Norwegian School of Economics

Bergen, Spring 2022

Parcel Delivery with Automated Parcel Lockers in Bergen

A Study on Potential Collaboration in the Parcel Delivery Industry in Bergen Using Mixed-Integer Linear Programming

Lars Falch Juvik and Jonas Finvik Øverås

Supervisor: Stein W. Wallace

Master Thesis, MSc in Economics and Business Administration

Majors: Business Analytics/Business Analysis and Performance Management

NORWEGIAN SCHOOL OF ECONOMICS

Abstract

Automated parcel lockers (APLs) have in the past year become a common sight in Bergen and have quickly become one of the preferred methods for picking up parcels in the business-to-customer market. As the largest postal companies keep increasing their number of APLs, and an increasing number of companies are implementing or exploring the possibilities to implement APLs in their operations, new problems and solutions arise.

This thesis focuses on postal companies' incentives to partake in collaborative efforts regarding APLs by sharing APLs, terminals, or both. We use mixed-integer linear programming to create different network design models to minimize the cost of delivering parcels with APLs for different scenarios. We then assess and compare the incentives to collaborate in the different scenarios by looking at the relative savings for each scenario.

The main findings show that the total cost decreases as collaboration and consolidation increase. We found that when companies share APLs and terminals, collaboration results in significantly higher savings when the cost of APLs is low relative to travel cost. However, we did not find that this was the case when companies only share APLs. In scenarios with several smaller companies, there is a higher incentive to collaborate, as collaboration can be valuable for smaller companies as they are less likely to use the full capacity of APLs when operating individually. This was the case when companies shared only APLs and when sharing both APLs and terminals. The further away the terminals are from each other, the larger the benefit of collaboration becomes when sharing terminals and APLs, but not when only sharing APLs. However, the total cost becomes higher when the terminals are placed further away from the city centre. Lastly, we found that it is possible to find several stable cost allocations when the companies share both terminals and APLs.

Keywords – Automated parcel lockers, mixed-integer linear programming, city logistics, parcel delivery, network design model, consolidation, collaboration

Acknowledgements

This thesis was written as the final part of our master's degree at the Norwegian School of Economics (NHH). The thesis is written as a part of the current research project CityFreight. CityFreight aims to research various aspects of freight transportation in Norwegian cities and use this knowledge as a basis for public authorities to develop cities in a sustainable and energy-efficient direction. CityFreight is done in cooperation with University of Bergen – Centre for Climate and Energy Transformation (CET), The Norwegian Public Roads Administration, Sparebanken Vest, City of Bergen, Vestland County, Bergen Chamber of Commerce and Industry, Nordic Edge AS, Université Centrale Lille, Politecnico di Torino, and Sichuan University Chengdu.

Firstly, we want to thank our supervisor, Professor Stein W. Wallace, for introducing us to the exciting topics of APLs and consolidation in the parcel delivery industry. We appreciate the many exciting discussions throughout the semester and for guiding us through both small and large problems. Secondly, we would like to thank PhD candidate Cosku Can Orhan for introducing us to the data on parcel deliveries by PostNord. Thank you.

Norwegian School of Economics

Bergen, June 2022

Lars Falch Juvik Jonas Finvik Øverås

Contents

Abbreviations

APL – Automated Parcel Locker

B2C – Business to Customer

EPM – Equal profit method

List of figures

List of tables

List of pictures

List of equations

1. Introduction

Automated parcel lockers (APL) made their appearance in Norway through Posten at the beginning of 2020. The lockers were initially introduced in busy areas in Oslo. Since their introduction, Posten has placed more than 3000 APLs in about 1000 different locations in Norway, both in rural and urban areas (Posten, 2021). When we started writing this thesis, PostNord had only placed APLs in Oslo but has now expanded to other areas in Norway, there among Bergen (International Post Corporation, 2021). As APLs rapidly establish themselves as one of the preferred methods for collecting parcels, with a possibly increasing number of companies partaking, new questions and problems surrounding the logistics of this phenomenon, as well as surrounding modern parcel delivery in general, appear.

In addition to Posten and PostNord, there are several other companies of various sizes in the business-to-customer (B2C) parcel delivery industry. We will look closer into the logistics of APLs when there are multiple players providing this service. More specifically, we will assess the economics surrounding collaborative efforts between postal companies in combination with further adoption of APLs.

1.1 Background

1.1.1 Automated parcel lockers

Automated parcel lockers or automated parcel machines are automated pick-up points for parcels. APLs are an alternative last-mile delivery method of parcels in the B2C market and serve as an alternative to pick-up points in stores, post offices, and home delivery of parcels. APLs offer more than other pick-up methods as one can collect parcels at any time, both day and night. They need very little space, as seen from Picture 1 below of one of Posten's APLs in Oslo. The APLs that Posten are using, SwipBox Infinity, are battery and Bluetooth-operated and do not need power supply or internet connection (Baldur, 2021). The customers download an app on their smartphones which communicates with the APL through Bluetooth. Swipbox also offers another model, the SwipBox Classic. This APL comes with a screen and barcode scanner, so the customer and courier do not need a smartphone. This type of APL does need power supply and internet connection. It is easy to add additional lockers to existing lockers for both types of APLs, making capacity less of a problem (Swipbox, 2022).

Picture 1 Swipbox APL (Baldur 2021).

There are several manufacturers of APLs and APL-software solutions. Private manufacturers who sell their solutions to different e-commerce operators, such as to Posten in Norway, dominate the market. In the Netherlands, PostNL decided to go for a local manufacturer of their APLs. In that way, PostNL could influence the production and design process (International Post Corporation, 2021).

When determining the location of APLs, there are several considerations. The article by International Post Corporation (2021) points to the possibility of scaling up the capacity by adding new modules to the APL as a requirement for a good location. It is also important to have access to many customers. Often used locations are on the outside of stores and at public transportation stops. Another consideration regarding the location of APLs is the legality of where the postal companies are allowed to place their APLs and practical considerations regarding accessibility.

In Norway, all the APLs are operated by individual postal companies alone. Another approach is space sharing. Space sharing is when several postal companies share the same

APL network. This solution could reduce the travel time for couriers and reduce the distance for customers to the nearest APL. Ann Snitko, Head of Product Development at OMNIC, an APL manufacturer, points to the space sharing model as the optimal one. She states that it is difficult for one carrier to fill up their parcel lockers per day (International Post Corporation, 2021). Another factor that space-sharing would improve is the total space needed for APLs. An example is that several APLs in residential buildings are likely not attractive to the residents, while one shared APL might take up much less space. A problem with space sharing of APLs is that some of the big postal companies already fully or almost fully utilize the capacity in their APLs. By opening for space-sharing, they could risk some of their APLs filling up by other postal companies and then having to reroute parcels to other lockers (International Post Corporation, 2021).

1.1.2 Freight transport in Bergen

Vahrenkamp (2016) states that only approximately 10% of city centre traffic is freight transport and that consolidation would only reduce these 10%. However, one could argue that this number is higher in Bergen, as fewer and fewer personal vehicles travel in the city centre. An example is the closing of Bryggen for all personal vehicles in the summer months, as well as the municipality looking at banning fossil fuel vehicles from the city centre in the future (Juven, 2021).

1.1.3 E-commerce growth

We have seen an increase in online shopping in the last few years. The Covid pandemic has only led to an even higher increase in e-commerce. Lund et al. (2021) found that e-commerce nearly grew fivefold in the UK compared to the average growth between 2015 and 2019. An article by Torkington (2021) refers to the Global Consumer Insights Pulse Survey from PWC of June 2021 when saying that customers do not think they will go back to their old shopping habits after the Covid pandemic is over. People's shopping behaviour is changing, and an increasing amount of our buying and selling is happening online rather than in physical stores. This development is an important consideration when looking at the impact and importance of improved delivery systems. The increase in e-commerce leads to an increase in parcel deliveries, making it essential to have efficient systems for delivering an increasing number of parcels.

1.1.4 Consolidation

Several studies show that the benefits of consolidation of parcel deliveries are slim for the big postal companies (Vahrenkamp, 2016). The cost of consolidation has often resulted in higher costs than benefits for the companies involved, though there might be significant additional benefits for society. Consolidation has often been implemented in the form of consolidation terminals. A consolidation terminal is a storage facility where small shipments are combined into larger and more economical truckloads bound for a similar destination (Sunol, 2021). Most consolidation projects in the past decades have not lasted beyond a couple of years for various reasons, including higher than expected operational costs, low carrier compliance, and other unforeseen events (Simoni et al., 2018). For consolidation terminals to be attractive and profitable for the postal companies, Allen et al. (2012) state that the public authorities need to subsidize the consolidation terminals.

One goal of consolidation is to avoid low-capacity utilization of delivery vehicles in urban areas. The significant focus of consolidation in the literature has been on the effects on traffic and less on the effects on the environment and financials (Allen et al., 2012). In the context of APLs, as stated in Chapter 1.1.1, sharing APLs between different companies is regarded as a viable form of consolidation. As opposed to a consolidation terminal, this is a form of consolidation that requires low initial cost and a followingly low financial risk. Another alternative to making a new consolidation terminal is that the companies share or partly share their terminals. This way, the parcels can be shipped to the terminal that results in the lowest total delivery cost. The parcels will in this way be shipped directly to the terminal of the postal company that shall deliver the parcel the last miles. This thesis will focus on these two forms of consolidation (sharing APLs and sharing terminals). We will not research consolidation terminals further.

1.1.5 APLs and consolidation from different perspectives

APLs can be assessed in a broader perspective as one of many potential improvements to the logistics of a city and as a part of the field of city logistics. One short definition of city logistics, according to Rodrigue & Dablanc (2020), is the following: *"…the means over which freight distribution can occur in urban areas and the strategies that can improve its overall efficiency while mitigating externalities…"*. For freight companies, improved city logistics means providing services more effectively, potentially leading to lower costs, among other factors.

There are naturally many additional stakeholders in city logistics, including the general population of a city. The public's concerns include, among other, factors related to the liveability of a city. This includes elements such as time spent in traffic, traffic safety, and access to public spaces. Pollution is naturally another public interest, both for the inhabitants within and outside a given city (Rodrigue & Dablanc, 2020).

Private consumers, in our case the customers of APLs, are another stakeholder in city logistics but will not be the focus of our thesis. Some concerns for customers of APLs include prices, distance to parcel pick-up locations, and the general experience and ease of picking up parcels.

According to Taniguchi (2014), there are three essential elements required for improving city logistics. These elements can be summarized as the following:

1) **Application of innovative technologies:** In our case, implementation of APLs belongs to this element.
2) **Change in the mindset of logistics managers:** In our case, this might be the companies' willingness to explore the possibilities of collaboration. This element can also be tightly connected with *Application of innovate technologies*. For example, secure and effective technology for information sharing between competitors might be essential for managers to consider collaboration.
3) **Public-private partnerships:** Public involvement is often essential for the private companies to consider all the relevant stakeholders' perspectives. As stated earlier, this might not always be profitable for the private companies, and subsidiaries or other economic benefits might be necessary. Public-private partnership is naturally a two-way dialogue, and it is also essential for the public authorities to be informed about potential side effects of potential policies.

1.2 Scope of the thesis

We are interested in how consolidation of parcel deliveries to automated parcel lockers can make city logistics more efficient and how costs and benefits can be divided. This thesis has an explorative approach with the purpose of gaining a general understanding of the economics of APLs and their effect on city logistics.

We create several mixed-integer linear programming models to assess and compare the cost of fulfilling certain shares of parcel demand through APLs in different scenarios. We will not focus on exact costs, delivery routes, or APL locations but rather compare different scenarios and assess how the output changes based on changes in various model attributes and parameters.

Our analysis consists of three main models, where each model contains three companies. We will assess and compare the costs for three companies of different sizes for each model. The different models are the following:

Model 1: Each company operates individually.

Model 2: The companies can share APLs.

Model 3: The companies can share APLs as well as terminals.

We are not considering the total costs of a company's parcel delivery but rather exploring the cost of APL delivery under different scenarios, which is then only a part of a company's entire parcel delivery system. An important note is that we do not assess the cost of transporting the parcels to the different terminals, which also is an important factor when making decisions regarding terminal locations.

The insight gained from this thesis could be used by postal companies, city planners, and policymakers as part of their basis for decision-making regarding parcel delivery and further implementation of APLs.

As data for our models, we will use relative parcel demand for different areas of Bergen based on parcel delivery data from PostNord, in addition to real travel time and distance data.

This thesis aims to gain a general understanding of to which extent APLs and consolidation between companies may improve city logistics in Bergen in different scenarios. We will concentrate on answering some key questions. As introduced in Chapter 1.1.5, there are several stakeholders concerning city logistics and APLs. As our model have the objective of minimizing costs for postal companies, the primary focus will be to assess companies' incentives to collaborate under various scenarios and circumstances. We will, however, also assess our results with the other various stakeholders in mind.

We want to explore and answer the following main questions:

- Are there benefits from companies collaborating when delivering parcels with APLs? (Companies sharing APLs or sharing both APLs and terminals).
- How does the incentive to collaborate change under different scenarios?

As mentioned, we will look at two types of collaboration—one where the companies share APLs and one where companies share both APLs and terminals. The former type of collaboration is a realistic scenario with relatively low practical barriers. The latter type of collaboration is far less realistic. However, we are interested in assessing the theoretical effects of this high level of collaboration to use as a reference for the potential benefits of collaboration, which may be fully or partly practiced.

2. Literature

2.1 Automated parcel lockers

Refaningati et al. (2020) did a case study on the efficiency and characteristics of an automated parcel locker system in Jakarta. When comparing the automated parcel locker system to a system of home deliveries, they discovered that the APL system required a 30.65% shorter trip length than the home delivery system. 717.8 km was driven to deliver 222 items by home delivery, while only 497.83 km was driven when delivering the same number of items to APLs.

A case study (van Duin et al., 2020) evaluated the effects of implemented APLs in De Pijp in Amsterdam. The study estimated a daily decrease in total last-mile delivery cost from €3,210.49 to €2,704.85 with the implementation of APLs, a cost-decrease of almost 16%.

A study (Chaberek, 2021) on APLs in Gdansk found that approximately 50% of customers picking up parcels from APLs did it by car. Therefore, when assessing how much effect implementation of APLs has on the amount of traffic and the environment, we must also consider to what extent the customers will pick up parcels by car. However, the study concluded that many of the APLs were placed in locations that were not pedestrian-friendly. The article further concluded that the extent to which parcels are picked up by car versus by foot or bike depends heavily on the location of the APLs in addition to the logistic structure of the city as different cities have various levels of car dependencies.

There is also literature on methods regarding the optimal location and quantity of new APLs. An article by Hyangsook (2019) assessing residential complexes in Korea presents a sequential decision-making set covering model that finds potential locations for APLs, determines the number of APLs, and selects the optimal locations for installing the APLs. The set covering model must cover a specified number of customers or places while at the same time minimizing cost. Another article by Luo et al. (2022) presents a model for designing a parcel locker network with the goal of minimizing the cost of the APL network while also ensuring accessibility for the customers.

Literature also shows that there can be efficiency gains if the customers are flexible in their desired pick-up point. Traditionally, recipients specify one pick-up point, but if the recipient is flexible and selects a set of pick-up points, there can be efficiency gains. According to an article by Ornstein (2019), the efficiency gains can be lower cost and shorter delivery time.

Parcelmonitor (2021) states that more than 65% of parcels worldwide are collected from parcel collection points within 48 hours. The report points to differences between regions of the world, with Europe having an even higher rate of 75.6%. The parcels which are not picked up after 48 hours can become a problem for the capacity of the APLs, thereby limiting the number of parcels which can be delivered to APLs. This capacity issue is not that prominent when parcels are picked up from pick-up points at grocery stores or postal offices. However, it becomes a bigger problem at APLs, because APLs only have a set number of compartments for the parcels. Therefore, variance in pick-up time arguably has a higher effect when parcels are picked up from APLs than from grocery stores or postal offices.

2.2 Route planning and optimization

Our models are classified as network optimization problems. A network optimization problem is defined by the inclusion of nodes and arcs. In our case, our nodes are different areas of Bergen where APLs may be placed, in addition to post terminals. Each arc is the drive from one area to another. Network optimization problems are further divided into two main groups. One is network flow problems, where the network is already defined. The other is network design problems where in addition to optimizing the flow of the network, one also determines which nodes the network should include. As these two types of problems are seemingly quite similar, a network design problem is regarded as much more difficult than a network flow problem. A network design problem must be formulated as an integer optimization problem. In our case, we will include both integer and continuous variables, and our optimization models are therefore classified as network design models using mixed-integer linear programming (Lundgren, Ronnqvist, & Varbrand, 2010).

As our network design problem has the potential to be very computationally heavy, we will use a heuristic approach. As our input data is already based on approximate estimates, and the focus of this thesis is to compare different scenarios on an equal basis rather than looking at exact routes and values of costs and benefits, we believe that a heuristic approach will not affect our conclusions. This will be discussed further when the model is presented in Chapter 4.

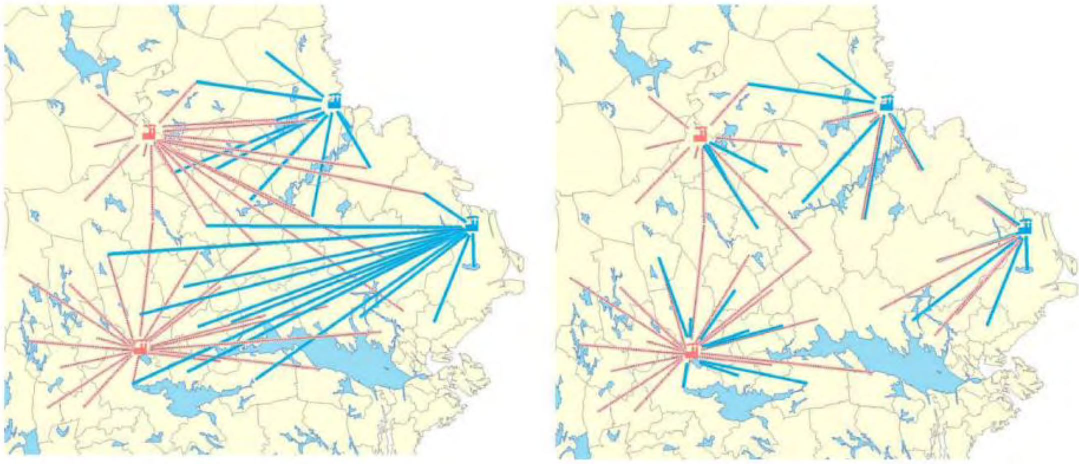
2.3 Consolidation

Implementations of consolidation in the parcel delivery industry have often met barriers due to various practical reasons. In our case, the companies are competitors, which leads to additional issues regarding trust, information sharing, leadership, and conflict of interest (Basso et al., 2019). According to Basso et al. (2019), there is extensive literature regarding sharing of costs and benefits of collaboration, but very limited literature about dividing losses and costs of unexpected problems during collaboration.

In an article by Frisk et al. (2010), the authors discuss the benefits of collaboration between forest companies in Sweden. The article also discusses the many possible types of cost and benefit allocation. Frisk et al. state that there is an increasing interest in collaborative planning as the savings can be around 5-15%. Furthermore, they find that better planning within a company can save around 5%, and collaboration between companies can save another 9%. Even though the forest industry and parcel delivery industry are quite different, they are both similar in that there is freight to be transported from supply points or terminals to demand points.

Picture 2 below from Frisk et al. (2010) shows how cooperation between companies leads to shorter travel distance for every company. The illustration shows how much smaller the distances become when collaborating by using the supply points as a shared resource. This will not be possible in the same way when looking at collaboration in the parcel delivery industry, as the goods transported are not homogeneous. In contrast to wood, each parcel is unique, whereas all wood consists of only a small assortment. Therefore, it does not matter which supply point the wood is picked up from. This is naturally not the case for parcel deliveries, and it is therefore essential that the parcels are sent to the correct terminal before being transported to the customer.

Picture 2 From (Frisk et al., 2010), illustrating cooperation in transport of wood.



The article by Frisk et al. (2010) also mentions backhauling when discussing how coordination can increase the capacity utilization of the delivery vehicles. Backhauling is when the delivery vehicles combine supply and demand points to find better routes. Backhauling can reduce the unloaded distance travelled. In the parcel delivery industry, one could think of the delivery vehicles delivering parcels and picking up returned parcels at the same demand point as backhauling. This demand point could for example be an APL.

According to Basso et al. (2019), an essential factor for why the collaboration presented by Frisk et al. worked was that a research and development organization functioned as a third party with no apparent conflict of interest. When this third party had to be replaced, the collaboration was discontinued as no suitable third parties were found.

2.4 Cost and benefit allocation methods

Collaboration and consolidation of parcel deliveries lead to both costs and benefits for the participants. There are several methods for cost and benefit allocation found in the literature. It is crucial that the allocation of costs and benefits is designed so that all participants want to participate in the collaboration. The participants must be better off in the coalition than if they are standing alone. This is an important part of our thesis because it does not matter if the savings from collaboration are high if all the savings are allocated to only one company, leading the others not wanting to participate in the coalition.

In the article by Frisk et al. (2010), a stable cost allocation is discussed. A stable cost allocation satisfies the efficiency condition and rationality condition. It is stable in that no participant is better off in another coalition. The rationality condition implies that no participant is better off alone or in another coalition than in the grand coalition consisting of all participants. The efficiency constraint is satisfied when the total cost of the coalition is split between the participants.

We will now look at two different allocation methods, the Equal profit method, and allocation based on Shapley values.

2.4.1 Equal profit method

One cost allocation method is the equal profit method or just EPM. This method is guaranteed to find a stable allocation if there is one. The EPM finds a stable allocation that minimizes the maximum difference in relative savings between the participants. This method is considered a fair allocation of the cost and benefits in that it aims to give as similar relative savings as possible among the participants. The article by Frisk et al. (2010) states that some allocation models have the problem of not being accepted by some participants because some do not perceive the allocations as fair. The EPM attempts to solve this problem by having as similar relative savings for each participant as possible.

The EPM allocation is found by solving the linear programming problem in Equation 1 below (Frisk et al., 2010). The objective of the LP problem is to minimize f, the largest relative difference in savings between the companies in set N. The first constraint in the formulation below is measuring the pairwise difference between the companies' costs. The EPM is guaranteed a stable allocation if there is one because the rationality and efficiency conditions are stated as constraints in the LP problem. The rationality constraint (2.) expresses that the sum of the costs allocated to companies in the subset of companies M, must be less than or equal to the cost of coalition M. This must hold for all smaller coalitions M in the set of all companies N. The efficiency constraint (3.) expresses that the sum of all costs allocated must be equal to the cost of the grand coalition, C(N).

Equation 1 EPM equation (Frisk et al., 2010)

$$\text{Minimize diffrence: } min\ f$$

$$s.t.$$

$$1.\ f \geq \frac{u_i}{c_i} - \frac{u_j}{c_j} \quad \forall\, i, j \in N$$

$$2.\ \sum_{j \in M} u_j \leq C(M) \quad \forall\, M \subset N$$

$$3.\ \sum_{j \in N} u_j = C(N)$$

$$4.\ u_j \geq 0 \quad \forall j \in N;\ f \in R$$

2.4.2 Shapley values

Another method is allocation based on Shapley values. This method allocates a cost or a profit to the participants based on a weighted average of the marginal cost/profit which the participant causes when included in the coalition (Frisk et al., 2010). An allocation based on Shapley values does not guarantee a stable allocation, but it satisfies some conditions which makes it a fair allocation. These conditions are efficiency, symmetry, dummy property, and additivity. The efficiency condition ensures that the total cost is allocated among the participants. The symmetry condition ensures that participants who imply equal costs or profits to the coalition should have the same cost or payoff. The dummy property condition ensures that a participant who causes no cost or profit by joining the coalition should not get allocated any profit or cost. The last condition, the additivity condition, ensures that the game cannot be divided into a set of smaller games that together achieve greater total gains or smaller total costs (Kenton, 2022). An example is that the total cost of a coalition with company 1 and 2 cannot be greater than the sum of the stand-alone costs of company 1 and 2.

The formula we use for calculating the Shapley values can be seen in the Equation 2 below. N is the set of the different companies, and M is a subset of the companies. C_m is the cost of the coalition consisting of companies in subset M. The Shapley value u_j is calculated for each of the three companies j in set N.

Equation 2 Formula for Shapley values (Frisk et al., 2010)

$$u_j = \sum_{M \subseteq N : j \in M} (\frac{(|N| - |M|! \, (|M| - 1)!}{|N|!}) \times (C_M - C_{M \setminus \{j\}}) \;\; \forall \, j \in N$$

3. Data

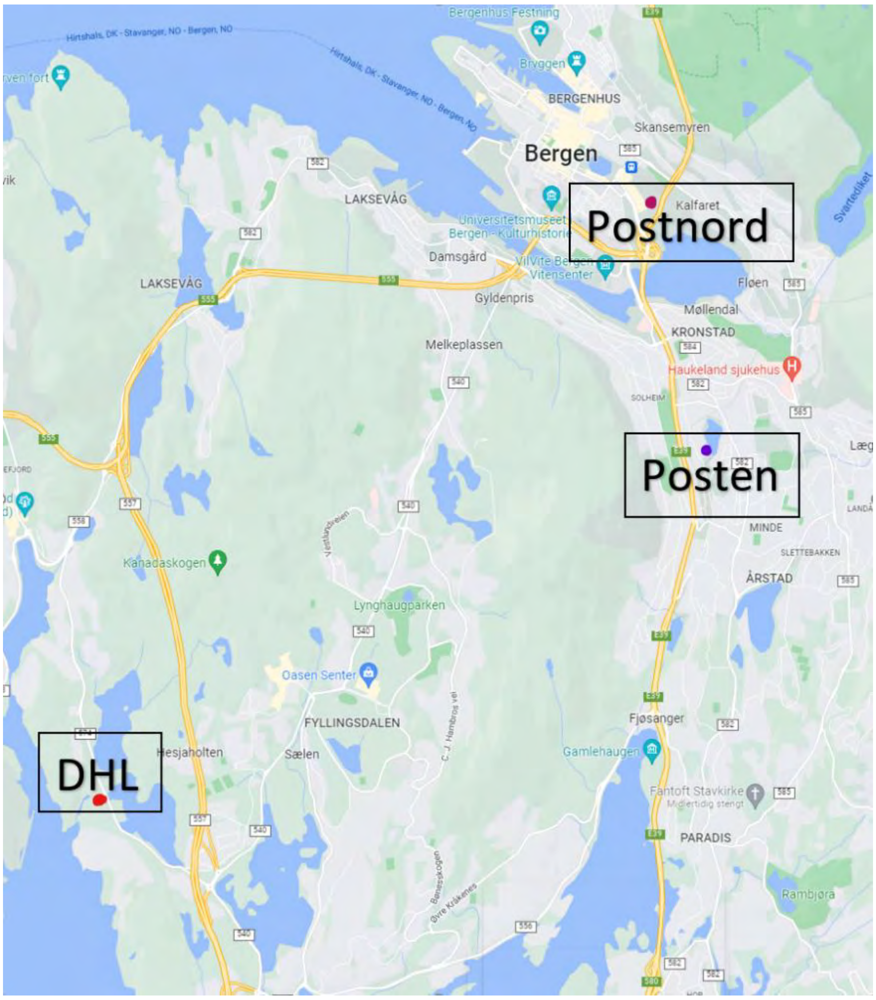
The geographical area that we consider in our research models consists of 122 postal codes that make up the urban area of Bergen municipality. We have merged some of the postal codes based on conditions that will be explained in Chapter 3.3. After merging certain postal codes, we end up with 74 areas in our models, in addition to the 3 terminals. We have retrieved data for distances between each area, travel time between each area, and an estimated parcel demand for each area. Time and distance data is retrieved through Google Maps API, and parcel demand data is retrieved from parcel delivery data provided by PostNord.

3.1 Companies

Our models contain three postal companies: one small company, one medium-sized company, and one large company. Our demand data is based on real data from PostNord. As we also include two other companies in our models, we scale PostNord's demand data up and down to represent a larger and smaller company. PostNord's operations in Bergen are smaller than Posten's but significantly larger than many of the remaining postal companies. We therefore categorize PostNord as the medium-sized company in our models. For the larger company, we use PostNord's demand but doubled for each area. Similarly, for the smaller company in our models, we use PostNord's demand and reduce it by half for each area. We name the large company Company 1, the medium-sized company Company 2, and the small company Company 3.

For terminal locations, we use the location of Posten's terminal for Company 1, the location of PostNord's terminal for Company 2, and the location of DHL's terminal for Company 3. Companies 1, 2, and 3 are only loosely based on Posten, PostNord, and DHL, as we have only used their terminal location and a proxy for their demand in our models.

Picture 3 Current terminal locations of chosen companies



3.2 Distance and time data

A total of 122 postal codes and 3 terminal locations amount to 125 individual geographical data points. This further amounts to 15’625 individual distance data points and the same number of travel time data points. We generated an API code from the Google Maps Platform (Google, 2022). We then used *R* with the package “mapsapi” (Dorman et al., 2022) to create a short R-code to retrieve all our distance and travel time data simultaneously. The data is retrieved between 11:30 and 12:30 on a weekday. The values of the time data will naturally depend on the time of the day. At this time of the day, there is a moderate amount of traffic, and generally not heavy traffic in any specific direction. Our models could be made more complex with multiple travel time data sets retrieved at different times of the day. However, we consider it sufficient with just one travel time data set for the purpose of our analysis.

The distance and time data were originally provided in meters and seconds. To run our models more efficiently, we have simplified and divided the distances by 100 and travel times by 60. The distance unit for our data is 100 meters and the time unit is one minute.

3.3 Parcel demand data

The data provided by PostNord consists of all parcel deliveries by PostNord in Bergen for the period January 2020 to November 2020. The original data were sorted into different categories, in which we were only interested in the categories involving B2C parcel delivery. In addition, the data contains information about to which postal code the parcels are delivered.

Most parcels for private customers are delivered to postal offices or grocery stores. As we are interested in each postal code's individual demand, data regarding where the parcels are delivered will not be representative, as post offices are not necessarily located in the customer's postal code. In addition, the number of post offices in each postal code is not proportional to the population of the respective postal code. Because of this, we use parcels delivered by home delivery as a proxy for the proportion of demand of each postal code, as these parcels are delivered in the same postal code as the location of the customer. However, home delivery makes up only a small proportion of total parcels delivered. We therefore scale the number of home delivery parcels per area, so the sum of parcel deliveries is equal to the total number of delivered parcels regardless of delivery method.

The size of the area of a postal code varies greatly, with densely populated areas generally having a smaller geographical area per postal code. We wanted to incorporate in the model that people living in one postal code could collect parcels from APLs in neighbouring postal codes if they are close. Therefore, we merged the demand of the postal codes that were under 5 minutes in driving distance from each other. First, we merged the demand of the postal codes with the lowest travel time between each other, and then we merged the new lowest travel time pair. This process carried on until there were no areas with less than a 5-minute driving distance from each other. In addition to merging the demand of these areas, we also created new distance and travel time data for these areas to the other areas in the dataset.

This was done by taking the average distance of the two areas which were merged. After doing this, we ended up with 74 different areas. These are the nodes in our models together with the 3 terminals.

3.4 Cost and capacity data

The data used for the various cost and capacity components in the models are rough approximate estimates. The data regarding cost and capacity presented here is only meant as an initial benchmark. Our aim is primarily to explore the effects of change of cost components relative to each other rather than to calculate the exact costs of different scenarios.

Because the models needed to be simplified to run, we decided to use one standardized car for every tour and one size for APLs. Standardized cars and APLs ensure that the model only needs one cost per distance-driven parameter, one cost per minute-driven parameter, one car-capacity parameter, one APL-cost parameter, and one APL-capacity parameter.

Travel cost

For the cost of traveling 100 meters, we make estimations based on a Maxus e-Deliver 3 delivery truck. This is a medium-sized electric van which is a common van for Posten. The price of this car is around 380’000 NOK. The cost per hundred meters driven parameter was found by using the price of the car of 380’000 NOK and using the car cost calculator at Smartepenger.no (Pedersen, 2021). The cost was calculated to 0.25 NOK per one hundred meters.

Time cost

The cost per minute driven is set to 5 NOK per minute. This number was found by dividing the average hourly wage of a postal driver, including employer’s tax and vacation pay by 60 (Utdanning.no, 2022).

Parcel capacity of car

The car capacity parameter is the number of parcels that each car has the capacity to carry. This parameter was calculated using the volume capacity of the Maxus e-Deliver 3, divided by the volume of an average parcel compartment on a Swipbox APL (Ludt, 2021). This calculation gave us 109 parcels as the max capacity of each car. However, because the parcels will usually be a bit smaller than the average parcel compartment, we rounded up the car capacity to 112. We rounded this to 112 as it is the closest multiple of 14, and 14 is the capacity of one Swipbox APL unit. This makes our model able to deliver full capacity to each APL on its route.

Average Swipbox parcel compartment size: $0.35 \cdot 0.25 \cdot 0.12 = 0.0574$ M^3 (Swipbox, 2022).

Capacity of car: $6.3M^3$ (Ludt, 2021).

$6.3/0.0574 \approx 109$ as maximum parcel capacity of each car.

Daily cost per APL

The APL cost parameter is the cost of each APL each day. This cost is, for example, the cost of buying or renting an APL, setting up the APL, and maintenance. This parameter is the cost of each APL. If a site has several APLs, the cost is multiplied by the number of APLs on the site. We calculated the value of this parameter by taking the approximate price of an APL and dividing it by our expected lifespan of an APL of 5 years. The price per APL was calculated by taking the revenue of Swipbox in 2021 of 242 billion DKK divided by the number of APLs they sold in 2021, which was approximately 10'000 units (Post & Parcel, 2022).

Cost per APL: (Revenue of 242'000'000DKK)/(10'000 APLs sold) = 24'200DKK ≈ 30'000NOK

30'000/5 years lifetime = 6'000NOK/year

6'000/365 = 16.4NOK/day

The APL capacity parameter is the number of parcels that each APL can hold. The number of 14 parcels is used because that is the number of parcels that the most common APL of Posten can hold today. This is the APL shown earlier, in Picture 1 of the APL from Swipbox.

Terminal capacity

The terminal capacity of the different terminals, which is used in Model 3, with shared APLs and terminals, is calculated by taking the sum of the different companies' total demand, as this is what they are at least capable of delivering today from their own terminal. Some terminals could naturally have a higher capacity than this. However, each company’s total demand is likely a good enough proxy for the different terminal capacities.

4. Method and Model

4.1 Introduction to model

We use AMPL with the solver Gurobi to create and run our mixed-integer linear programming models. Our models have the following general structure:

1. A company has a total number of X_c parcels which can potentially be delivered by APLs.
2. A proportion P of this demand will be delivered through APLs. We see 43% as an appropriate cap for P as it is unlikely, at least in the near future, that more than 43% of the potential parcels are delivered through APLs. See Chapter 4.4.3 for more details on this.
3. We minimize the cost of delivering $P{\cdot}X_c$ parcels through APLs.
4. As we are exploring APLs as a close-proximity parcel pickup method, customers can only pick up parcels from an APL within a specified area. Our analysis consists of 74 different areas, plus 3 terminals. An APL in the model can be used by anyone within the same area but not by anyone outside this area.

There are two main types of cost that make up the total cost in our models. These are travel costs and the costs related to APLs. As our models only include variable costs, the cost per parcel delivered will increase as the number of parcels delivered increases. For example, if we only deliver 5% of the potential demand, the cost per parcel will be very low as parcels will only be delivered in the immediate proximity of the terminal. If the fulfilled demand increases, the companies must place APLs in less dense areas or areas far from the terminals, causing the cost per parcel to increase.

As stated earlier, another consideration and limitation of our models are that the parcels that are not delivered by APLs will be delivered by other means. This means that there is an alternative cost for each unfulfilled potential demand, which we do not consider in our models.

4.2 Factors to study

Through our mixed-integer linear programming models, we are interested in finding how the following factors determine the cost of parcel delivery.

- Size of companies
- Location of terminals
- Proportions between stepwise costs of APLs compared to variable travel cost

Size of company and demand

As this thesis explores APLs in the context of it being a tool for parcel pickup close to the customer, our model only lets a customer pick up parcels from APLs in their local area. In our analysis, the size of a company is synonymous with a company's demand. Depending on the company's total demand, particular areas might have less demand than the capacity of an APL unit. For a small company with low demand, there could be few areas with demand higher than the capacity of a single APL unit. In our model, this could lead to many APLs with unused capacity. This could further lead to a potential incentive for smaller players to share APLs. Larger companies might also want to share APLs, though they would need to fulfil a higher percentage of their demand in order to experience unused capacity in their APLs.

Location of terminals

Given that a company delivers parcels to APLs from only one terminal, the terminal's location is in our models, in addition to the company's size, the determinant of how costs vary between different companies.

(Cost of delivering N packages Company 1) = (Cost of delivering N packages Company 2) + (Difference due to terminal location) + (Difference due to size of the company)

As a measure of a location's centrality, we can measure the average cost of traveling from one location to all other locations. However, as different areas have different levels of demand, we need to weigh the average travel cost to a location by the potential parcel demand at that location. We can then establish a more relevant centrality measure by calculating the average travel cost multiplied by the demand in each area.

By this measure, out of all the 77 areas in our analysis, Posten's terminal is the most central area of Bergen, while PostNord's and DHL's terminals are the 11th and 39th most central areas in Bergen, respectively.

Table 1 Centrality of terminals

Terminal	Average travel time (minutes)	Average distance (100 meters)	Average travel cost	Centrality measure	Centrality rank
Posten	14	88	90.46	12428.55	1
PostNord	16	98	104.21	13952.69	11
DHL	17	124	117.14	17581.48	39

Stepwise costs of APLs compared to variable travel cost

As introduced in the previous chapter, we will model the cost of delivering to and operating APLs based on travel time, distance, and costs per APL unit. The travel time and the distance between two locations will naturally be highly correlated. Therefore, we would expect similar patterns in our results if we only modelled with either only travel time cost or only distance cost as a measure of travel cost. Both are, however, included to make the model more realistic.

As we do not have exact data for any of our three cost components, our focus is on how the relations between these costs affect the results of our models. Given that the parameter values for travel costs are equal between different scenarios, we are interested in how changes in APL cost change our results. Our hypotheses regarding the relation between APL cost and travel cost are the following:

Low APL cost	**High APL cost**
More APLs with unused capacity	Less unused capacity
Less important for players to share APLs as unused capacity is not costly. Higher emphasis on travel costs.	Players more willing to share APLs in order to not spend money on unused costly space.

4.3 Sets, parameters, and variables

Our first model contains three sets, presented in Table 2 below. We have one set *A,* containing all areas, consisting of all demand points and terminals. We include a time element *T* in the form of timeslots where a delivery car may perform a drive. A delivery car can also choose to not drive in a timeslot, which makes it "stand still" for no cost. Therefore, the timeslots do not represent actual times of the day but function as a tool to make sure cars drive their routes in the right order. The timeslots are also essential in our model to ensure that if a car drives to one area, it must eventually leave it and end up in a terminal in the last timeslot. This is to eliminate subtours (see more in Chapter 4.4.4). The timeslot set contains enough timeslots to ensure that for each round a car drive from a terminal and back again, it can stop at an optimal number of areas. For example, if a car needs to deliver to five areas in a round, we will need at least six timeslots (five drives to the areas and one drive back to the terminal). By some trial and error, we decided to run our models with twelve timeslots as we found that no round will need more drives than this. However, the model will be more computationally heavy for each additional timeslot, so it should be limited to as close to the maximum number of drives any round needs as possible. For example, if a car only needs to drive five drives, but the number of timeslots is twelve, it will stand still for no cost for seven of these timeslots.

We also include a set R for delivery rounds from a terminal and back to the terminal again. There can be a maximum number of twelve drives in each round, due to the maximum timeslots of twelve. We have run our models so that each company will deliver up to 43% of their potential demand through APLs, and we include R_max rounds, which for each company is $\frac{(demand\ for\ company)*0.43}{(car\ capacity)}$. A delivery car must drive back to the terminal when the car is out of parcels, thus completing the round.

Table 2 Model sets

Set	*Description*	*Value*
A	*Area*	*See appendix* 3
T	*Timeslot*	*{1,2,3,…,T_end}*
R	*Round*	*{1,2,3,…,R_max}*

Table 3 Model parameters

Parameter	*Description*	*Value*
M	*Large integer*	*10 000*
T_end	*Total number of timeslots*	*12*
Car_cap	*Parcel capacity of delivery car*	*112*
Apl_cap	*Parcel capacity of APL*	*14*
Distance_cost	*Cost of driving 100 meters in NOK*	*0.25*
Time_cost	*Cost of driving 1 minute in NOK*	*5*
Apl_cost	*All cost affiliated to an APL in one day*	*16.4*
$Distance_{i,j}$	*Distance between area i and j*	*See Chapter 3.2*
$Time_{i,j}$	*Travel time between area i and j*	*See Chapter 3.2*
$Demand_{i}$	*Demand for parcels with APLs in area i*	*See Appendix 3*

Table 4 Model variables

Variable	*Description*	*Type*
$Drives_{i,j,t,r}$	*Drive from area i to area j in timeslot t at round r*	*Binary*
$Demand\_fulfilment_{j,t,r}$	*Parcels delivered to area j in timeslot t at round r*	*Integer*
N_APL_{i}	*Number of APLs in area i*	*Integer*

4.4 Model 1 - Model with one company

Our first model aims to explore and compare costs between the different companies when they are operating individually. This model consists of a single company, where the decisions regarding positioning of the APLs and the routes are independent of other companies.

4.4.1 Objective function

The objective function minimizes the total cost of delivering the parcels to the APLs. The total cost consists of distance, time, and APL costs. The first part of the objective function multiplies the *distance_cost* of travelling 100 meters with the total distance driven. The second part multiplies the *time_cost* of driving 1 minute with the total time driven. The last part multiplies the daily cost related to an APL with the total number of APLs set up. The sum of these parts gives us the total cost of the solution.

1.1 $$Minimize: total\_cost$$

$$= distance\_cost \times \sum_{i \in A} \sum_{j \in A} \sum_{t \in T} \sum_{r \in R} (dis_{i,j} \times drives_{i,j,t,r})$$
$$+ time\_cost \times \sum_{i \in A} \sum_{j \in A} \sum_{t \in T} \sum_{r \in R} (time_{i,j} \times drives_{i,j,t,r})$$
$$+ apl\_cost \times \sum_{j \in A} n\_apl_j$$

4.4.2 Constraints

1.2 $\sum_{t \in T} \sum_{r \in R} \text{demand\_fulfilment}_{j,t,r} \leq \; demand_j \quad \forall \, j \in A$

1.3 $\sum_{t \in T} \sum_{j \in A} \text{demand\_fulfilment}_{j,t,r} \; = \; car\_cap \quad \forall \, r \in R$

1.4 $\sum_{i \in A} \text{drives}_{i,j,t,r} \times \; M \; \geq \text{demand\_fulfilment}_{j,t,r} \quad \forall \, j \in A, t \; \in \; T, r \; \in \; R$

1.5 $\text{apl\_cap} \times n\_apl_j \; \geq \sum_{t \, \in \, T} \sum_{r \, \in \, R} \text{demand\_fulfilment}_{j,t,r} \quad \forall \, j \; \in \; A$

1.6 $\sum_{j \, \in \, A} \; \text{drives}_{'posten\_terminal',j,1,r} = 1 \;\; \forall \, r \in R$

1.7 $\sum_{i \, \in \, A} \; \text{drives}_{i,'posten\_terminal',T\_end,r} = 1 \;\; \forall \, r \in R$

1.8 $\sum_{i \, \in \, A} \text{drives}_{i,j,t,r} = \sum_{i \, \in \, A} \text{drives}_{j,i,t+1,r} \quad \forall \, j \; \in \; A, t \; \in \; T\text{:} \, ord(t) \; \leq \; T\_end - 1, r \; \in \; R$

1.9 $\sum_{j \, \in A} \sum_{i \, \in \, A} \text{drives}_{i,j,t,r} \; \leq \; 1 \quad \forall \, t \; \in \; T, r \; \in \; R$

1.2 The total number of parcels delivered in each area must be less or equal to the demand in that area.

1.3 For every round driven, the sum of parcels delivered is equal to the car capacity. This ensures that all vehicles utilize their full capacity.

1.4 This constraint ensures that parcels can only be delivered to an area if there has been a drive to that area. By setting *M* sufficiently high, the delivery of parcels is not restricted by the constraint if there is a drive to that area.

1.5 This constraint states that the APL capacity in an area must be greater or equal to the actual delivered number of parcels to that area.

1.6 This constraint ensures that each round starts in the terminal. In the description of the model above, we use Posten’s terminal as an example, which is the case when we look at Company 1 operating independently with only its own terminal.

1.7 This constraint states that for every round, each final drive must end in the terminal, which in the model description above is Posten’s terminal.

1.8 Every car must eventually leave from the same place as it arrived. The number of times a car drives to an area must equal the number of times it drives from this area This is the case for all timeslots except T_end, which is the last timeslot for a round.

1.9 Each vehicle can at most make one drive for each timeslot.

4.4.3 Heuristics - stepwise approximation of model in AMPL

As our original model is too computationally heavy to run with AMPL, as explained in Chapter 2.2, we have modified the model to run it in several smaller steps instead of all at once. We removed the *Rounds* set from the models we ran in AMPL and instead ran the model once for each round from a terminal and back to the terminal. For each new round, the demand parameter is updated to exclude the demand that is fulfilled in all earlier rounds. We then introduce another variable, *next_demand*, which updates for each run.

- next_demand_j: Demand in area j for next round.

1.10 $\text{next\_demand}_j = \text{demand}_j - \sum_{t \in T} \text{demand\_fulfilment}_{j,t} \ \forall \, j \in A$

For each round after the first round, demand equals next_demand_j of the previous round. This modification to the model makes the optimization process manageable for the computer to run but does make the optimization worse than if we were able to run the model all in one go. The model selects the first round based on the route with the lowest cost. Followingly, the second round is the route with the second-lowest cost.

For example, the first round is just a short drive to the nearest areas surrounding the terminal, while the sixth and seventh rounds must drive further away from the terminal to find demand which can be fulfilled. This causes the costs to increase more than realistically for each additional demand fulfilled. The more demand that is fulfilled, the longer the routes become. Therefore, we have capped our demand fulfilment from APLs to 43% of the total parcel demand to avoid very unrealistic and long routes. The heuristic approach would not have worked effectively if we said that 100% of the demand should be fulfilled. This would force the model to run the long and unrealistic final rounds, which would make the total cost much higher than the total cost of the model presented above where all rounds are optimized at the same time.

We see 43% as an appropriate cap as it is unlikely, at least in the near future, that more than 43% of all B2C parcels are delivered through APLs. The heuristic makes it so that the individual delivery routes will not represent a realistic scenario, and we can therefore not use the individual routes for analysis. This makes it not able to use the model for route planning.

The only aspect of the model which changes when introducing our heuristic approach is that the rounds set is removed. This does not affect our results notably because we are still able to compare the total cost for different scenarios on an equal basis. By limiting the demand fulfilment to 43% we limit the difference in total cost between the heuristic approach and the model presented above. Even though the heuristics limits what we are able to analyse, we still see it as appropriate for our purpose, which is to compare different scenarios on an equal basis.

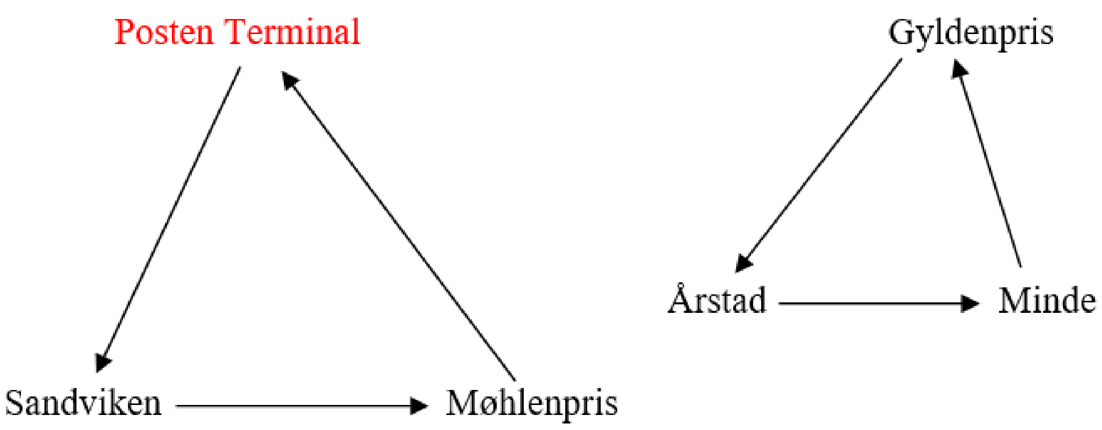
Implementing the heuristic approach still allows us to explore the following:

- Whether specific changes in parameters/data between different scenarios change the number of APLs that are placed/needed.
- Whether specific changes in parameters/data between different scenarios change total time and distance travelled.
- Differences in costs between different scenarios based on the two points above.

4.4.4 Time set

The subtour problem is a common problem when creating delivery route models. A subtour is a tour within a tour that is not connected to the original tour (Aggarwal, 2020). An example of a subtour is seen in Picture 4, where the tour or round between Gyldenpris, Årstad, and Minde is not connected to the original tour, which starts at the Posten terminal. In our model, we use the time set to specify when the drives are performed between the different APLs and terminals so that we avoid subtours, making all tours one connected set of drives.

Picture 4 Subtour example



4.5 Model 2 - Model with shared APLs

In this model, where the three companies share APLs, there are some changes from the model with individual companies. For model 2 and 3, we create a new set Q for the three terminals so that the models are easier to describe. For model 2, we also add set C for the three companies.

4.5.1 New sets, parameters and variables

Table 5 Additional set for Model 2

Set	*Description*	*Value*
C	*All postal companies*	$\{1,2,3\}$
Q	*All three terminals*	$\{posten, postnord, dhl\}$

Table 6 Modification of demand parameter for Model 2

Parameter	*Description*	*Value*
$Demand_{j,c}$	*Demand for parcels with APLs in area j for company c*	*See Appendix 3*

Table 7 Modification of variables for Model 2

Variable	Description	Type
$Drives_{i,j,t,r,c}$	Drive from area i to area j in timeslot t at round r for company c	Binary
$Demand\_fulfilment_{j,t,r,c}$	Parcels delivered to area j in timeslot t at round r for company c	Integer

4.5.2 New objective function

2.1
$$\text{minimize: total}cost$$
$$= \text{distance\_cost} \times \sum_{i\in A}\sum_{j\in A}\sum_{t\in T}\sum_{r\in R}\sum_{c\in C}(\text{dis}_{i,j} \times \text{drives}_{i,j,t,r,c})$$
$$+ \text{time\_cost} \times \sum_{i\in A}\sum_{j\in A}\sum_{t\in T}\sum_{r\in R}\sum_{c\in C}(\text{time}_{i,j} \times \text{drives}_{i,j,t,r,c})$$
$$+ \text{apl\_cost} \times \sum_{j\in A} n\_apl_j$$

For this model, we must also summarise the cost by each company *c* in *C*. Company 1 has company number 1, Company 2 has company number 2, and Company 3 has company number 3.

4.5.3 New constraints

2.2 $$\sum_{t \in T} \sum_{r \in R} \text{demand\_fulfilment}_{j,t,r,c} \leq \text{demand}_{j,c} \quad \forall j \in A, c \in C$$

2.3 $$\sum_{t \in T} \sum_{j \in A} \text{demand\_fulfilment}_{j,t,r,c} = \text{car\_cap} \quad \forall r \in R, c \in C$$

2.4 $$\sum_{i \in A} \text{drives}_{i,j,t,r,c} \times M \geq \text{demand\_fulfilment}_{j,t,r,c} \quad \forall j \in A, t \in T, r \in R, c \in C$$

2.5 $$\text{Apl\_cap} \times N\_APL_j \geq \sum_{t \in T} \sum_{r \in R} \sum_{c \in C} \text{demand\_fulfilment}_{j,t,r,c} \quad \forall j \in A$$

2.6 $$\sum_{j \in A} \text{drives}_{q,j,1,r,c} = 1 \quad \forall r \in R, q \in Q, c \in C$$

2.7 $$\sum_{i \in A} \text{drives}_{i,q,T\_end,r,c} = 1 \quad \forall r \in R, q \in Q, c \in C$$

2.8 $$\sum_{i \in A} drives_{i,j,t,r,c} = \sum_{i \in A} drives_{j,i,t+1,r,c} \quad \forall j \in A, t \in T: ord(t) \leq T\_end - 1, r \in R, c \in C$$

2.9 $$\sum_{j \in A} \sum_{i \in A} \text{drives}_{i,j,t,r,c} \leq 1 \quad \forall t \in T, r \in R, c \in C$$

All the constraints above are the same as the corresponding constraint presented under model 1, but now the constraints must also hold for all companies.

4.6 Model 3 - Model with shared terminals and APLs

This model is very similar to Model 1, the model with one company. Unlike Model 2, we do not include the set *C* for companies, because there are no restrictive differences between the different companies other than terminal capacity. Set *Q*, which was used in Model 2, is also included in Model 3. The only differences from Model 1 are the ones written below.

4.6.1 New set and parameter

Table 8 Additional sets in Model 3

Set	*Description*	*Value*
Q	*All three terminals*	$\{posten, postnord, dhl\}$

Table 9 Additional parameters for Model 3

Parameter	*Description*	*Value*
$Terminal\_capacity_q$	*The terminal capacity of the terminal q*	*See Appendix 4*

4.6.2 New constraints

3.1 $\sum_{r \in R} \sum_{j \in A} \text{drives}_{q,j,1,r} \times \text{car\_cap} \leq Terminal\_capacity_q \quad \forall\, q \in Q$

3.2 $\sum_{q \in Q} \sum_{j \in A} \text{drives}_{q,j,1,r} = 1 \;\forall\, r \in R$

3.3 $\sum_{i \in A} \text{drives}_{i,q,t\_end,r} = \sum_{j \in A} \text{drives}_{q,j,1,r} \;\forall\, r \in R, q \in Q$

3.1 The total number of parcels that are delivered from terminal q must be less than the terminal capacity of terminal q.

3.2 Every first drive in every round must start in one of the companies' terminals.

3.3 Every final drive in every round must end in the same terminal as the round started in.

Constraint 3.2 replaces constraint 1.6 from Model 1. Constraint 3.3 replaces constraint 1.7 from Model 1.

When we use the heuristic model without the *Rounds* set and instead run the model once for each round, we need the remaining number of parcels that can be transported from each terminal to update after each round, in the same way as the demand of each area updates. This is accomplished in the model by introducing another variable, $next\_capacity_q$, which updates for each run.

- next_capacity_q: Capacity at terminal q for next round.

3.4 $$\text{next\_capacity}_q = \text{terminal\_capacity}_q - \sum_{i \in A} \text{car\_cap} \times \text{drives}_{q,i,1} \quad \forall\, q \in Q$$

This equation subtracts the number of parcels that one car carries from $terminal\_capacity_q$ if a drive was performed from the respective terminal in this round. For each round after the first round, $terminal\_capacity_q$ equals $next\_capacity_q$ of the previous round.

5. Results and Analysis

For our analysis, we will assess scenarios where different percentages of total parcel demand are fulfilled by APLs. As explained earlier, the maximum demand that will be fulfilled by APLs is 43%. First, chapter 5.1, 5.2, and 5.3 considers a benchmark scenario using the data presented in Chapter 3. After this, we make systematic changes in parameters to assess different scenarios and discuss the most significant changes between the scenarios.

5.1 Analysis of Model 1 – Individual companies

For the first part of our analysis, we will assess the results from our first model, where each company works independently of the others. We will assess how cost, distance travelled, and time travelled develops as the number of parcels delivered to APLs increases. We will also compare the differences between the companies and assess to which degree the differences are attributed to the size of the company or the location of the terminal.

Company 1

Table 10 Cost for Company 1 by possible demand fulfilled

Parcels delivered	Percentage of possible demand delivered	Accumulated cost	Cost per parcel
448	11%	874.6	1.95
896	21%	2027.6	2.26
1344	32%	3321.4	2.47
1792	43%	4691.9	2.62

Company 2

Table 11 Cost for Company 2 by possible demand fulfilled

Parcels delivered	Percentage of possible demand delivered	Accumulated cost	Cost per parcel
224	11%	614.6	2.74
448	21%	1308.5	2.92
672	32%	2087.6	3.11
896	43%	3006.1	3.35

Company 3

Table 12 Cost for Company 3 by possible demand fulfilled

Parcels delivered	Percentage of possible demand delivered	Accumulated cost	Cost per parcel
112	11%	396.7	3.54
224	21%	846.8	3.78
336	32%	1363.7	4.06
448	43%	1894.3	4.23

As we see from Table 10, Table 11 and Table 12, the cost per parcel increases approximately linearly by parcels delivered. The increase as more demand is fulfilled is because we only include variable costs in the model. The increase in cost per parcel by parcels delivered is further slightly intensified by the heuristics, which makes the model run the lowest cost route first, then the second-best route, and so on. As the demand in the least costly areas runs out, the routes become longer and with more and more stops.

We also see quite large differences in cost per parcel between the companies. As stated, these differences can be attributed to two factors: the companies' size and the terminals' location. To assess to which extent each of these factors determines differences in costs between companies, we run our model with the demand of one company and the terminal location of the other company.

In Table 13, we see the cost per parcel of delivering 43% of potential parcel demand for each combination of the companies' demand and terminal location.

Table 13 Cost per parcel with different combinations of Company 1's, Company 2's and Company 3's demand and terminal location.

	Posten terminal	**PostNord terminal**	**DHL terminal**
Company 1 demand	2.62	2.84	2.90
Company 2 demand	3.12	3.35	3.29
Company 3 demand	4.13	4.31	4.23

Comparing the most cost-effective company to the least cost-effective, we see that Company 1's cost per parcel would increase from 2.62 to 2.90 per parcel if they moved to Company 3's terminal. This indicates that at a demand fulfilment of 43% for Company 1, their terminal location is worth 0.28 more than Company 3's location per delivered parcel. For Company 3, Company 1's location is worth 0.10 more than their own location per delivered parcel. We see, however, that even if the companies switched terminal locations, Company 1 would still have far lower costs per delivered parcel. This means that a significant majority of the cost differences are attributed to the difference in potential demand (size of the company).

We see that Posten's terminal is the most cost-effective for any demand level. However, with Company 1's demand level, PostNord's terminal is more cost-effective than DHL's terminal, but with Company 2 and 3's demand level, DHL's terminal is more cost-effective than PostNord's terminal. This means that for both Company 2 and 3, DHL's terminal is worth more than PostNord's terminal.

5.2 Analysis of Model 2 - Model with shared APLs

We will now compare the previous model where each company operated independently with a scenario with everything equal except that the companies now share APLs. Sharing the APLs can either be interpreted as the companies in a coalition mutually deciding the locations of their shared co-owned APLs, or it can be interpreted as publicly owned APLs that any company may use.

Table 14 Comparison of total cost between Model 1 and Model 2 at 43% demand fulfilment.

	Travel cost	**APL cost**	**Total cost**
Model 1 – individual	5803.25	3788.2	9591.5
Model 2 – shared APLs	5754.91	3771.98	9526.72
Percentage saving from Model 1 to Model 2	0.84%	0.43%	0.68%

As we see from Table 14, there are some savings for the travel cost and some for APL cost, but the savings are quite low. There are, however, some reasons to think that the attributes and combination of attributes for the different companies in this model create a low incentive to share APLs and that there might be other scenarios where the benefits are higher. One reason why there might be low incentives to share APLs in this scenario could potentially be due to Company 3's terminal being far away from the other terminals. Therefore, the other companies might have little or no incentive to share APLs with Company 3 as the travel cost for this might be too high. Another reason might be that Company 1 and, to some extent, Company 2 has a high potential demand and can fill entire APLs in most areas by themselves, and therefore do not have much to gain from sharing APLs. Because of these two factors, this scenario, with its current company attributes, does not seem to fully explore to which extent there might be benefits in sharing APLs. We will analyse this more in Chapter 5.5, where we will model different scenarios with different values for different APL costs, different demands for certain companies, and different terminal locations.

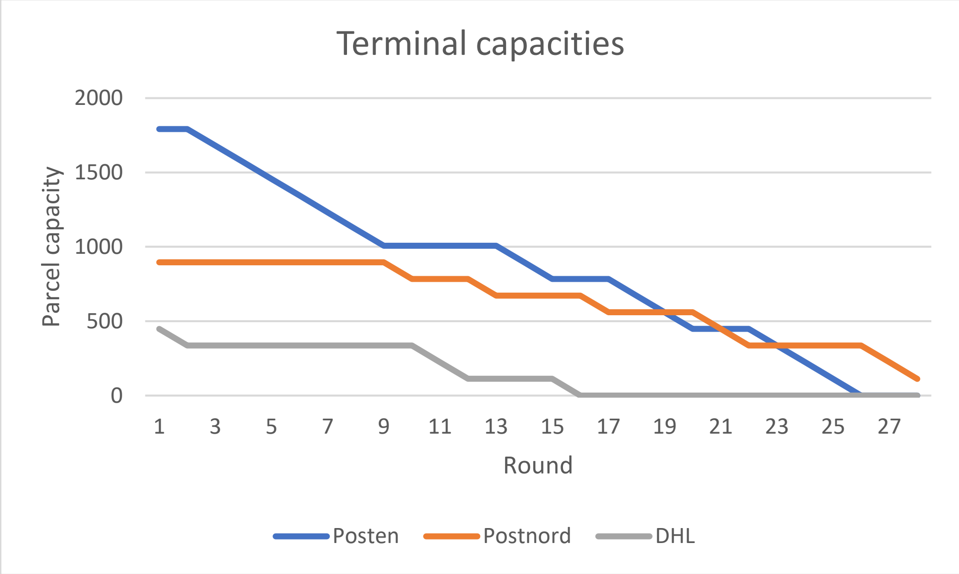
5.3 Analysis of Model 3 - Model with shared APLs and terminals

For this model, the companies can fully cooperate by sharing APLs and terminals. However, the terminal capacity for each company is proportional to the demand of the company. The total demand for all three companies is 7301 parcels. Followingly, 43% of 7301 parcels equals 3067 parcels, which will be delivered in 28 rounds of 112 parcels each round. We run the model 28 rounds, and the results can be seen in Appendix 2. We can see from Figure 1 that the cost per parcel increases each round, similarly to Model 1.

Figure 1 Cost per parcel by number of delivery rounds.

The terminal capacities for the 28 rounds can be seen in Figure 2 below. We see that Company 1's terminal is primarily the terminal used in the first nine rounds, and then the two other terminals are also used. The terminal of Company 3 reaches zero capacity at round 16. It is by then only possible to deliver parcels from the terminals of Company 1 and Company 2. Company 1 might have the best location of the three terminals, but as the demand from the surrounding areas decreases, it becomes optimal to also deliver from the other terminals.

Figure 2 Terminal capacities.



5.3.1 Analysis of Model 1 and 3 – differences in cost

When we add up the total cost in Model 1 for each of the three companies, we get an accumulated cost of 9591.5 (3006+4691.9+1894.3). The accumulated cost of Model 3 for the same number of parcels delivered is 7065.6. This is a reduction in total costs of 2525.9 or 26% compared to the total cost of Model 1 for all companies. This reduction in total cost results from lower travel costs and lower APL costs.

Lower travel costs amount to 2460.45 of the reduction in total cost. Full consolidation in Model 3 allows, for example, the terminal of Company 3 to fulfil every company's demand in the surrounding areas of Company 3's terminal. This is because full consolidation causes the demand of the three companies to be added together as one big demand which can be fulfilled from all three terminals. In Model 1, where each company operates on their own, Company 3 can, for example, find it most beneficial to deliver parcels to areas far from their own terminal as the demand of the closest areas runs out, which causes the travel costs to increase. An important note is that neither of the models include the cost of transporting the parcels to the different terminals, as this is outside the scope of the models. However, this element would likely make the savings of Model 3 compared to Model 1 smaller.

Lower APL costs amount to only 65.6 of the total savings of 2525.9, meaning the companies have slightly better utilized the capacity of the APLs and require four less APLs. An important factor to note is that the reduction of both travel and APL costs depends on the parameters we set in the model for APL cost, distance, and time travelled. Therefore, we will also explore how changes in APL cost, company size, and terminal locations affect the benefits of collaboration based on this model later in Chapter 5.5.

Table 15 Comparison between total cost between Model 1 and Model 3 at 43% demand fulfilment.

	Travel cost	APL cost	Sum
Model 1 – individual	5803.25	3788.2	9591.5
Model 3 – shared terminals and APLs	3342.8	3722.8	7065.6
Percentage saving from Model 1 to Model 3	42.24%	1.73%	26.33%

5.4 Effects of the heuristics

Our heuristic approach, which minimizes cost for each round instead of all rounds at once, will not minimize total cost as well as if we used a model that minimized total costs for all rounds simultaneously. An issue with the heuristic model is that the first rounds do not consider the later rounds. The result is that the later rounds can become long and ineffective. This issue would be solved if all rounds were optimized simultaneously, but this was not practically viable due to the run time of the model. The effect of this heuristic approach was limited by only allowing 43% of total demand to be fulfilled, thereby not allowing the model to run these long and unrealistic rounds when the demand runs low. Therefore, the total cost using this heuristic model is likely not too different than if the cost of all rounds were minimized simultaneously.

Since the heuristic models do not take the remaining rounds into account, this can result in a lower level of collaboration in model 2 and 3 than when all rounds are planned at the same time. An example of this could be if company 1 delivers to an area in the early rounds, they might not have any more demand left in this area for later rounds. In the later rounds, it might become optimal for company 2 to also deliver in this area. If company 1 had not already delivered to this area, the two companies could have collaborated in utilizing the APLs. This effect of the heuristic approach will in most cases underestimate the effect of collaboration, so the results of collaboration presented above and in the sensitivity analyses can be seen as a minimum effect of collaboration.

When we compare different scenarios, for example, comparing one scenario consisting of only small companies with one scenario consisting of companies of various sizes, the heuristic will have the same effect on both scenarios. Therefore, the conclusions regarding whether there are different levels of benefits between the different scenarios still holds.

5.5 Sensitivity analysis

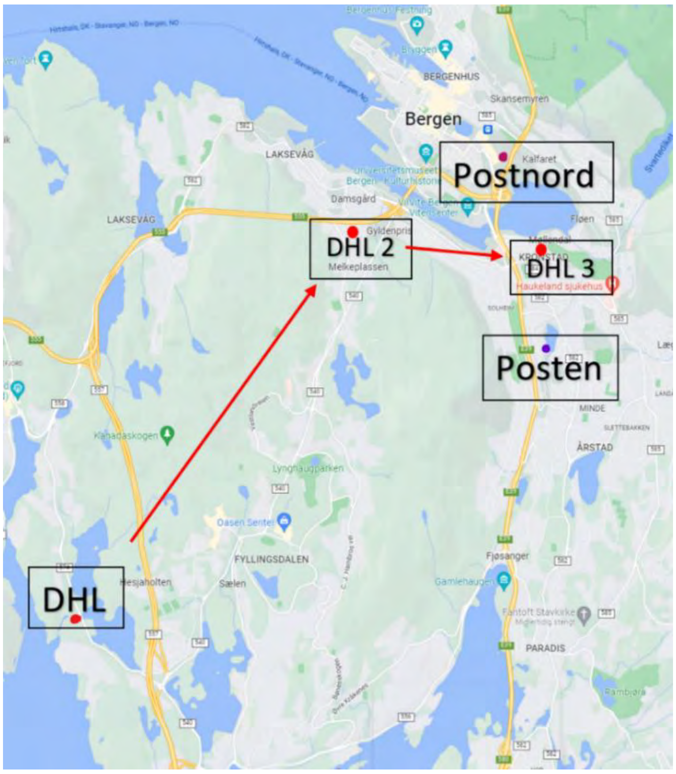
As stated in the Data chapter, the input data in the presented results are rough estimates of reality. This part of the analysis will use the already presented results and its data as a benchmark. We will look at seven additional scenarios. We will look at how the benefits of collaborating change between the benchmark scenarios presented in Chapters 5.1, 5.2, and 5.3 and these scenarios. The different scenarios are the following:

1. Cost of APLs
    a. High APL cost
    b. Low APL cost
2. Size of companies
    a. Decrease the demand of Company 2 to the size of the demand of Company 3
    b. Decrease the demand of Company 1 and Company 2 to the size of the demand of Company 3
3. Distance between terminals
    a. Company 3's terminal closer to the other two terminals
    b. Company 3's terminal even closer to the other two terminals
    c. All three terminals further away from Bergen city centre

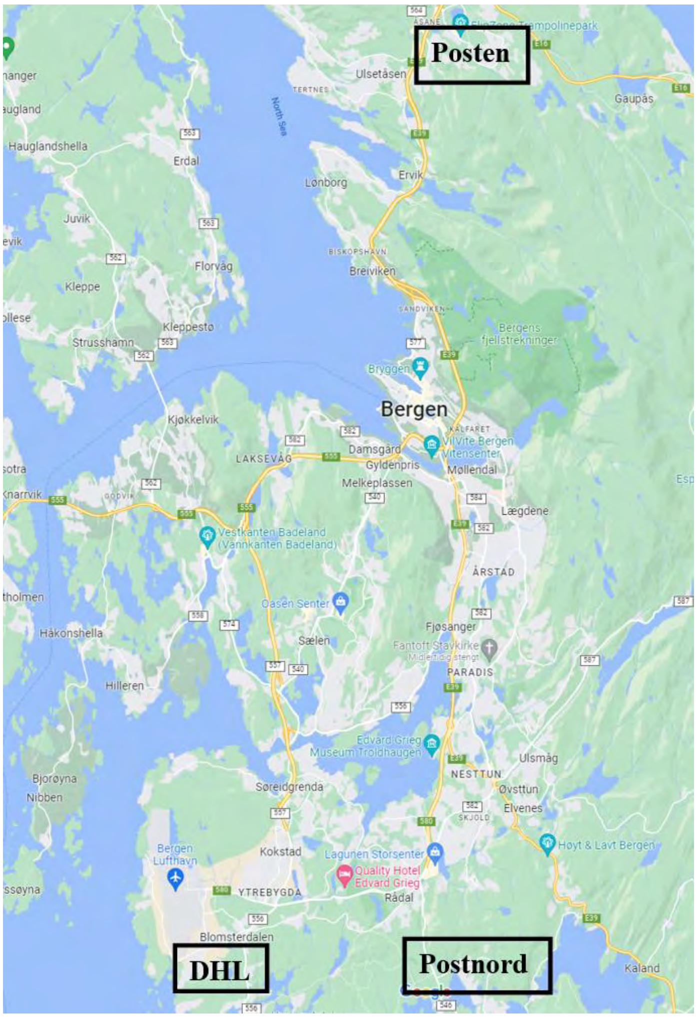
These seven scenarios are meant to explore the companies' benefits and willingness to share APLs and collaborate under different scenarios, as well as the effect on the total cost.

For scenarios 1a and 1b, the cost of APLs will be doubled and reduced by half, respectively. Regarding distance between terminals, Picture 5 displays where Company 3's terminals are placed in scenarios 3a and 3b. Picture 6 displays where all the terminals are located in scenario 3c. This is not an unrealistic scenario because we have seen plans from many postal companies to relocate their terminals further away from the Bergen city centre, for example, the new terminal of PostNord in Os (Postnord, 2021).

Picture 5 Location of Company 3's terminal in different scenarios.



Picture 6 Locations of terminals in scenario with terminals located further from the city centre.



5.5.1 Sensitivity analysis Model 2 compared to Model 1

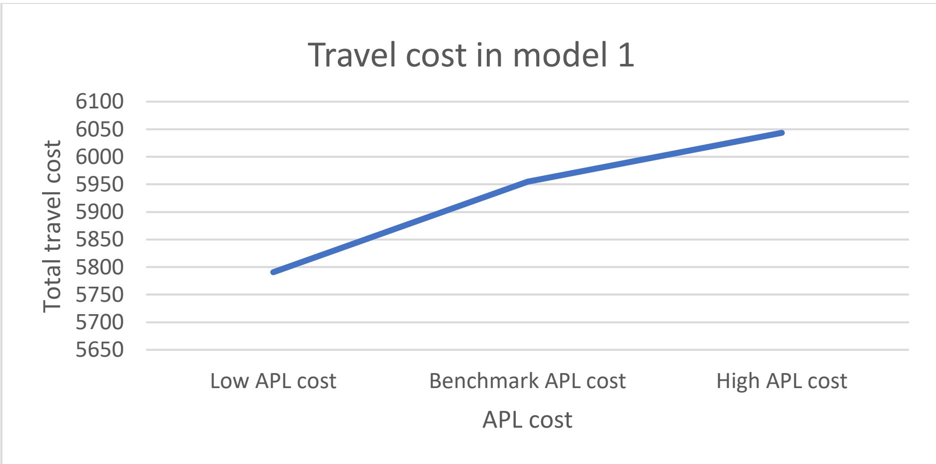
Sensitivity analysis 1: Cost of APLs

Table 16 Savings (reduction in cost from Model 1 to Model 2) from sharing APLs with different APL costs.

	Low APL cost	**Original APL cost**	**High APL cost**
Saving travel cost	-0.03 %	0.84 %	-0.50 %
Saving APL cost	0.84 %	0.43 %	0.87 %
Total savings	0.19 %	0.68 %	0.26 %

The savings from sharing APLs are quite low in all these scenarios. As both the scenario with higher APL cost and lower APL cost decreases the benefits of collaboration compared to the benchmark scenario, we do not detect a linear pattern between APL cost and incentive to share APLs. As the savings in all these scenarios are close to none, we will not analyse these differences much further. We expected savings to increase when APL cost increases since unused APL capacity is then more costly, potentially leading to a higher effort to share APLs. However, whether the companies can improve the utilization of APLs, depends on how well they could utilize them when operating individually. Companies will to a great extent, already when operating independently, adjust their routes in order to utilize their APLs better. As seen in Figure 3 below, when operating independently, companies will drive longer routes as APL cost increase in order to utilize the capacity of their APLs better. This displays how companies perform a trade-off between travel and number of APLs as APL cost increase.

Figure 3 Total travel cost for different APL costs in Model 1.



Sensitivity analysis 2: Size of companies

Table 17 Savings (reduction in cost from Model 1 to Model 2) from sharing APLs in scenarios where companies have different parcel demands.

	Benchmark scenario	**Company 2 decreased demand**	**Company 1 and Company 2 decreased demand**
Saving travel cost	0.84 %	0.25 %	2.40 %
Saving APL cost	0.43 %	1.99 %	8.33 %
Total savings	0.68 %	0.89 %	4.10 %

Out of the different scenarios, the one where the demand of all the companies decreased to Company 3's demand is the one with the highest potential savings from sharing APLs, with 4.1% in total savings. We also see that the companies not only are saving from reduced travel costs but are also saving significantly from reduced APL costs. This indicates that companies have a higher incentive to share APLs when both/all parties have limited ability to utilize entire APLs at a given location. Therefore, as demand decreases, it becomes more cost-efficient to collaborate.

Sensitivity analysis 3: Location of terminals

We have seen from earlier in this subchapter that in scenarios where the companies have the original benchmark demand, the benefits of collaboration were low. We will therefore assess how changing the locations of the terminals, according to Picture 5 and Picture 6, affects the benefits of sharing APLs when all the companies have low demand.

Table 18 Cost when sharing APLs in scenarios with different terminal locations and all companies have low demand.

	Original locations	Company 3 at location 2	Company 3 at location 3	All terminals away from city centre
Total APL cost	1623.6	1640	1689.2	1654.4
Total travel cost	4306.8	4333.1	4146.8	5395.5
Total cost	5930.4	5973.1	5836	7051.9

We see from Table 18 that the total cost is quite similar regardless of whether Company 3's terminal is at location 1, 2, or 3. However, the cost is significantly higher when all the terminals are further away from the city centre.

Table 19 Savings (reduction in cost from Model 1 to Model 2) from sharing APLs in scenarios with different terminal locations.

	Original locations	Company 3 at location 2	Company 3 at location 3	All terminals Away from city centre
Saving travel cost	2.40 %	2.61 %	3.44 %	0.77 %
Saving APL cost	8.33 %	6.54 %	4.63 %	6.48 %
Total savings	4.10 %	3.72 %	3.79 %	2.18 %

From Table 19, we see that moving Company 3's terminal closer to the other companies' terminals did not increase the benefits of sharing APLs. The total savings are around 4% when having Company 3 at any of these three terminals. Moving Company 3's terminal closer increased potential savings from travel costs but reduced potential savings from APL costs. The distance between the terminals is naturally just one out of many factors at play here as each location has several different attributes that determine potential savings, other than just its proximity to other terminals. However, we see that moving all three terminals further away from the city centre significantly decreases the benefits of sharing APLs. In this scenario, the savings due to reduced APLs are still high, but the savings due to travel cost is significantly lower than in the other scenarios.

5.5.2 Sensitivity analysis Model 3 compared to Model 1

Sensitivity analysis 1: Cost of APLs

Table 20 Savings (reduction in cost from Model 1 to Model 3) from sharing APLs and terminals with different APL costs.

	Low APL cost	Original APL cost	High APL cost
Saving travel cost	45.08 %	42.40 %	46.71 %
Saving APL cost	5.76 %	1.73 %	3.02 %
Total savings	35.03 %	26.33 %	21.97 %

The change in relative savings of travel cost and APL cost between these scenarios does, like the corresponding analysis for Model 2, not seem to have a linear trend as APL cost changes. The total savings are, however, decreasing significantly as APL cost increase. However, this is due to the proportions between APL and travel costs. When APL cost is low, travel cost naturally makes up a higher percentage of total cost than when APL cost is high. As seen in Table 20, most of the savings are through reduced travel costs, so the higher the travel cost compared to APL cost, the higher the total savings are for this model.

Sensitivity analysis 2: Size of companies

Table 21 Savings (reduction in cost from Model 1 to Model 3) from sharing APLs and terminals in scenarios where companies have different parcel demands.

	Original demand	Company 2 decreased demand	Company 1 and Company 2 decreased demand
Saving travel cost	42.40 %	46.29 %	55.66 %
Saving APL cost	1.73 %	3.50 %	8.41 %
Total savings	26.33 %	29.80 %	41.05 %

The results here are similar to those from sensitivity analysis 3 from Chapter 5.5.1, where savings from APL cost is over 8% when all companies have the demand of Company 3. The total savings when comparing Model 1 to Model 3 are here also highest when all the demands are set to the demand of Company 3. However, the savings in travel costs are much higher when the companies share both APLs and terminals compared to just APLs, as in sensitivity analysis 3 from Chapter 5.5.1. There is a considerably increased incentive to consolidate when the model consists of several smaller companies. This is because when demand runs low, the companies are not always able to utilize the full capacity of the APLs by themselves.

Sensitivity analysis 3: Distance between terminals

Table 22 Cost when sharing APLs and terminals in scenarios with different terminal locations.

	Original location	Company 3 at location 2	Company 3 at location 3	All terminals away from city centre
Total travel cost	3342.8	3565.3	3499.5	4344.1
Total APL cost	3722.8	3706.4	3722.8	3722.8
Total cost	7065.5	7271.7	7222.3	8066.9

Table 23 Savings (reduction in cost from Model 1 to Model 3) from sharing APLs and terminals in scenarios with different terminal locations.

	Original location	Company 3 at location 2	Company 3 at location 3	All terminals away from city centre
Saving travel cost	42.40 %	38.95 %	55.43 %	46.69 %
Saving APL cost	1.73 %	2.59 %	2.16 %	3.40 %
Total savings	26.33 %	24.60 %	24.31 %	32.79 %

These scenarios show that the total cost is lowest when Company 3's terminal is far away from the two other terminals at its current location and second lowest at location number 3. We see from Table 22 that almost all the difference in total cost between the different terminal locations can be attributed to travel cost. The original location of Company 3's terminal could be the best location because it cheaply covers an area far away from the other two terminals. The original location leads to the lowest total cost for all companies, but it is not the one with the highest relative savings compared to Model 1.

The highest relative savings from Model 1 to Model 3 is when all terminals are placed further away from the city centre. The consolidation benefits are highest when the three terminals can deliver parcels in separate areas because the three companies share the total demand in Model 3. The total relative savings from Model 1 to Model 3 are 32.79% when all terminals are placed further away from the city centre, but the total cost is highest in this scenario. We can see from Table 22 that the total cost is 8066.9 in Model 3 when all terminals are placed further away from the city centre. The total APL cost is similar to the other scenarios, but the total travel cost is 4344.1, which is much higher than the other three scenarios. This is as expected because a high level of the demand is from the city centre and its surrounding areas, so travel distances and travel times become higher as the companies relocate their terminals. The relocation of the terminals to the outside of the city centre could likely have some other benefits which may outweigh the increased cost of last-mile delivery. Such benefits could be larger terminals, the possibility for larger cars, and lower rent, but these benefits are not something we will consider further in our analysis.

As we see from Table 23, the savings from collaboration are the highest when alle the terminals are further away from the city centre. For the corresponding analysis for Model 2, the results were the opposite, and the scenario with all terminals away from the city centre showed the lowest savings from collaboration. This is because when the companies also share terminals, large distances lead to larger savings as the companies can use each other's terminals to cover areas that otherwise would be costly for themselves. However, when the companies only can share APLs, the terminals might be too far away from each other for it to be beneficial to "meet in the middle" in order to share APLs, and the companies will to a smaller extent collaborate.

5.6 Effects on traffic from collaboration

We have seen that the travel costs are marginally reduced when the companies share APLs compared to operating alone, and even more when the companies also share APLs and terminals. This is the case for every scenario in the sensitivity analyses, except for the first scenario using Model 2, where there are some increased travel costs compared to Model 1. This increase is seen when the APL cost is high and low, as seen in Table 16, but the increase is only marginal, so there is nothing to conclude from this. All other results show a decrease in travel costs when the companies collaborate. This shows that when the companies collaborate, they drive less, and there is less traffic. The more the companies collaborate, the more the traffic is reduced. This may transfer to emissions as well, depending on the type of fuel and fuel source.

5.7 Allocation of costs and benefits

The grand coalition cost calculated in the benchmark scenario with Model 3 was 7065.6. The individual costs calculated in Model 1 were 4691.9, 3006.1, and 1894.3 for Company 1, Company 2, and Company 3, respectively. We will now look at different ways the cost of the grand coalition can be divided between the three companies when the companies share terminals and APLs. We will not look at cost allocations for scenarios other than the benchmark scenario using Model 3 because we are primarily interested in comparing the different cost allocations. The findings in this chapter can be transferred to the other scenarios in Chapter 5.4 to some extent, but it is important to note that there may not be a stable cost allocation when the different parameters change.

Table 24 Total costs for individual companies and different coalitions in the benchmark scenario.

Coalition	Optimal cost
Grand Coalition	7065.6
Company 1 (16 rounds)	4691.9
Company 2 (8 rounds)	3006.1
Company 3 (4 rounds)	1894.3
Company 1+Company 2 (16+8 rounds)	6396
Company 1+Company 3 (16+4 rounds)	5147
Company 2+Company 3 (8+4 rounds)	3537

5.7.1 Egalitarian method

One allocation method which was not discussed in the theory chapter is the egalitarian method, where the cost is divided by the number of companies in the coalition. This allocation method demonstrates why a good and fair cost allocation is essential. The egalitarian method would give an equal cost to each company of 7065.6/3 = 2355.2. This allocation can neither be seen as fair nor stable. Company 3, the smallest company, is allocated a higher cost than their stand-alone cost, so they would not want to be a part of the coalition. Therefore, the individual rationality condition is violated.

5.7.2 Cost allocation based on shapely values

See Appendix 1 for calculations of the Shapley values. The absolute savings are quite similar for all companies when we use Shapley values to allocate the cost of the grand coalition. The relative savings are highest for Company 3, while it is lowest for Company 1. The sum of the three Shapley values equals the grand coalition costs of 7065.6, which means that all the cost is allocated, and the efficiency condition is met.

.

Table 25 Cost allocation based on Shapley values in the benchmark scenario

Company	Shapley value	Stand alone cost	Absolute savings	Relative savings
Company 1	3847.3	4 691.90	844.60	18 %
Company 2	2199.3	3006.10	806.80	27 %
Company 3	1018.98	1 894.30	875.32	46 %

We see that all the Shapley values are lower than the respective companies' stand-alone costs, which means that the individual rationality condition is met. For the allocation to be stable, the rationality condition must also hold for all other smaller coalitions. The rationality condition for the three remaining coalitions can be seen from the three equations below. We see that the rationality condition is met for all smaller coalitions, so we can conclude that the rationality condition is met, and that the Shapley allocation is stable.

$$u_{posten} + u_{postnord} = 3847.3 + 2199.3 = 6046.6 \leq 6396$$

$$u_{posten} + u_{dhl} = 3847.3 + 1018.98 = 4866.28 \leq 5147$$

$$u_{postnord} + u_{dhl} = 2199.3 + 1018.98 = 3218.28 \leq 3537$$

The Shapley method allocates a cost to the participants based on a weighted average of the marginal cost that the participants cause when joining the grand coalition. Company 1 brings a higher marginal cost to the coalition than the two other companies. Company 3 is the one that causes the lowest cost, and it is therefore allocated the lowest Shapley value.

5.7.3 Cost allocation based on Equal Profit Method

Compared to the companies' stand-alone costs, the relative savings are all around 25-28%, which can be seen from the table below. The goal of the EPM is to get similar relative savings for each of the companies, so it is expected that the relative savings will be similar for the three companies. The EPM is guaranteed to give a stable allocation, meaning that both the efficiency and rationality conditions hold.

Table 26 Cost allocation based on EPM in the benchmark scenario.

Company	EPM cost allocated	Stand alone cost	Absolute savings	Relative savings
Company 1	3528.60	4691.90	1163.30	25 %
Company 2	2166.94	3006.10	839.16	28 %
Company 3	1370.06	1894.30	524.24	28 %

If we compare the allocation of the EPM to the Shapley allocation, we see that Company 2 has about the same savings in both allocations. The big difference is the cost allocation of Company 3 and Company 1. Using Shapley allocation, Company 1 has 18% in relative savings compared to 25% for the EPM allocation. Company 3 has 46% in relative savings using the Shapley allocation compared to 28% for the EPM allocation.

5.7.4 Suggestion to cost allocation

An egalitarian allocation may be the simplest allocation method, but it is too simple in this case. It will not be fair to allocate the same cost to Company 1 and Company 3 because their stand-alone costs are too different. Therefore, Company 3 will not want to collaborate with the two others if allocated such a high cost. The EPM gives as similar relative savings as possible compared to the companies' stand-alone costs. This can therefore be seen as a fair allocation method, while it at the same time is guaranteed to meet both the efficiency and rationality conditions. The allocation based on Shapley values is a fair allocation because it fulfils the four axioms stated in Chapter 2.4.2. The Shapley allocation allocates more cost to Company 1 and less to Company 3 than the EPM allocation because Company 1 causes more cost in the grand coalition than Company 3 does. This can be seen as a fair principle. A big downside to the Shapley allocation is that the calculations of the cost of the different coalitions can be very computational heavy if there are many companies. This is not a problem with only three companies, but it will be if more companies are included. We suggest using an allocation based on either Shapley values or the EPM allocation.

6. Discussion

6.1 Public authorities perspective

We found in Chapter 5.4.1 that when the demand of all companies was set to the lowest, the potential savings from sharing APLs were by far at their highest. The companies had both reduced travel costs and APL costs. This showed that companies attain higher benefits from collaboration when their demand is low, or in other words, when the companies are smaller. The key takeaway from this for public authorities is that they could look into ways to help smaller companies collaborate to be more cost-effective and reduce traffic. If the public authorities help the smaller companies collaborate through subsidiaries or other economic incentives, the companies could be nudged to try to collaborate and thereafter see the savings they can get by collaborating. Another form of incentive could, for example, be that the collaborating companies are allowed to use the public transport lane in rush hours.

Subsidizing collaboration between at least the smaller postal companies could reduce traffic and emissions. A goal for public authorities could be to avoid some of the negative consequences of having many small companies, by securing some form of collaboration between the smaller companies, to avoid excessive traffic with postal vehicles and APLs operating far below their capacity.

Another question for the public authorities to deal with is whether the APLs should be private or public. An issue that could arise if the APLs continue to be private as they are today, is that there might become a significant number of APLs in public places, such as outside shopping centres and outside of grocery stores. This could take up unnecessary amounts of space, at least if the delivery to APLs increases and the companies need more APLs. A solution for the government could be only to allow public APLs in public areas so that the companies deliver to the same APL, and in that way, reduce the number of APLs needed. This would likely cause some coordination problems between the companies, for example, running out of capacity in the shared public APLs. However, public APLs would likely reduce the space taken up by APLs and, at the same time, perhaps make it easier for the companies to collaborate. Moreover, a public APL is for everyone to use, so it could likely be a smaller barrier for the companies to start further collaboration than if they had each their own APLs.

6.2 External validity

The findings of this thesis are based on data from the city of Bergen but are possible to generalize to other cities. The data used for Bergen, such as distance, time, and demand data, can be changed to another city or adjusted to reflect Bergen's situation more precisely. The models developed in this thesis can be used on any dataset with sufficient data on distance, time, and demand. The parameters used for the different costs can also be changed if anyone wants to use more realistic numbers for these parameters. The goal of the thesis has not been to calculate the exact costs or specific numbers related to traffic in Bergen but rather to create models which can answer our research questions. The findings are therefore generalizable to other cities as well.

However, an important note is that when the cities become larger than Bergen or more than three postal companies are considered, the way the data is sorted may need to change. An example is that the model becomes increasingly difficult to run as more data points are included. A solution to this could be to make adjustments, such as combining the demand of areas less than 10 minutes in driving distance from each other rather than the 5 minutes we used when sorting our demand data.

6.3 Further research

An interesting factor to include in further research is where people are traveling or located throughout the day. This could improve estimations on where people are likely to want to pick up parcels. Implementing this information would enable us to more precisely locate where the demand for APLs will be and thereby get more precise results from the model. It could, for example, be certain bus stops or shopping centres. We used the parcels delivered by PostNord as a proxy for demand in our model, but adjusting this data additionally, could generate more realistic demand data.

Another addition that could improve our models is to include information about traffic flow at different times of the day. The time it takes to drive the different routes likely varies a lot based on the time of the day and the amount of traffic. This addition to the models would therefore improve the routes so that they would also take traffic into account. Including traffic flow would require a more precise time aspect in the model as well to be able to differentiate between different times of the day.

Our analysis has mainly focused on postal companies, which in addition to APLs deliver parcels by other methods. Further research could have a more holistic approach where costs and benefits of various combinations of delivery methods are analysed together. In addition, costs of transporting parcels to the terminals could be considered.

The concept of APLs may also be extended to businesses outside traditional parcel delivery, such as grocery stores and other stores selling private goods. Further studies could focus on assessing APL's broader potential and how they can be used directly between the sellers and buyers of products without a postal company as the middleman.

7. Conclusions

In this thesis, we have developed different network design models for parcel delivery in Bergen using mixed-integer linear programming. The purpose of these models was to assess postal companies' benefits and incentives to collaborate and assess to which extent costs can be reduced through collaboration and consolidation. In addition, we performed sensitivity analyses to look at how different levels of APL costs, terminal locations, and company sizes affect costs and the benefits of collaboration. Lastly, we also looked at different ways of allocating the cost when the companies collaborate.

We developed three models, one where there is no collaboration between the postal companies (Model 1), one where the postal companies can share APLs (Model 2), and one where the postal companies can share both APLs and terminals (Model 3). We first ran our model with a benchmark scenario with one small, medium, and large company. For our benchmark scenario, Model 1 had a total cost for all companies of 9591.45, when 43% of all demand was delivered. Model 2, where the companies share APLs, presents a total saving compared to Model 1 of 0.68%. Finally, model 3, where both APLs and terminals are shared between the companies, led to a reduction in total costs of 26% compared to Model 1.

From the first sensitivity analysis, we did not find that different levels of the APL-cost parameter affected the companies' incentive to collaborate when only sharing APLs. However, when companies also shared terminals, collaboration resulted in far higher savings when APL cost was low relative to travel cost.

From the second sensitivity analysis, we found that in scenarios where we decreased the demand of the larger companies, the companies saved significantly more from collaboration. This was the case both when companies only had the option to share APLs and when they had the option to share both APLs and terminals.

The third sensitivity analysis showed that the further away the terminals are from each other, the more beneficial it is to share both APLs and terminals. When all terminals are further away from the city centre, the benefits from sharing both APLs and terminals are the highest, but the lowest when only sharing APLs. However, the total costs are the highest when all the terminals are placed further away from the city centre.

The three different cost allocation methods presented different relative savings for each company. The egalitarian method is seen as neither a fair nor stable allocation, while cost allocation based on EPM, and Shapley values were both stable for the benchmark scenario. This indicates that full collaboration with sharing APLs and terminals can be theoretically beneficial for all parties. Allocation based on Shapley values gave high relative savings to Company 3 and low relative savings to Company 1, compared to the EPM allocation.

Bibliography

Aggarwal, A. (2020, December 6). *Techniques for Subtour Elimination in Traveling Salesman Problem: Theory and Implementation in Python*. Retrieved from Medium: https://medium.com/swlh/techniques-for-subtour-elimination-in-traveling-salesman-problem-theory-and-implementation-in-71942e0baf0c

Allen, J. B. (2012). *The Role of Urban Consolidation Centres in Sustainable Freight Transport.* Retrieved from Transport Reviews: https://www.researchgate.net/publication/254324483_The_Role_of_Urban_Consolidation_Centres_in_Sustainable_Freight_Transport

Baldur, B. (2021, May 18). *Nettnord*. Retrieved from Posten Norge dekker Norge med pakkebokser: https://nettnord.no/posten-norge-dekker-norge-med-pakkebokser/

Basso, F., D'Amours, S., Ronnqvist, M., & Weintraub, A. (2019). A survey on obstacles and difficulties of practical. *International Transactions in Operational Research*, 775-793.

Chaberek, G. (2021). The Possibility of Reducing Individual Motorised Trafficthrough the Location of Collection Points Using the Example ofGda ́nsk, Poland. *Sustainability*, 13.

Dorman, M., Buckley, T., Dannenberg, A., Bhaskar, M., & Fonseca-Zamora, J. (2022, 01 13). Retrieved from cran.r-project: https://cran.r-project.org/web/packages/mapsapi/index.html

Frisk, M., Göthe-Lundgren, M., Jörnsten, K., & Rönnqvist, M. (2010). Cost allocation in collaborative forest transportation. *EJOR*.

Google. (2022). Retrieved from Google Maps Platform: https://mapsplatform.google.com/

Guajardo, M. (2021). *BAN402 - Decision Modeliing in Business, collaboration and benefits sharing.*

Hyangsook, L. (2019). Development of a Decision Making System for Installing Unmanned ParcelLockers: Focusing on Residential Complexes in Korea. *KSCE Journal of Civil Engineering*, 1-2.

International Post Corporation. (2021, July). Retrieved from 2021 - Last mile delivery hype or saviour? Let’s talk parcel lockers: https://www.ipc.be/services/markets-and-regulations/e-commerce-market-insights/e-commerce-articles/parcel-lockers

Juven O, D. S. (2021, January 7). *Får forby fossilbiler - byrådet i Oslo og Bergen jubler*. Retrieved from NRK.no: https://www.nrk.no/osloogviken/far-forby-fossilbiler---oslo-og-bergen-jubler-1.15316658

Kenton, W. (2022). *Shapley Value*. Retrieved from Investopedia: https://www.investopedia.com/terms/s/shapley-value.asp

Ludt, Ø. (2021, October 13). *Posten kjøper 50 nye Maxus*. Retrieved from mtlogistikk.no: https://www.mtlogistikk.no/elektrisk-varebil-maxus-maxus-e-deliver-9/posten-kjoper-50-nye-maxus/609889

Lund, S., Madgavkar, A., Manyika, J., Smit, S., Ellingrud, K., & Robinson, O. (2021, February 18). *The future of work after COVID-19.* Retrieved from McKinsey Global Institute.

Lundgren, J., Ronnqvist, M., & Varbrand, P. (2010). *Optimization* (1:2 ed., Vol. 1). Linkoping: Studentlitteratur.

Luo, R., Ji, S., & Ji, Y. (2022, January 6). An active-learning Pareto evolutionary algorithm for parcel locker network design considering accessibility of customers. *Computers & Operations Research*.

Ornstein, I. R. (2019). Flexible parcel delivery to automated parcel lockers: models, solution methods and analysis. *EURO J Transp Logis*, 1.

Parcelmonitor. (2021, December 8). Retrieved from Dwell Time Analysis of Parcels in Collection Points: https://www.parcelmonitor.com/blog/dwell-time-analysis-of-parcels-in-collection-points/

Pedersen, R. (2021, January 5). *Beregn årlige bilkostnader for ny bil*. Retrieved from Smartepenger: https://www.smartepenger.no/kalkulatorer/872-bilkostnader

Post & Parcel. (2022, February 28). Retrieved from SWIPBOX INSTALLS MORE THAN 150,000 PARCEL LOCKER COMPARTMENTS IN RECORD YEAR: https://postandparcel.info/146990/news/e-commerce/swipbox-our-long-term-strategy-has-paid-off/

Posten. (2021). *Hent pakker i Pakkeboks*. Retrieved from posten.no: https://www.posten.no/motta/fleksibelt/pakkeboks?gclid=CjwKCAjwu_mSBhAYEiwA5BBmf_rhEdzhBcDEYMq7ZJnOGrpXXVN4RYuQZHdxDKTMNGtwGCewU9N4QRoCN44QAvD_BwE

Postnord. (2021, August 30). *PostNord med ny terminal for Bergen: - Endelig har vi har tatt over Lyseparken.* Retrieved from Postnord.no: https://www.postnord.no/nyheter/postnord-med-ny-terminal-for-bergen

Refaningati, T. T. (2020). Analysis of Characteristics and Efficiency ofSmart Locker System (Case Study: Jabodetabek).

Rodrigue, J.-P., & Dablanc, L. (2020). *City Logistics_ Concepts, Policy and Practice*. Retrieved from globalcitylogistics.com: https://globalcitylogistics.org/home/a-freight-and-the-city/what-is-city-logistics/

Simoni, M., Bujanovic, P., Boyles, S., & Kutanoglu, E. (2018). Urban consolidation solutions for parcel delivery considering location, fleet. *Case Studies on Transport Policy*, 112-124.

Sunol, H. (2021, March 14). *Cyzberg Warehouse Technology*. Retrieved from Consolidation Warehouse – Its Meaning, Benefits, and Drawbacks: https://articles.cyzerg.com/consolidation-warehouse-meaning-benefits-and-drawbacks

Swipbox. (2022, February 16). Retrieved from Swipbox: https://www.swipbox.com/

Taniguchi, E. (2014). Concepts of City Logistics for Sustainable and Liveable Cities. *Procedia - Social and Behavioral Sciences*, 310-317.

Torkington, S. (2021). The pandemic has changed consumer behaviour forever - and online shopping looks set to stay. *World Economic Forum.*

Utdanning.no. (2022). *Postbud*. Retrieved from Utdanning: https://utdanning.no/yrker/beskrivelse/postbud

Vahrenkamp, R. (2016). *25 Years City Logistics: Why failed the urban consolidation centres?* . Retrieved from European Transport.: https://www.researchgate.net/publication/316878308_25_years_city_logistic_Why_failed_the_urban_consolidation_centres

van Duin, J., Wiegmans, B., van Arem, B., & vam Amstel, Y. (2020). From home delivery to parcel lockers: a case study in Amsterdam. *Transportation Research Procedia*, 37-44.

Appendix

Appendix 1: Shapley value calculations

U_Company 1 = ((3-1)!*(1-1)!)/3!*4691.9+((3-2)!*(2-1)!)/3!*(6396-3006.1+5147-1894.1)+((3-3)!*(3-1)!)/3!*(7065.6-3537) = 3847.3 kr is the cost allocated to Company 1 in the grand coalition if we use shapely values

U_Company 2 = ((3-1)!*(1-1)!)/3!*3006.1+((3-2)!*(2-1)!)/3!*(6396-4691.9+3537-1894.3)+((3-3)!*(3-1)!)/3!*(7065.6-5147) = 2199.3kr is the cost allocated to Company 2 in the grand coalition if we use shapely values

U_Company 3 = ((3-1)!*(1-1)!)/3!*1894.3+((3-2)!*(2-1)!)/3!*(5147-4691.9+3537-3006.1)+((3-3)!*(3-1)!)/3!*(7065.6-6396) =1018.98 is the cost allocated to Company 3 in the grand coalition if we use shapely values

Appendix 2: Model 3 benchmark results

Parcels delivered	Percentage of total parcel demand	Accumulated cost	Cost per parcel
112	2 %	190.45	1.70
224	3 %	393.40	1.76
336	5 %	596.35	1.77
448	6 %	808.55	1.80
560	8 %	1023.00	1.83
672	9 %	1237.45	1.84
784	11 %	1459.40	1.86
896	12 %	1685.10	1.88
1008	14 %	1913.80	1.90
1120	15 %	2146.25	1.92
1232	17 %	2378.70	1.93
1344	18 %	2616.15	1.95
1456	20 %	2855.60	1.96
1568	21 %	3095.05	1.97
1680	23 %	3338.75	1.99
1792	25 %	3588.95	2.00
1904	26 %	3843.65	2.02
2016	28 %	4105.00	2.04
2128	29 %	4366.70	2.05
2240	31 %	4643.15	2.07
2352	32 %	4932.60	2.10
2464	34 %	5224.05	2.12
2576	35 %	5517.40	2.14
2688	37 %	5813.85	2.16
2800	38 %	6110.35	2.18
2912	40 %	6421.55	2.21
3024	41 %	6732.75	2.23
3136	43 %	7065.60	2.25

Appendix 3: Parcel demand in benchmark scenario

Area (postal codes)	Small company	Medium company	Large company
5003+5032+5033+5035	19	38	75
5004+5005	11	21	42
5006	13	27	53
5007	8	15	31
5008+5015+5054+5055+5058	37	75	149
5009+5052+5053	39	78	157
5010	4	7	15
5011	7	14	27
5012+5013+5014	5	10	20
5018+5016+5017+5022	13	26	52
5019	11	22	45
5031	3	7	13
5034+5037	12	23	46
5036+5038+5041+5106	25	49	99
5039	7	15	29
5042	8	15	31
5043+5045	2	5	9
5056+5057	17	34	67
5059+5068	4	7	15
5063+5093	25	51	102
5067+5072	16	31	62
5073	11	22	44
5081	9	18	36
5082+5231+5232	26	52	104
5089+5094+5096+5097	37	75	149
5098	7	14	28
5099	16	32	65

5101+5104	10	19	38
5105	28	56	111
5113+5117+5118+5119	22	44	88
5114	8	17	33
5115+5116+5130	14	27	54
5121+5122	10	20	40
5124	7	14	28
5131	8	16	33
5132	8	17	33
5134	10	21	41
5135	8	16	32
5136	11	21	42
5137	2	5	9
5141	15	30	61
5142+5143+5145+5147	35	70	141
5144	8	16	33
5146+5161	19	37	74
5148+5154+5155	28	57	114
5151	14	28	57
5152+5153	13	27	53
5160	3	5	11
5162	10	20	40
5163	5	10	20
5164	14	29	57
5165	8	16	31
5170+5172	16	33	65
5171+5176+5179	46	92	183
5173	10	19	39
5174	15	30	60
5178	14	27	54

5183	7	14	28
5184	8	17	33
5221	19	39	78
5222+5236	15	30	61
5223	8	16	32
5224	8	17	34
5225	14	28	55
5227+5228	14	28	56
5230	3	6	13
5235	12	25	49
5237+5251	28	55	111
5238	15	30	60
5239	25	50	100
5252	17	33	66
5253	13	26	53
5254+5257	13	27	53
5258	12	23	46

Appendix 4: Terminal capacities in Model 3

Posten	1792
PostNord	896
DHL	448

Appendix 5: AMPL Model 1 Mod-file

```
#all places (postal codes and terminals)
set place ordered;

#timeslots
set timeslot ordered;

#Big M
param M;

#Total amount of timeslots
param t_end;

#Capacity of 1 car
param car_cap;

#Cost per km
param distance_cost;

#Cost per hour
param time_cost;

#Cost per APL
param apl_cost;

#Distance between two places
param dis{place,place};

#Time between two places
param time{place,place};

#Demand in place
param demand{place};

#Box capacity
param box_capacity;


#Places where a car drives to and from in the optimal route
var drives{place, place, timeslot}, binary;


#Delivered to each place by each car
var demand_fulfilment{place, timeslot} >= 0, integer;

#Number of boxes at place
var n_box{place} >=0, integer;

#Demand for next car
var next_demand{place};
next_demand_ {i in place}:
	next_demand[i] = demand[i] - sum{t in timeslot} demand_fulfilment[i,t];

#Variables only for analysis
var distance_cost_sum = (distance_cost * sum{ j in place, i in place, t in
timeslot} (dis[j,i]*drives[j,i,t]));
```

```
var time_cost_sum = (time_cost * sum{  j in place, i in place, t in timeslot}
(time[j,i]*drives[j,i,t]));
var apl_cost_sum =  (apl_cost * sum{p in place} n_box[p]);

#Minimize total cost
minimize cost: distance_cost_sum + time_cost_sum + apl_cost_sum;

subject to
#Delivered parcels must be less than total demand in area
demand_fulfilment_ {i in place}:
	sum{t in timeslot} demand_fulfilment[i,t] <= demand[i];

#Deliver full car capacity
demand_ful: sum{i in place, t in timeslot} demand_fulfilment[i,t] = car_cap;

#(Drive to place at timeslot) = 1 if demand_fulfilment at place for timeslot is
positive
drive_deliver { i in place, t in timeslot}:
	sum{j in place} drives[j,i,t]*M >= demand_fulfilment[i,t];

#Box capacity at place must be greater than delivered amount
box_capacity_constraint {i in place}:
	box_capacity*n_box[i]>=sum{t in timeslot}demand_fulfilment[i,t];

#Car has to start in terminal
carstart_posten:
	sum{i in place} drives['posten',i,1] = 1;

carend_posten:
	sum{j in place} drives[j,'posten',t_end] = 1;

#Car has to leave from same place as it arrived
create_loop_timeslot {i in place, t in timeslot: ord(t)<=t_end-1}:
	sum{j in place} drives[j,i,t] = sum{j in place} drives[i,j,t+1];

#One drive per time
	drive_time {t in timeslot}:
		sum{j in place, i in place} drives[j,i,t] <= 1;
```

Appendix 6: AMPL Model 1 Run-file

```
reset;
#option presolve_eps 2.34e-14;
model 1selskap.mod;
data 1selskap_dhl.dat;
option omit_zero_rows 1;
option solver gurobi;
option  gurobi_options'logfile=RunProgress.log';
solve;
display  travel_cost, distance_cost_sum, hour_cost_sum, box_cost_sum, n_box,
cost, demand_fulfilment > results_terminalboks1.txt;


let {p in place} demand[p] := next_demand[p];
solve;
display  travel_cost, distance_cost_sum, hour_cost_sum, box_cost_sum, n_box,
cost, demand_fulfilment > results_terminalboks2.txt;


let {p in place} demand[p] := next_demand[p];
solve;
display  travel_cost, distance_cost_sum, hour_cost_sum, box_cost_sum, n_box,
cost, demand_fulfilment > results_terminalboks3.txt;

let {p in place} demand[p] := next_demand[p];
solve;
display  travel_cost, distance_cost_sum, hour_cost_sum, box_cost_sum, n_box,
cost, demand_fulfilment > results_terminalboks4.txt;

let {p in place} demand[p] := next_demand[p];
solve;
display  travel_cost, distance_cost_sum, hour_cost_sum, box_cost_sum, n_box, cost
> results_terminalboks5.txt;

let {p in place} demand[p] := next_demand[p];
solve;
display  travel_cost, distance_cost_sum, hour_cost_sum, box_cost_sum, n_box, cost
> results_terminalboks6.txt;

let {p in place} demand[p] := next_demand[p];
solve;
display  travel_cost, distance_cost_sum, hour_cost_sum, box_cost_sum, n_box, cost
> results_terminalboks7.txt;

let {p in place} demand[p] := next_demand[p];
solve;
display  travel_cost, distance_cost_sum, hour_cost_sum, box_cost_sum, n_box, cost
> results_terminalboks8.txt;
```

Appendix 7: AMPL Model 2 Mod-file

```
#all places (postal codes and terminals)
set place ordered;

#timeslots
set timeslot ordered;

#Companies
set company;

#all three terminals
set terminals;

#Big M
param M;

#Total amount of timeslots
param t_end;

#Capacity of 1 car
param car_cap;

#Cost per km
param distance_cost;

#Cost per hour
param time_cost;

#Distance between two places
param dis{place,place};

#Time between two places
param time{place,place};

#Demand in place
param demand{place, company};

#Box capacity
param box_capacity;

#Cost buying box
param apl_cost;

#Places where a car drives to and from in the optimal route
var drives{place, place, timeslot, company}, binary;

#Delivered to each place by each car
var demand_fulfilment{place, timeslot, company} >= 0, integer;

#Number of boxes at place
var n_box{place} >=0, integer;

#Variables only for analysis
var distance_cost_sum = (distance_cost * sum{j in place, i in place, t in
timeslot, c in company} (dis[j,i]*drives[j,i,t,c]));
var time_cost_sum = (time_cost * sum{j in place, i in place, t in timeslot, c in
company} (time[j,i]*drives[j,i,t,c]));
```

```
var apl_cost_sum =  (apl_cost * sum{p in place} n_box[p]);

#Demand for next car
var next_demand{place,company};
next_demand_ {i in place, c in company}:
	next_demand[i,c] = demand[i,c] - sum{t in timeslot}
demand_fulfilment[i,t,c];


#Minimize total cost
minimize cost: distance_cost_sum + time_cost_sum + apl_cost_sum;


subject to
#Delivered per tour
demand_ful {c in company}:
	sum{i in place, t in timeslot} demand_fulfilment[i,t,c] = car_cap;

#Delivered parcels must be less than total demand in area
demand_fulfilment {i in place, c in company}:
	sum{t in timeslot} demand_fulfilment[i,t,c] <= demand[i,c];

#(Drive to place at timeslot) = 1 if demand_fulfilment at place for timeslot is
positive
drive_deliver {i in place, t in timeslot,c in company}:
	sum{j in place} drives[j,i,t,c]*M >= demand_fulfilment[i,t,c];

#Box capacity at place must be greater than delivered amount
box_capacity_constraint {i in place}:
	box_capacity*n_box[i]>=sum{c in company, t in
timeslot}demand_fulfilment[i,t,c];

#Car has to start in terminal
carstart {q in terminals}:
	sum{i in place} drives[q,i,1,1] = 1;

#Car has to end in terminal
carend {q in terminals}:
	sum{j in place} drives[j,q,t_end,1] = 1;

#Car has to leave from same place as it arrived
create_loop_timeslot {i in place,c in company, t in timeslot: ord(t)<=t_end-1}:
	sum{j in place} drives[j,i,t,c] = sum{j in place} drives[i,j,t+1,c];

#One drive per timeslot
	drive_time {t in timeslot, c in company}:
		sum{j in place, i in place} drives[j,i,t,c] <= 1;
```

Appendix 8: AMPL Model 2 Run-file

Note that the code below is only the four first rounds, but the rest of the code follow the same format. The number of timeslots for round one and two are 5, while we needed to adjust the number of timeslots for the remaining rounds to 6 so that the solution did not become infeasible.

```
reset;
option presolve_eps  6.82e-14;
model Boks.mod;
data Boks.dat;
option omit_zero_rows 1;
option solver gurobi;
option  gurobi_options'logfile=RunProgress.log';

let t_end := 5;
let timeslot := timeslot5;

solve;
display travel_cost_sum_postnord, travel_cost_sum_posten, travel_cost_sum_dhl,
distance_cost_sum, hour_cost_sum, box_cost_sum, n_box, cost, demand_fulfilment >
results_boks1.txt;


let {p in place, c in company} demand[p,c] := next_demand[p,c];
solve;
display  travel_cost_sum_postnord, travel_cost_sum_posten, travel_cost_sum_dhl,
distance_cost_sum, hour_cost_sum, box_cost_sum, n_box, cost, demand_fulfilment >
results_boks2.txt;


let t_end := 6;
let timeslot := timeslot6;

let {p in place, c in company} demand[p,c] := next_demand[p,c];
solve;
display  travel_cost_sum_postnord, travel_cost_sum_posten, travel_cost_sum_dhl,
distance_cost_sum, hour_cost_sum, box_cost_sum, n_box, cost, demand_fulfilment >
results_boks3.txt;



let {p in place, c in company} demand[p,c] := next_demand[p,c];
solve;
display  travel_cost_sum_postnord, travel_cost_sum_posten, travel_cost_sum_dhl,
distance_cost_sum, hour_cost_sum, box_cost_sum, n_box, cost, demand_fulfilment >
results_boks4.txt;
```

Appendix 9: AMPL Model 3 Mod-file

Note that the AMPL code below does not match exactly with the model presented in chapter 4.6 Model 3 - Model with shared terminals and APLs. This is because we in the AMPL code decided to create one terminal capacity-constraint for each of the three terminals.

```
#All places
set place ordered;

#Timeslots
set timeslot ordered;

#All three terminals
set terminals;

#Companies
set company;

#Big M
param M;

#Total amount of timeslots
param t_end;

#Capacity of 1 car
param car_cap;

#Cost per km
param distance_cost;

#Cost per hour
param time_cost;

#Distance between two places
param dis{place,place};

#Time between two places
param time{place,place};

#Demand in place
param demand{place};

#Box capacity
param box_capacity;

#Cost buying box
param apl_cost;

param posten_cap;

param postnord_cap;

param dhl_cap;

#Places where a car drives to and from in the optimal route
var drives{place, place, timeslot}, binary;
```

```
#Delivered to each place by each car
var demand_fulfilment{place, timeslot} >= 0, integer;

#Number of boxes at place
var n_box{place} >=0, integer;

#Variables only for analysis
var distance_cost_sum = (distance_cost * sum{ j in place, i in place, t in
timeslot} (dis[j,i]*drives[j,i,t]));
var time_cost_sum = (time_cost * sum{  j in place, i in place, t in timeslot}
(time[j,i]*drives[j,i,t]));
var apl_cost_sum =  (apl_cost * sum{p in place} n_box[p]);

#Capacity variables
var posten_capacity_next = posten_cap - sum{i in place}
car_cap*drives['posten',i,1];
var postnord_capacity_next = postnord_cap - sum{i in place}
car_cap*drives['postnord',i,1];
var dhl_capacity_next = dhl_cap - sum{i in place} car_cap*drives['dhl',i,1];

#Demand for next car
var next_demand{place};
next_demand_ {i in place}:
      next_demand[i] = demand[i] - sum{t in timeslot} demand_fulfilment[i,t];


#Minimize total cost
minimize cost: distance_cost_sum + time_cost_sum + apl_cost_sum;
;


subject to
#Delivered per tour
demand_ful:
      sum{i in place, t in timeslot} demand_fulfilment[i,t] = car_cap;

#Delivered parcels must be less than total demand in area
demand_fulfilment_posten {i in place}:
      sum{t in timeslot} demand_fulfilment[i,t] <= demand[i];

#(Drive to place at timeslot) = 1 if demand_fulfilment at place for timeslot is
positive
drive_deliver {i in place, t in timeslot}:
      sum{j in place} drives[j,i,t]*M >= demand_fulfilment[i,t];

#Box capacity at place must be greater than delivered amount
box_capacity_constraint {i in place}:
      box_capacity*n_box[i]>=sum{t in timeslot}demand_fulfilment[i,t];

#Terminal capacity constraints
term_cap1:
sum{i in place}drives['posten',i,1]*car_cap <= posten_cap;

term_cap2:
sum{i in place}drives['postnord',i,1]*car_cap <= postnord_cap;

term_cap3:
sum{i in place}drives['dhl',i,1]*car_cap <= dhl_cap;
```

```
#Every first drive in every round must start in one of the companies’ terminals.
carstart:
	sum{i in place, q in terminals} drives[q,i,1] = 1;

#Every final drive in every round must end in the same terminal as the round
started in.
startend {q in terminals}:
	sum{i in place} drives[q,i,1] = sum{j in place} drives[j,q,t_end];

#Cars have to leave from same place as it arrived
create_loop_timeslot {i in place, t in timeslot: ord(t)<=t_end-1}:
	sum{j in place} drives[j,i,t] = sum{j in place} drives[i,j,t+1];

#One drive per time
	drive_time {t in timeslot}:
		sum{j in place, i in place} drives[j,i,t] <= 1;
```

Appendix 10: AMPL Model 3 Run-file

The code below from the run-file from model 3 is only an excerpt from the run-file containing the three first rounds. The remaining rounds follow the same format.

```
reset;
#option presolve_eps 2.34e-14;
model Terminalogboks.mod;
data TerminalOgBoks.dat;
option omit_zero_rows 1;
option solver gurobi;
option  gurobi_options'logfile=RunProgress.log';
solve;
display  travel, distance_cost_sum, hour_cost_sum, box_cost_sum, n_box, cost,
demand_fulfilment, posten_cap, postnord_cap, dhl_cap > results_terminalboks1.txt;


let {p in place} demand[p] := next_demand[p];
let posten_cap := posten_capacity_next;
let postnord_cap := postnord_capacity_next;
let dhl_cap := dhl_capacity_next;
solve;
display  travel, box_cost_sum, cost > results_terminalboks2.txt;


let {p in place} demand[p] := next_demand[p];
let posten_cap := posten_capacity_next;
let postnord_cap := postnord_capacity_next;
let dhl_cap := dhl_capacity_next;
solve;
display  travel, box_cost_sum, cost > results_terminalboks3.txt;
```