This shows that when crowd-delivery is feasible the locations required will grow with the demand.

In conclusion, increasing the demand influence the network design as more locations are required and the costs per parcel decrease. The cost will, however, stabilize and a minimum cost per parcel exists. An increase in demand also provides economies of scale for professional delivery, which might result in an infeasible situation for crowd-delivery. When professional costs continue to decrease the cost difference with crowd-delivery will decrease making it harder to counter the location costs. Therefore, it might be important to decrease the crowd-delivery costs as well, to assure that crowd-delivery is a profitable option.
6.3 Sensitivity

The crowd-delivery network will have to perform deliveries for multiple online stores, which means that the demand will fluctuate on a daily basis. Therefore, the network should be able to handle fluctuations and small changes in demand. Figure 6.25 shows that the optimal solution changes when 100 parcels are added to the network. This shows that the network design might not be stable. However, to analyse the network stability it is important to analyse how a solution might perform under different demand scenarios.

![Figure 6.25 number of crowd-hubs with small demand changes](image)

To analyse the stability of a solution Figure 6.26 and Figure 6.27 were created. In these analyses, the solution for the customer case (1,253 parcels and 3,784 parcels) was taken and applied to the other the demand scenarios in the graph. This application of other demand scenarios was then compared to the optimal solution for that demand scenario which created the figures below. These figures show that a different demand deviation increases the costs significantly in the low demand case making crowd-delivery far more expensive than the optimal solution. In the case with higher demand, this difference has decreased to an acceptable level. Further, the difference with optimal increases when more parcels enter the network as the optimized case. This effect results from the capacity constraints because almost all extra demand needs to be transported professionally.

![Figure 6.26 network stability for 1253 parcels](image)  ![Figure 6.27 Network stability for 3784 parcels](image)

These figures show that the demand deviation has an important influence on the total costs of a crowd-delivery network. In the case of “low” demand, the effect of a different demand deviation will have a huge effect on the cost per parcel. Therefore, it might be important to place crowd-hubs only in places where demand is guaranteed. Further, resulting from the increase in costs for higher demand it could be wise to have some spare capacity in the crowd-hubs.
6.4 Cost
The demand section showed that the costs have a significant influence on the network design and the feasibility of crowd-hubs. In this section, the effects of costs changes are discussed more detailed. The crowd-delivery costs, for example, have a major influence on the feasibility of crowd-hubs. Figure 6.28 shows that increasing the crowd-delivery costs reduces the number of crowd-hubs used. For the 5.800 parcels case, the increase in costs shows that crowd-delivery becomes infeasible. For the 2.800 parcels case, this same effect is shown but the decrease in crowd-hubs is slower because of the higher professional delivery costs.

![Figure 6.28 Number of Hubs used for crowd-delivery costs](image)

As a result of the decreasing number of crowd-hubs, the use of crowd-delivery drops in a similar rate because the profitability of crowd-delivery decreases. Figure 6.29 shows this decrease in crowd-delivery. In addition, this figure shows that the decreasing the crowd-delivery costs from €2,50 to €2,- has little effect on the use of crowd-delivery. Therefore, crowd-delivery costs need to be lowered to reach feasibility but for the use of crowd-delivery, it might also be beneficial to have a slightly higher compensation as it might influence the acceptance rate.

![Figure 6.29 percentage of demand via crowd-hubs under increasing crowd-delivery costs](image)
Figure 6.28 and Figure 6.29 show the effects for crowd-delivery costs changes at all destinations. However, there might be a cost difference between destinations. The crowd-delivery costs in the more rural areas might be more expensive as the traffic intensity is lower resulting in the requirement of a bigger compensation for crowd-delivery. Figure 6.30 shows how the network design is influenced by this idea. In this figure either the crowd-delivery costs are decreased for the urban areas or increased for the rural areas. This shows that similar effects occur to the number of crowd-hubs but these effects are limited.

The changes in crowd-delivery cost also influences the network cost, which is shown in Figure 6.31. This figure shows that varying the crowd-delivery costs only in certain areas has a less drastic effect on the cost than when all the costs change. For example, reducing the costs in urban areas will result in a decrease in cost that is far smaller than changing all the crowd-delivery costs. The most interesting effect is the difference between the non-Randstad and rural case. This difference originates from the cities outside the Randstad, where the costs do not increase in the rural case resulting in significant savings for crowd-delivery.
The location costs have a significant influence on the profitability of crowd-hubs, as shown by Figure 6.32. With increasing the location costs the profitability of crowd-delivery is decreasing. In the case of 5,800 parcels, the number of crowd-hubs drops because the cost difference between crowd and professional delivery is relatively small. This same reason results in the infeasible situation for the higher location costs in the 5,800 parcels case. For the 2,800 parcels case, the decline in locations is more stable but it shows that the feasibility of crowd-hubs is significantly influenced by the location costs.

![Image](Figure 6.32 Number of hubs used with increasing location costs)

In conclusion, the crowd-delivery costs and the location costs have an important influence on the network design and the profitability of crowd-hubs. An increase in costs reduces the profitability of crowd-hubs and reduce the number of crowd-hubs used within the solution. In the cases with a higher demand and lower professional deliver costs the influence of the location costs and crowd-delivery costs will be higher.

### 6.5 Cost-difference (crowd/professional delivery)

The previous sections show that for higher demand cases the use of crowd-delivery could be infeasible. The decrease in crowd-delivery results from economies of scale for professional delivery, which reduces the difference between professional and crowd-delivery costs. For this reason, Figure 6.23 and Figure 6.24 show a decrease in the number of crowd-hubs within the €3,- case, whereas the number of crowd-hubs in increasing for the €2,- and €2,50 case. Building on this idea, Figure 6.33 and Figure 6.34 were created to show the effect of this cost difference. These figures show that for crowd-delivery to be interesting a sufficient cost difference between crowd and professional delivery needs to exists.

In Figure 6.33 and Figure 6.34 it shows that a cost difference of €0,75 needs to exist to have most of the parcels to be delivered by occasional drivers. This cost difference results in a crowd-delivery cost of around €2,50 per parcel. With an increase of this cost difference the percentage of crowd-delivery increases as well, as more crowd-hub will obtain sufficient savings for a crowd-hub to be feasible.
Figure 6.34 shows an far smaller percentage of crowd-delivery because it only has a limited number of possible network connections. This shows that the having a sufficient service area for a crowd-hub is of significant importance to the usability of crowd-delivery. As a result of the smaller service area, the bigger cost difference is required to obtain similar levels of crowd-delivery. A sufficiently big service area will be important for crowd-hubs to be feasible, but for the more densely populated areas the use of a smaller service area could be profitable (see section 6.1).

Figure 6.33 and Figure 6.34, also show, that increasing the demand will increase the percentage of packages via crowd-hubs. Due to this effect a smaller cost difference can be used when demand is increasing, as similar percentages of crowd-delivery can be reached. When more packages flow through the network the percentage of parcels via the crowd will increase for similar levels of cost difference. This effect, however, becomes smaller as demand is increasing, since the distance between the lines is decreasing.

To summarize, a significant cost difference is required for the crowd-delivery to be a feasible option. With a cost difference of €0.75 the use of crowd-delivery will rise rapidly as the first crowd-hubs reach a feasible demand level. Second an increase in demand will increase the percentage of crowd-delivery, so a smaller cost difference could be used when demand increases.

6.6 Capacity

In the demand section of this chapter, it was briefly mentioned that the feasibility of a crowd-hub can be influenced by the capacity. As the cost difference between professional and crowd-delivery became too small to offset the location costs within the crowd-hub capacity. This same effect is shown in Figure 6.35, which shows the effect of increasing the capacity on the number of crowd-hubs. An decrease in capacity should reduce the number of crowd-hubs because the increased capacity allows the crowd-hubs to handle more packages. Therefore, the same number of parcels can be handled by less locations. However, Figure 6.35 also shows that the number of crowd-hubs can be increasing. This is the result of the cost difference between professional and crowd-delivery. When this cost difference is becoming smaller more parcels are needed for a crowd-hub to be feasible but when the capacity is to low not enough parcels can be handled by a crowd-hub to be feasible. However, when the capacity increases a feasible level of parcels can be reached, resulting in a rapid increase in locations used. This are the spikes in Figure 6.35, which occur due to the cost difference between Randstad and Other destinations. As a result of this cost difference in the professional costs it can occur that only part of the destinations are feasible for crowd-delivery. This is also the reason why two spikes are shown for the 5.800 parcel case, as there the increase in crowd-hubs first comes from the Non-Randstad destinations and second from the Randstad area.
Increasing the capacity also influences the total costs of the delivery network as can be seen in Figure 6.36. With an increase in capacity, the total costs decrease as fewer locations are needed or more parcels can be delivered by occasional drivers. This figure, also, shows that the influence of the capacity on the total costs is relatively limited, because the location costs are a relatively small part of the total network costs. The effect on the total cost does seem to be bigger for the 5,800 parcels case, which can be explained by the increase in crowd-delivery when the capacity is increasing.

6.7 Parcel acceptance

With the inclusion of crowd-delivery the uncertainty increases, because the acceptance of assigned parcels by occasional drivers is unknown. As a result, professional drivers will have to perform deliveries that were originally assigned to occasional drivers. To account for some of this uncertainty, an acceptance rate of parcels was applied to the network design, which should account for the extra cost of having this professional repair. A decrease in acceptance rate, therefore, affects the total costs, which is shown in Figure 6.37. This figure shows the acceptance of parcels significantly influences the total costs and feasibility of crowd-hubs. Figure 6.38 shows that the number of crowd-hubs used will decrease with the lower acceptance rate. Therefore, it might be important to find ways to increase the acceptance of parcels and prevent the need for professional repairs.
6.8 Starting locations

It might not be a wise thing to implement a crowd-delivery network throughout the Netherlands in one go. Instead, it is better to have a starting point and extend from there. To identify the best place for Trunkrs to start building its crowd-delivery network Figure 6.39 and Figure 6.40 were created. These figures show the locations that might be most interesting to start with. Figure 6.39 shows the most profitable locations within the current demand situation. With an increase in location costs to €60, these locations were still profitable, which might make them interesting as starting locations since the first investments might be the highest. These locations are mostly located on the border of the Randstad area and are able to serve the cities and the rural areas around. As a result, they benefit from the high demand in cities but also service the areas with more significant savings.

![Figure 6.39](image1.png)

![Figure 6.40](image2.png)

For a starting location, it is also important that there is sufficient demand to perform crowd-delivery. Figure 6.40 shows where locations will be used when demand is very low, which shows that to guarantee sufficient demand for the crowd-hubs the locations near Amsterdam are the most interesting. Therefore, the starting location for the crowd-delivery network should be a location near Amsterdam that could be used to deliver the city and the more rural areas around Amsterdam because this will probably be the most profitable location.
6.9 Calculation time

During the analysis, the calculation time proved to be a limiting factor of using the optimisation as performed in this research. When demand or possible network connections increase, the calculation time would increase as well. Figure 6.41 shows the effect of an increasing demand on the calculation time, which shows that the calculation time could increase rapidly. When both the possible network connections and the demand increases, the effects on the calculation time enhance each other. The problems with a long runtime obtained a close to optimal solution within the first steps of the optimisation but improving on this solution required a substantial part of the calculation time. An example of this is the case with 2800 parcels and the 5KM case of network connections. This problem had an out-of-memory error after 42 hours. At this point, the best objective found had a gap of 0.01% with the best bound. However, this best objective had not changed since the first 10 minutes of the optimisation when the gap was 0.05%. This shows that for larger instances the methodology used could benefit from a time limit. Another option to counter the increase in calculation time is dividing the problem into sub-problems, where only part of the Netherlands is considered in an optimisation. This could improve the calculation time without significantly influencing the solution because the use of a crowd-hub is only locally influenced by other hub locations.

![Figure 6.41 calculation time in seconds](image)
7 Conclusions

The network design is influenced by multiple variables as is shown in the results chapter. In this chapter, first, some general conclusions are discussed. Second, an answer to the research questions is formulated.

7.1 General conclusions

The results chapter discusses a broad set of results and graphs, which show the effects of different parameters. However, for some additional insight on the effects and the implications for the network design some general conclusions are discussed below. These are conclusions on crowd-delivery costs, network connections, location specifications, and network stability.

7.1.1 Crowd-delivery costs

The profitability of crowd-hubs within the delivery network is highly depended on the crowd-delivery costs. With an increase in demand, the professional delivery costs and its costs difference with crowd-delivery will decrease. This affects the feasibility of crowd-hubs when crowd-delivery costs do not change. Crowd-hubs are not profitable when the cost savings of crowd-delivery cannot offset the location costs. Therefore, it might be important for Trunkrs to reduce the crowd-delivery costs when the transport demand increases.

A reduction in crowd-delivery costs might be possible by reducing the compensation paid to occasional drivers. However, this might influence the parcel acceptance, which will increase the costs per parcel. Therefore, a trade-off in compensation paid exists. A more sustainable reduction in crowd-delivery costs can be obtained when the crowd-delivery costs are reduced without influencing the parcel acceptance. Therefore, the efficiency of crowd-delivery might require some improvements. For example by increasing the number of parcels per occasional driver or improving the assignment of parcels. With an optimal assignment of parcels, the total detour of occasional drivers can be limited, which might reduce the crowd-delivery costs.

The cost reductions for crowd-delivery are crucial when the professional costs are decreasing but the professional delivery costs will not be equal for all destinations. Therefore, the focus of reducing crowd-delivery should be in areas where professional delivery is efficient. For example, the urban areas that are easily accessible and have relatively high demand rates. Areas, where the professional delivery costs are higher (for example rural areas) are more profitable for crowd-delivery and allow for a higher crowd-delivery cost.

Within this research, only a cost difference between the Randstad area and the rest of the Netherlands was assumed. However, delivery within (historic) city centres might also have a higher professional delivery cost. Therefore, by obtaining more insight into the professional delivery costs per destination the savings potential and maximum crowd-delivery costs for a profitable crowd-hub can be found. This will increase the efficiency of the delivery network because it helps to identify interesting areas for crowd-delivery.

To summarize, the crowd-delivery costs and its cost difference with professional delivery is crucial for the profitability of crowd-hubs. Therefore, it is important to assure that a sufficient cost difference exists (around €0,75). As a result, it will probably be important to reduce the crowd-delivery costs, without reducing parcel acceptance. Second, with a detailed insight into the professional delivery cost, the interesting areas for crowd-delivery can be identified and this will show where a higher crowd-delivery cost is justified.
7.1.2 Network connections
The delivery network can profit from increasing the delivery range of crowd-hubs. As the possible network connections in the network increase, the network costs will decrease because either the use of crowd-delivery increases or fewer locations are required. Therefore, the service area of crowd-hub should be maximized. This can possibly be done by improving the information on occasional drivers. With detailed information on the planned route of occasional drivers, the collection of parcels can be moved to the beginning of their route, which improves the delivery range of crowd-hubs. This is especially important for rural areas because the delivery distances are bigger in these areas. For this reason, the analysis showed that city-locations are not feasible within the rural areas. However, significant savings can be obtained within these areas as professional delivery costs will be higher. Therefore, it might also be interesting to improve the service area with a slightly higher crowd-delivery compensation.

7.1.3 Locations
The feasibility of crowd-hubs is also influenced by the location costs and the capacity of crowd-hubs. When the cost difference between professional and crowd-delivery decreases the influence of these parameters will increase. The location costs need to be offset within the capacity for a crowd-hub to be feasible. Therefore, increasing capacity and decreasing location costs improves the profitability of crowd-hubs. An increase in capacity can possibly be obtained by improving the agreements with the existing businesses but this might increase the location or crowd-delivery costs. As a result, the increased capacity might not have the desired effect. The location costs might decrease as the number of locations increase because recruitment costs per location might drop and the connection to the existing network might be more efficient. This possible decrease in location costs might, however, be crucial for crowd-hubs to be feasible when professional delivery costs decrease.

7.1.4 Network stability
The usability of a crowd-delivery network depends on how stable the network design is. As delivery is performed for online stores, the demand will fluctuate in destination and amount. However, the network is designed on a strategic level and has to cope with these fluctuations, which will increase costs as the network design cannot be optimal for all cases. To assess the usability of the network design the network stability was analysed. This showed that the network stabilizes when demand increases and that a shift in demand distribution can highly influence the network costs. Therefore, it might be important to analyse the demand distribution and only use crowd-delivery in areas where a daily demand is guaranteed. In addition, it is wise to have some additional capacity over the analysed case. This improves the stability of the network as fluctuations in demand can be handled more efficiently. The spare capacity is needed because on days of high demand the network will otherwise require professional delivery for the extra parcels which will more rapidly increase the network costs.

7.2 Research questions
To draw a conclusion for this research the research questions need to be answered. Therefore, the following sections provide an answer to the sub-questions and main research question. This is done per sub-question. After which these answers an answer the main research question is formulated.

7.2.1 Model (goal, variables, and constraints)
The first sub-question of this research is how the network design model should be constructed. This model has been discussed in detail in Chapter 4. Therefore, this section only gives an overview of the model used. To do so, this section discusses the goal, constraints, and variables in the model.
The network extension with crowd-delivery can be modelled as a variation of the hub location problem, with the goal to minimize the total network costs. The goal should be to minimize the total costs because the network should be designed to obtain a maximum profit. The network should, therefore, only include crowd-delivery hubs that are profitable. Furthermore, a maximization of the profit does not provide additional insight because a constraint exists for all demand to be delivered. As a result, the network design model should aim to minimize the total network costs, which consist of the location costs, professional costs, and crowd-delivery costs.

This optimization of the network design is restricted by the requirement for all demand to be delivered, a crowd-hub capacity, and a parcel acceptance rate. All demand needs to be delivered by the network because the network is designed to perform a crowd-delivery service for online stores, who demand their packages to be delivered. The crowd-hubs are capacitated because they have a limited storage space and only a few people might be willing to perform crowd-delivery. Finally, an acceptance rate is in place because some parcels assigned to a crowd-hub might not be delivered by the occasional drivers. This would require a professional repair with a higher delivery cost.

Within the network design, multiple choices need to be made, which are considered as variables within the optimization. The main decision within the network design is how a destination is connected to the existing delivery network. This is either done directly by professional delivery or via one of the possible crowd-hubs. For the demand assigned to a crowd-hub, a decision needs to be made on how many parcels are delivered by occasional drivers and how many use the professional repair flow. This decision has been included to assign the correct costs and to analyse the additional uncertainty within the network. The final decision variables included is which possible crowd-hubs are included in the delivery network. These variables are included to account for the location costs and represent the crowd-hubs that could be interesting additions to the delivery network.

7.2.2 Location
The second sub question asked where the crowd-hubs should be located within the delivery network. This question was in place to identify where crowd-hubs should be implemented in the network. The analysis showed that crowd-hubs can be used throughout the Netherlands and are not limited to a certain area. For a crowd-hub to be used it is important that sufficient demand is located within the range of the crowd-hub. Therefore, crowd-hubs should be located near the demand destinations and in such a way that the delivery range is maximized. An example of this are the locations in the more rural areas. The rural destinations have a significant savings potential as the professional costs are higher in these areas but to be profitable the delivery range of these locations should be larger. Therefore, highway-locations were more interesting within these areas. This delivery range will be most important when demand is still relatively low. When the demand is higher the delivery range may become smaller because more hubs will be feasible and the demand density will have increased.

In the current situation of Trunkrs, no crowd-delivery has been implemented into the delivery network. Therefore, it is important to identify the most profitable crowd-hub, which could function as a starting point for the implementation of crowd-delivery. This location should be located in a place where sufficient demand is located and substantial savings can be made. For Trunkrs this is a location on the edge of Amsterdam, which can deliver in and around Amsterdam.
7.2.3 Profitable
For crowd-delivery to be an interesting addition to the delivery network, the crowd-hubs included should be profitable and reduce the total network costs. Therefore, the third sub-question on when crowd-hubs are profitable was included within the research. For a crowd-hub to be profitable the demand should be sufficient, the crowd-delivery costs should be low enough, capacity sufficient, and location costs low enough.

The most important parameter for a crowd-hub to be efficient are the crowd-delivery costs. When demand increases the savings per parcel by crowd-delivery are lower, which affects the profitability of crowd-hubs. Therefore, with an increase in demand, the crowd-delivery costs should be reduced to have profitable crowd-hubs.

Second, the profitability of crowd-hubs is influenced by the demand within the range of a crowd-hub. A sufficient amount of daily demand needs to be handled at the crowd-hubs to offset the location costs. For example, in the more rural areas, the savings per parcel are bigger but a larger delivery range is needed for crowd-hubs to be profitable.

Third, the crowd-hub capacity can limit the profitability of crowd-hubs because the savings per parcel via crowd-delivery might not be high enough to offset the location costs within the crowd-hub capacity. Therefore, a sufficient capacity is needed for a crowd-hub to be profitable.

Fourth, the location costs influence the profitability of a crowd-hub because when a higher investment needs to be made more parcels by crowd-delivery are required for a crowd-hub to be profitable. Therefore, with a decrease in location costs the profitability of a crowd-hub will increase.

7.2.4 Demand
The crowd-delivery network will be designed to handle the transport demand and to deliver the packages to the consumer. Therefore, the network should be able to handle different demand scenarios, which is why the fourth question was on how demand affects the network design. The network design changes significantly as the demand increases. When demand is increasing the number of crowd-hubs and the use of crowd-delivery will increase. With the increase in demand, an increasing number of crowd-hubs reaches feasibility. As a result, an increasing number of crowd-hubs are used and the costs per parcel will decrease. In addition, the increase in demand will increase the efficiency of professional delivery and reduce the professional delivery costs. As a result of these decreasing costs, the use of crowd-delivery could become infeasible. Therefore, the crowd-delivery costs should be reduced as demand is increasing. With a lower crowd-delivery cost the use of crowd-delivery and the number of crowd-hubs will continue to rise.

The increase in crowd-hubs and the reduction in costs are the long term effects on the crowd-delivery network when an increase in demand is permanent. However, the crowd-delivery network will also have to handle the daily fluctuations in demand. These fluctuations will increase the network costs slightly especially in cases with high demand. Further, a shift in demand distribution will also increase the network costs. Therefore, the network design should allow for some additional capacity compared to the analysed case to handle days with a higher transport demand. Further, crowd-hubs should only be used in areas where sufficient daily demand is guaranteed because in low demand the network is still unstable.
7.2.5 Delivery network

To conclude the research an answer to the main research question is formulated in this section of the conclusion. The main research question was:

_How should the delivery network of Trunkrs be designed, such that crowdsourced delivery can be implemented?_

For the implementation of crowd-delivery within the existing delivery network the network should be designed in an efficient way where only profitable crowd-hubs are included. Therefore, the network design analysis has been done with an optimisation of the total network costs.

These profitable crowd-hubs can be located throughout the Netherlands as a spread of locations over the Netherlands has shown to be profitable. For these crowd-hubs to be profitable it is important that sufficient demand is within range of a crowd-hub. These parcels are needed to offset the location costs for a crowd-hub to become feasible. Therefore, increasing the delivery range can provide significant savings. The delivery range can even prove to be crucial for a crowd-hub to be feasible when demand density is lower.

A second requirement for a crowd-hub to be profitable is that savings per parcel should be sufficient. The cost difference between professional delivery and crowd-delivery should be enough to offset the location costs within the capacity of a crowd-hub. Therefore, it might be important to reduce the crowd-delivery costs or operate crowd-hubs in areas that are less efficient for professional delivery. To reduce the crowd-delivery costs the crowd-hubs might have to move closer to the demand to allow for a smaller compensation.

Third, a profitable crowd-hub requires sufficient demand. Therefore, increasing the demand increases the number of locations used and reduce the total network costs. A change in demand can however also increase the network costs because the network is not able to deal with these changes. Therefore, the network should be designed to be stable and a guaranteed daily demand needs to be within the delivery area of a crowd-hub. When demand levels are low the network might not be able to handle the shifts in demand distribution. Therefore, having insight in how demand might distribute could help to design a stable delivery network.

To conclude, crowd-delivery can be implemented throughout the delivery network as crowd-hubs can be feasible throughout the network. For a crowd-hub to be added to the delivery network, the delivery area should be big enough to serve a significant number of parcels, while still having a low crowd-delivery cost.
8.1 Recommendations for Trunkrs

As Trunkrs is moving towards implementing their crowd-delivery network there are some points to consider during the network design. Therefore, this section provides some recommendations on the implementation, analysis to perform, and runtime improvements.

To successfully implement the crowd-delivery network it will be important for Trunkrs to build a sustainable delivery network, which provides sufficient savings compared to the existing delivery network (around €0.75 per package). To have sufficient savings Trunkrs should implement crowd-hubs into the delivery network that have a sufficient demand and where crowd-delivery can provide sufficient savings. In addition, in cases of low demand the network is proven to be unstable. Therefore, having the assurance of stable demand within range of the crowd-hubs benefits the profitability of crowd-hub. A crowd-hub location that fits these criteria in the current situation is a crowd-hub on the edge of Amsterdam, which is able to serve in and around the city. Therefore, the implementation of crowd-delivery should start within this area. Following on this crowd-hub location the crowd-delivery network can be extended by identifying similar locations, where the savings and demand are sufficient.

Since the demand that can be serviced by a crowd-hub is of importance to the profitability of a crowd-hub, Trunkrs should aim to maximize the service area of a crowd-hub. In this way, the crowd-hubs will be able to have a more stable demand and significant savings can be obtained. Therefore, Trunkrs should choose a crowd-delivery network where the packages join an occasional driver as early in its route as possible, over delivering a parcel to the edge of a residential area. To increase the delivery area of a crowd-hub, detailed information on the occasional drivers planned routes might be required. With the exact route of an occasional driver, the parcel assignment can be done more efficiently and a larger distance can be covered. A result that can be reached because the parcels can join the occasional driver earlier on its route. However, this might mean that a shift to a dynamic routing and parcel assignment is required.

While building the crowd-delivery network, Trunkrs might want to perform some additional analysis because it improves the insight and could benefit the network design. The crowd and professional delivery costs have an important influence on the profitability of crowd-hubs. Therefore, detailed information on professional delivery costs per destination could help determine a maximum for the crowd-delivery costs. Further, obtaining information on how much compensation is needed for an occasional driver to accept certain parcels could help identify if crowd-delivery is a feasible option. When combining the information on compensation required and the professional delivery costs, the routing of parcels can also be optimized, which could reduce the delivery costs.

During the analysis within this thesis, it showed that the runtime can increase rapidly for specific cases. To improve the calculation time, the problem could be divided into smaller sub-problems because the use of a crowd-hub is only locally influenced. When combining the solutions of these sub-problems a good solution for the total problem can be found.
8.2 Recommendations for future research

This second part of the recommendations provides some direction to possible future academic research. These studies could be performed to further develop the field of crowd-delivery. The suggestions include stochastic modelling, the acceptance rate, routing, and inter crowd-hub connections.

A major factor of crowd-delivery is the increased uncertainty within the network. As a result, the network should be designed to handle fluctuations in demand and capacity. To improve the solution and the stability of the network it could be interesting to use stochastic modelling. With the use of stochastic modelling the uncertainty and multiple scenarios can be included within the network design model. As a result, the solution should improve and a better understanding of the network performance could be obtained. However, the complexity of the problem increases as new variables need to be added. Therefore, a heuristic solution approach might be required.

One factor of the uncertainty within the network design is the acceptance of parcels by occasional drivers. This research included an acceptance rate into the analysis, which showed a significant influence on the network design. However, a more detailed view on the effects of parcel acceptance should help the network performance. Therefore, research could be done on why parcels are accepted and how the acceptance rate can be improved. In addition, further research can be done on the effect of unaccepted parcels within the network design. This can be done by designing the process to handle the unaccepted parcels and by identifying the costs that are made for these parcels.

Operating the delivery network has costs that influence the network design. To better estimate the costs of operating the network a location routing problem approach can be used. With the use of a location routing problem the decision of using crowd-delivery for a destination is also influenced by demand that is close. As a result, a more detailed professional cost can be considered. This more detailed costs can be crucial as the cost difference between professional and crowd delivery is an important factor in the profitability of crowd-hubs.

In addition to a location routing problem approach for the network design, the routing problem remains to be an important field of research. The crowd-delivery costs are important for the profitability of crowd-hubs. Therefore, within be the parcel assignment it might interesting to identify a difference in crowd-delivery costs between occasional drivers or to use a market system in the assignment. With a market system, the occasional drivers might be motivated to accept parcels for a lower compensation.

In the current network design, it is assumed that all packages flow through the existing delivery network and no inter-crowd-hub connections exist. However, it could also be possible to transfer parcels between crowd-hubs, which opens new possible parcel flows. This could be an interesting extension for the inclusion of smaller online stores and to use crowd-delivery in other levels of the delivery network. To include this idea the model needs to be extended to include inter-hub connections and to allow for changes in the existing delivery network.
References


