Optimal location of charging stations for electric vehicles

Master's Thesis

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Abstract

The electrification of road transportation requires a massive investment in charging infrastructure to keep up with the demand for underway charging. A substantial research effort is put into the problem of finding optimal locations for said charging facilities. These efforts are, however, often concentrated on covering a maximum number of routes, without considering the effect on the power grid when these charging facilities and chargers are connected to the power grid. Or they focus on the simulation of the load the charging facilities exert on the power grid and minimizing this load. This thesis suggests three mathematical models for covering a set of routes while ensuring connectivity to the grid as a compromise between these approaches. The motivation for the development of this method is to showcase the usefulness of practical implementations of mathematical programming in infrastructure planning. We test the models on a case where we use data from Trøndelag county in Norway to find the optimal locations for charging facilities, and the number of chargers needed at each facility to account for traffic. We do this while minimizing the total costs while ensuring that we do not exceed the limit of available electricity in the grid.

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Chapter 1

Introduction

As the challenges of global warming manifest themselves in our society, a transition away from fossil fuels is necessary. Previously emission-heavy sectors are in the process of transitioning to solutions with less climate impact. An important sector where this transition is ongoing and evident is road transportation. Road transportation in Norway was responsible for the emission of 8.7 million tons CO_2 equivalents in 2022. These emissions were 17.9 % of the total national emission in that year [41]. On a global scale, road transportation accounted for the emission of 5.87 *Gigaton* (Gt) CO_2 the same year [21]. There is an ongoing technological race to develop emission-free transportation methods. However, this process will be significantly hindered if the planning and construction of the necessary infrastructure to support these emission-free vehicles is lagging behind.

In this thesis, we will present how mathematical programming and optimization can be used in the early-stage planning of these necessary infrastructure projects. We will especially focus on the determination of locations for charging facilities with fast chargers, the number of chargers installed at each facility, and how to integrate these into the existing electricity grid to best make use of available capacity in said grid. We will also use these techniques to identify the lack of coverage of charging infrastructure within a specific area and where to install the missing infrastructure.

1.1 Decarbonisation of road transportation

The decarbonization of road transportation is an ongoing process, and there has been a surge of technological advancement in the last decade in the field of *alternative fuel* *vehicles* (AFV). Biofuels and hydrogen are examples of technologies already in use in various segments of road transportation. Biofuels, such as biodiesel and bioethanol, are already mixed with normal fuel types, and 17 % of the total volume of liquid fuel sold for use in road transportation in Norway must be biofuels [2]. They are, however, expensive, with biodiesel being sold with a premium of 97 % in May of 2022 compared to diesel [28]. This price difference seems to be among the hindering factors of the adoption of biofuels as energy carriers in road transportation. *Fuel cell electric vehicles* (FCEV) have been on the market for more than 15 years, but the adoption of hydrogen as an energy carrier has been slow. After the surge of *battery electric vehicles* (BEV) in the last few years, it seems like this is the prevailing technology at the moment, especially in the car market.

The range of BEVs has increased drastically in the last decade, from an average of 127 km in 2010 to 349 km in 2021 [22]. The charging technology has also made a great leap forward to keep up with the increasing size of batteries. Novel alternatives to charging a vehicle's battery pack exist, such as changing the battery pack on the roadside, but charging the battery is still the most common approach [19]. The chargers used for this can either be so-called destination chargers, where you recharge at the end of a trip, or fast chargers that allow charging while the car is underway to its destination because of a lower recharge time than the destination chargers achieve.

Destination chargers are, for the most part, *alternating current* (AC) chargers. These chargers deliver electricity directly from the grid and take advantage of the internal converter of the car and use this to convert AC to *direct current* (DC). This conversion must occur because it is only possible to charge a battery by DC. AC chargers are often located at people's homes, car parks, or along street parking. AC chargers tend to have a power output of 3 to 22 kW but exist in versions that can deliver up to 50 kW. DC chargers have an external converter outside the car. This external converter is significantly faster than the internal car converter. DC chargers are, therefore, faster at charging a battery. This is the reason why most fast chargers are DC chargers.

There is no clear definition of what a fast charger is, but all chargers capable of delivering a power output greater than 50 kW are often lumped together under this umbrella. However, chargers with as low power output as 50 kW are starting to become obsolete, as new chargers are launched with power outputs greater than 300 kW, with the charger with the highest available power output reaching 360 kW [3]. It should be mentioned that the recharge speed also depends on the car being charged. Most car models can not make use of these very high power outputs.

1.2 Electrification of transportation in a Norwegian perspective

The Norwegian government is responsible for some of the most aggressive support schemes in the world for BEVs. The goal behind these support schemes is that all new cars and smaller vans sold in 2025 should be zero-emission vehicles. This also applies to new city buses. Additionally, all heavier vans, 75 percent of long-distance busses, and 50 percent of trucks should be zero emission within 2030 [6]. These goals are more ambitious than those the *European Union* (EU) has established. They state that all new cars and vans must have zero emission by 2035 [43]. The current status of the new car sales in Norway is that 78.3 percent was zero emission in 2022 [39].

The rapid electrification of road transportation in Norway is, however, accompanied by challenges, mainly revolving around recharging and power grid infrastructure. It is estimated that the need for fast chargers in 2025 is 9000 and could reach as high as between 10000 and 14000 in 2030 [29]. An additional 1500 to 2000 fast chargers for road freight transport are needed in the same time frame [29]. The electricity used for transportation in Norway in 2016 was 1 *Terrawatt hour* (TWh) [38]. This reached 1.7 TWh in 2020 and is expected to increase with an additional 13 TWh within 2040 [16, 42]. An analysis from 2020 suggests that the planned electrification of all sectors will cause the need for upgrades to the power grid ranging from 9 to 16 billion *Norwegian kroner* (NOK) [17]. The electrification of road transport is estimated to be responsible for 2.6 to 3.6 billion NOK of these upgrades [17].

The upgrade of the grid in Norway is partially paid for by the parties requesting grid connection. These parties can, for instance, be regular homeowners, new or existing industrial plants, or, in the context of this thesis, the operators of a charging facility for BEV's. They must pay a certain fraction of the total cost of the necessary upgrades that need to be done to connect them to the grid. The contribution is calculated by the network company responsible for the area within which the requests for connection to the grid originate. The framework for the calculation of this contribution is given by Norwegian law [1]. This contribution to the cost of construction is identified as a major barrier to the establishment of more charging facilities and chargers by the operators of said facilities [29]. The most desirable locations for the operators of the charging facilities are, therefore, those with the lowest contribution to construction and the highest amount of potential use [30].

1.3 Problem statement

As mentioned in Section 1.2, the most desirable locations from an economic perspective are those with the highest potential use and the least amount of investment necessary. From a more regional planning perspective, the same consideration can be taken, but with a different goal than maximizing profit. The authorities in charge of such strategic long-term planning might be interested in exploring what the minimum number of charging facilities and chargers needed is to satisfy travelers in non-urban areas. Assuming that we adopt this perspective and the goal is to adequately cover an area in the most cost-efficient way possible so that the car user can travel with confidence of sufficient access to charging facilities, the important factors are

- distance between charging facilities,
- electricity supply,
- the number of chargers at each facility,
- and the total cost of establishing said charging infrastructure and connecting it to the electricity grid.

The distance between charging facilities must be small enough so that one can recharge before running out of electricity. At the chosen charging facility locations, the number of installed chargers must be proportional to the amount of passing traffic to minimize queueing and waiting time. There must also be enough capacity in the electricity grid to power these chargers. These constraining factors form the basis for the problem we want to look at in this thesis. The problem can be described as finding out where the optimal locations for charging facilities within a certain geographic area are, when considering the travel distance, the required number of chargers, and the electricity supply, while trying to minimize the cost of establishing these facilities. To find the optimal solution to this problem, these factors have to be taken into account simultaneously.

1.4 Thesis structure

In Chapter 2, we present some strategies utilized by other researchers for facility location problems similar to the one we consider in this project. The research gap, inputs, outputs and assumptions for our project are laid out in Chapter 3. This leads to the mathematical models presented in Chapter 4. The method of data collection is described in Chapter 5 and these data form the basis for our experiments. The implementation and result of these are presented in Chapter 6. We finally summarize our findings and suggest some further avenues of research in Chapter 7.

Chapter 2

Literature review

2.1 General introduction to facility location

Facility location problems, such as the problem of locating the optimal placements of charging facilities for BEVs, have a rich history as a part of optimization research. These problems are still being studied decades after their first formulation and have several uses within logistics, supply chain management, telecommunications, and advertising, among others. Their history dates back a long way, and a classic example is the Weber problem formulated as early as 1909 and published in 1929 [46]. The modern area of research can be said to have been established with Hakimi [15]. A number of sub-classes of the facility location problem exist. The broad categories *covering-based problems*, *median-based problems* and *other problems* are suggested as a partition of the problems by Daskin [5]. These can further be divided into the subcategories p-median, p-center, set-coverage, maximum coverage, and fixed charge facility location problems as shown in Figure 2.1 [5].

As we point out later in this chapter, problems are often given case-specific names, but can nevertheless be categorized using the partitioning in the previous paragraph. We give a brief introduction to the mathematical definition of the three most relevant problem types in Section 2.2. In Section 2.3, we see how these models are used in different settings when working on charging infrastructure for AFVs and BEVs. We also mention some notable research on charging infrastructure placement in Norway in Section 2.4.

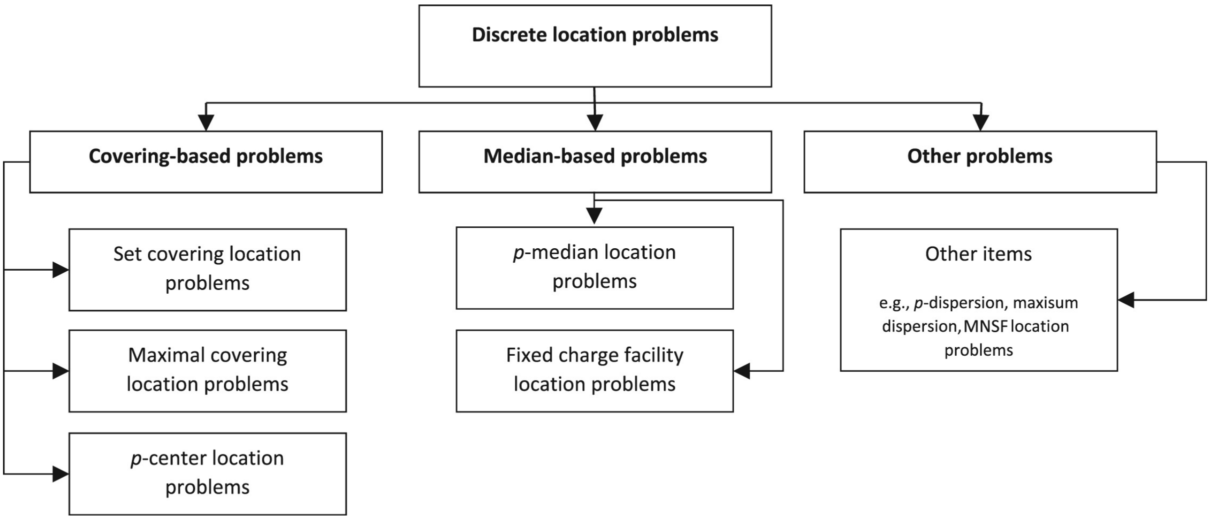

Figure 2.1: Classification of location problems [5].

2.2 Mathematical formulation of common problems seen in location-allocation research

We will in this section give an overview of mathematical formulations for three relevant location-allocation problems used when deciding optimal placements of refueling infrastructure for AFVs. The following mathematical models borrow notation from Owen and Daskin [33]. The notation is not necessarily consistent with the notation used in the rest of the thesis.

P-median problems

If one has exactly p facilities to locate, one can minimize the demand-weighted travel distance between the facilities and the nodes with demands. This measurement was first introduced by Hakimi [15].

Indices and input data:

- i = index of demand node
- j = index of potential facility site
- h_i = demand at node i
- d_{ij} = distance between demand node i and facility site j
- P = number of facilities to be located

Decision variables:

- $X_j = \begin{cases} 1 & \text{if a facility is located at site } j, \\ 0 & \text{otherwise,} \end{cases}$
- $Y_{ij} = \begin{cases} 1 & \text{if demand at node } i \text{ is served by a facility at site } j, \\ 0 & \text{otherwise.} \end{cases}$

The problem can now be formulated as follows:

$$\begin{aligned} \text{minimize} \quad & \sum_i \sum_j h_i d_{ij} Y_{ij}, \\ \text{subject to:} \quad & \sum_j X_j = P, \\ & \sum_j Y_{ij} = 1 \quad \forall i, \\ & Y_{ij} - X_j \leq 0 \quad \forall i, j, \\ & X_j \in \{0, 1\} \quad \forall j, \\ & Y_{ij} \in \{0, 1\} \quad \forall i, j. \end{aligned}$$

Set covering problems

A set covering problem differs from the p-median problem in that it seeks to minimize the cost of the number of facilities needed to cover the demand for each node i. We need the additional notation below to formulate the problem:

- c_j = fixed costs of siting a facility at node j
- S = maximum acceptable service distance (or time)
- N_i = set of facility sites j within acceptable distance of node i

$$\begin{aligned} \text{minimize} \quad & \sum_j c_j X_j, \\ \text{subject to:} \quad & \sum_{j \in N_i} X_j \geq 1 \quad \forall i, \\ & X_j \in \{0, 1\} \quad \forall j. \end{aligned}$$

Maximum covering problems

The maximum covering problem seeks to cover a maximum proportion of the demand with a given number of facilities to be installed. The variable

$$Z_i = \begin{cases} 1 & \text{if node } i \text{ is covered,} \\ 0 & \text{otherwise,} \end{cases}$$

is also needed to formulate the mathematical model for this problem.

$$\begin{aligned} \text{maximize} \quad & \sum_i h_i Z_i, \\ \text{subject to:} \quad & Z_i \leq \sum_{j \in N_i} X_j \quad \forall i, \\ & \sum_j X_j \leq P, \\ & X_j \in \{0,1\} \quad \forall j, \\ & Z_i \in \{0,1\} \quad \forall i. \end{aligned}$$

2.3 Models used for charging station allocation

Various strategies have been implemented to deal with the location of refueling stations for AFVs. The choice of method and framework will depend on factors such as the type of chargers to be placed (destination chargers or fast chargers), long versus short travel distance, urban or non-urban area, etc. Several strategies have been proposed and tested for optimal refueling station allocation.

Fredriksson et al. [11] use the categories flow-capturing models, set-covering models, vehicle movement simulation models, agent-based models, and equilibrium models when referring to other research. Other authors prefer the categories p-median, p-center, set covering problems and maximum covering problems, more in accordance with the partition we show in Figure 2.1 [24]. The current section gives an outline of some of the methods in the context of locating refueling facilities for AFV's.

One possible tactic is to choose a certain number of locations to satisfy as much demand as possible in the form of traffic flows, or routes, going from an origin node O to a destination node D. Routes and flows can, for example, follow the shortest paths between nodes O and D. A flow is "captured" or in other terms, the demand is satisfied, if the flow passes a node where a charging facility is installed [20]. This has been named the *Flow Capturing Location Model* (FCLM). This model is, as we see it, a version of a set covering problem.

The problem can then be modified so that a flow is captured if an adequate number of refueling stations are spaced correctly to cover the route. This is called the *Flow Refueling Location Model* (FRLM) [25]. In the FRLM, a range is given to the vehicles so that several chargers are needed to cover a single flow. If the range is longer than the longest route, the problem is simplified to the FCLM, where only one location is needed to cover a flow. This is relevant in the case of regional or national planning of establishing charging infrastructure but not when considering routes shorter than a typical BEV's effective range.

The approach of the FRLM and FCLM is based on maximizing the number of flows that can be covered by a certain number of locations, and although this might have some value for strategic planning on a government level, the reality is that most charging station operators will not have a certain number of stations to place, but rather a budget based on the possible profit and the economic risks involved in establishing the location. It is also lacking in the evaluation of power grid capacity at any given location.

The FCLM and FRLM have been continuously developed since their inception. The different directions the research has taken are summarized in Figure 2.2 [24].

Similarly to the FRLM and the FCLM, Fredriksson et al. [11] propose a set covering model for what they call the *Route Node Coverage* (RNC) problem, which is a variant of a set covering problem. They utilize a probabilistic random-walk methodology to find the routes most likely to be traveled. This is to avoid having to enumerate all possible routes. More random walks, or routes, are added as the problem is expanded. The probability of a route being chosen by a driver is given by factors such as traffic levels. A route is covered if a charger is located along the route. The authors conclude that their approach results in placements at nodes with high traffic flow and where drivers can choose alternative routes to avoid heavy traffic. However, they do not take into account factors that can affect the practicality of placing a charging station at the given nodes. Such problems include the capacity of the regional power grid and electrical substations.

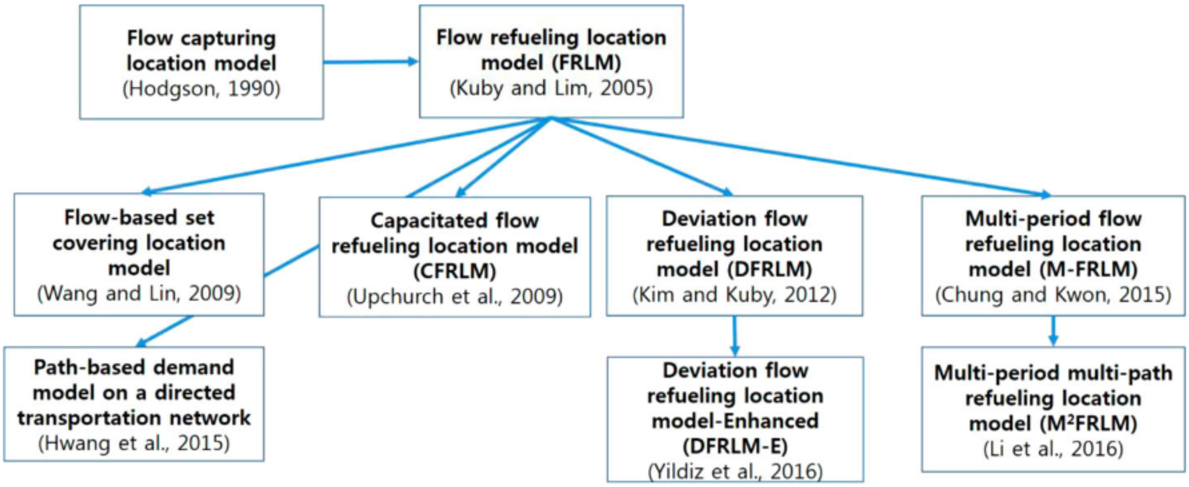

Figure 2.2: Schematic overview over the evolution of the Flow capturing location model in the field of alternative fuel station planning [24].

Maximum coverage problems are, for example, found when charging stations are placed in urban areas. The goal is to cover as much of the needs of the inhabitants and users as possible with a given number of chargers. A well-known example is from Lisbon, where, among other things, daytime and nighttime demand is used to construct a maximum coverage solution for a specific neighborhood [10].

Another alternative model used in urban planning is the p-median model. Research performed with Beijing as a case study shows that of maximum covering, set covering and p-median problem, the latter is the most effective when considering the drivers that already drive a BEV [18]. These two approaches are included in this review to showcase that the practitioner must choose the model according to the goal and prerequisites for the project they are undertaking. If the number of chargers to be placed is given, the same method cannot be used when the goal is to minimize the number of charging facilities needed to cover a geographical area.

2.4 Norwegian case studies

There has been some research effort put into the optimal placement of chargers in Norway. Peratinos and Piene [34] look at the covering of a number of generated routes between large cities in Norway using the FRLM. They do not take into account the number of chargers needed at each facility or their integration into the power grid.

There are, however, authors who have taken this into account. Ivarsøy [23] uses publicly available data on the power grid. He then simulates the load on the grid, traffic flow, and charging needs. This is used to construct an optimization problem for finding the optimal placements of charging facilities and their size. This is solved with the help of a *particle swarm optimization algorithm*. The algorithm is then tested on a 74 km stretch of highway. The approach is based on data from *NVE atlas*, which contains geographical information on overhead power lines but not underground power cables. The approach is, therefore, limited to geographical areas where most, if not all, of the grid consists of overhead lines.

Chapter 3

Problem definition

This chapter defines the problem we investigate in this thesis. We also define the scope of the project and the assumptions that are made.

3.1 Research gap

As shown in Chapter 2, a lot of research effort is spent on facility location problems of the nature we describe in Section 1.3. Most of it is concentrated on covering a set of routes without taking into account the number of chargers needed or whether the grid can support this infrastructure. Or if they do consider grid capacity, it is often a detailed analysis that is not possible with the power grid data that is available for the public in Norway without a lot of effort put into simulations. Our project aims to showcase a practical approach to using mathematical programming in a real-world planning application. The focus is, therefore, on using real-world data in a practical way.

3.2 Inputs

As mentioned, a substantial part of this thesis is centered on using as much concrete data as possible. In this section, we define the necessary data input needed to do this. The necessary inputs are:

- Location of potential charging facilities sites.

- Location of possible connection points to the grid.
- Capacity in the grid.
- Distance between intersections in the road network.
- Traffic volume.
- Cost of various infrastructure.

3.3 Output

The output of this project should be the optimal placement of the charging facilities and the number of chargers in each facility. Optimal placement in this context means a list of intersections at which the charging facilities, and subsequently the chargers, should be placed. The connection point used in the grid should also be a result of the optimization process.

3.4 Assumption

Even though one goal of this project is to provide a realistic and applicable method for using optimization in a real-world application and using as much available data as possible, a number of assumptions are made:

- Road intersections are considered potential locations for charging facilities. Closeness to intersections is pointed at as an important aspect of an optimal location for a charging facility [36].
- All intersections are suitable for installation of a charging facility.
- There are no area restrictions. There is room for charging facilities at all intersections. This is regardless of how many chargers are placed at each facility. The available area is often a limiting factor in the planning infrastructure.
- All paths/trips start and end at an intersection.
- All cars are electric. That means a 100 % penetration rate for BEVs. Since infrastructure planning and construction have a significant lag, we take into account the goals set by the Norwegian government presented in Section 1.2. Even though the shift to a fully electric vehicle fleet will take a significant time, planning must be in front of this development.

- All cars start with a full battery (100 % *state of charge* (SoC)) at the start node of the path.
- All trips start and end within the defined area. This means that it is a closed system. If a vehicle is arriving at the edge of the system with low SoC, it may not be possible to reach a charging facility location that is an output of our model, before running out of energy.
- Vehicle range is not affected by factors such as temperature or road gradient. These can significantly impact the range, especially in a cold and mountainous region like Norway.
- Road conditions are not considered. Snow, ice and other factors that can affect the range of a BEV are not part of our evaluation.
- All energy available at the start of the trip is used to drive the vehicle. Energy is not used for other components of the car, such as the air conditioner or heating. In an electric car, the use of these can significantly impact the range.
- The SoC is replenished to 100 % after reaching a charging facility.
- All free capacity in the grid can be utilized for charging of BEVs.
- It is possible to connect to the grid only at locations of electrical substations/ transformer stations. An electrical substation, also known as a transformer station, is where the voltage in the grid is adjusted between different transmission levels. The terms electrical substation and transformer station are used interchangeably in this text.
- The cost per length unit of laying a cable from a connection point in the grid to a charging facility is the same regardless of what terrain the cable crosses. This assumption is a simplification of the fact that there is a major difference in cost if, for instance, the cable has to cross water, which is not considered in this project.

Chapter 4

Mathematical Model

4.1 Minimum covering model

The road network is represented by a set of nodes, denoted N, and a set of arcs, denoted A. Each node represents an intersection, and the arcs represent the roads that connect a pair of adjacent intersections. T is a set of electrical substations/transformer stations.

The objective of the model is to minimize the number of charging stations deployed while ensuring that the entire area is covered. This means that it should be possible to travel from any node i to any other node j while considering the limited range of an electric car.

To achieve this, charging facilities must be placed along the routes from i to j if the distance exceeds the range of the electric car after subtracting a buffer for range anxiety. Range anxiety refers to the fear of not reaching a charging facility before the vehicle's battery reaches a SoC of 0 %. Additionally, the model aims to minimize the cost of connecting chargers to electrical substations with free capacity.

The objective function is formulated as

$$\text{minimize} \sum_{k \in N} (x_k C_k + \sum_{t \in T} y_{kt} G_{kt}), \tag{4.1}$$

where x_k is a binary variable that represents whether one or more chargers are placed at node k (1 for placement, 0 otherwise), and C_k denotes the cost associated with preparing node k for placement of one or more chargers at that node. The variable y_{kt} is binary and indicates whether there is a cable connecting node k to transformer station t (1 if connected, 0 otherwise). The cost of digging and laying a cable from node k to transformer station t is denoted G_{kt}. This cost is based on the Euclidean distance from the location to the electrical substation.

A car should be able to travel between any two nodes in the network and recharge if needed. Therefore, a set of routes, L, is generated. The set $L_{ij} \subseteq L$ consists of all generated routes with start and end nodes i and j, respectively. For any route $l \in L$, $N_l \subseteq N$ is the ordered node set of the route. Hence if $l \in L$, then $i, j \in N_l$. We also have $A_l \in A$, that is, the set of arcs connecting the nodes in the route l. The arcs have a weight equal to the distance between the nodes they connect. The length of route l is denoted by D_l and is the sum of the weights of A_l. The constraint

$$\sum_{k \in N_l \setminus \{i,j\}} x_k \geq \left\lfloor \frac{D_l}{R - E} \right\rfloor \quad \forall l \in L \tag{4.2}$$

ensures that the number of nodes, $\sum_{k \in N_l \setminus \{i,j\}} x_k$, with one or more chargers placed on the internal nodes on the route l is greater than or equal to the number of times a car has to charge. This number is given by the floor of the length of the route divided by the practical range of the vehicle. This practical range is given by the theoretical range, R, of the vehicle subtracted by a buffer representing the range anxiety, E, that the drivers experience.

To ensure that each node with a charging station is connected to the power grid, the model introduces the variable y_{kt}. The constraint

$$x_k = \sum_{t \in T} y_{kt} \quad k \in N \tag{4.3}$$

ensures that all established charging stations are connected to the grid. To ensure that the capacity of the electrical substations is not exceeded, the number of nodes k connected to substation t is bound by B_t, which is how many chargers transformer station t can supply electricity to. This leads to the constraint

$$0 \leq \sum_{k \in N} y_{kt} \leq B_t \quad \forall t \in T. \tag{4.4}$$

The mathematical problem for this set covering problem is summarized as follows:

$$\begin{aligned}
\text{minimize} \quad & \sum_{k \in N} (x_k C_k + \sum_{t \in T} y_{kt} G_{kt}), && (4.5) \\
\text{subject to:} \quad & \sum_{k \in N_l \setminus \{i,j\}} x_k \geq \left\lfloor \frac{D_l}{R - A} \right\rfloor \quad \forall l \in L, && (4.6) \\
& x_k \leq \sum_{t \in T} y_{kt} \quad k \in N, && (4.7) \\
& 0 \leq \sum_{k \in N} y_{kt} \leq B_t \quad \forall t \in T, && (4.8) \\
& x_k \in \{0, 1\} \quad \forall k \in N, && (4.9) \\
& y_{kt} \in \{0, 1\} \quad \forall k \in N, t \in T. && (4.10)
\end{aligned}$$

This mathematical model aims to optimize the placement of charging stations in a road network by minimizing costs while ensuring sufficient coverage and connectivity to the power grid. Coverage is important when considering the electrification of transportation. This gives freedom of mobility to BEV users.

4.2 Minimum covering model considering traffic

From a planning perspective, the minimum coverage explored in Section 4.1 is not necessarily enough to satisfy the needs of BEV users. Although they might have the opportunity to travel to their destination, and chargers are placed so that their route is covered, they might experience problems if there are too few chargers at each charging facility. The number of cars per charger has to be low enough to avoid long charging queues. BEV drivers seem to experience elevated levels of anxiety when arriving at charging facilities with few chargers [4]. Therefore, a bound is put on the number of cars per charger. This limit on the number of vehicles per charger is denoted κ.

The traffic, denoted τ_{uv}, is specific to each arc (u, v) in the graph. Therefore, the traffic of the route l is $\tau_l = max\{\tau_{uv} : (u, v) \in A_l\}$. The number of individual chargers necessary on a route is given by $\lceil \frac{\tau_l}{\kappa} \rceil$. This ensures that there are enough chargers on the route to cover the theoretical maximum traffic the route experiences. A new integer variable, w_k, equals the number of chargers placed at node k. This leads to the constraint

$$\sum_{k \in N_l} w_k \geq \left\lceil \frac{\tau_l}{\kappa} \right\rceil \quad \forall l \in L. \tag{4.11}$$

The number of chargers at node k that draw electricity from the electrical substation t is called z_{kt}. This variable is set to be the same as the number of chargers, w_k. The constraint

$$w_k = \sum_{t \in T} z_{kt} \quad \forall k \in N \tag{4.12}$$

replaces constraint (4.7). It is important to note that the chargers located at any node k can be connected to different substations. So multiple electrical substations can supply the chargers located at any given node. The number of chargers connected to electrical substation t is bounded by B_t, which implies

$$0 \leq \sum_{k \in N} z_{kt} \leq B_t \quad \forall t \in T. \tag{4.13}$$

To ensure that chargers are only placed at nodes that are already established, we impose

$$w_k \leq x_k M \quad \forall k \in N, \tag{4.14}$$

where M is a sufficiently large number. This forces w_k to be zero when x_k is zero. The same is done for connection between the chargers and transformer stations, implying

$$z_{kt} \leq y_{kt} M \quad \forall k \in N, t \in T. \tag{4.15}$$

Since the number of chargers that can be placed, w_k is bounded by the availability of electricity, M can be determined by considering the maximum value that z_{kt} can take.

The new objective function,

$$\text{minimize} \sum_{k \in N} (x_k C_k + w_k O + \sum_{t \in T} y_{kt} G_{kt}), \tag{4.16}$$

accounts for the separate cost of establishing a charging infrastructure at node k and the cost of placing w_k chargers at this node. Here, O is the cost of one charger.

The model can now be written as:

$$\begin{aligned}
\text{minimize} \quad & \sum_{k\in N}(x_kC_k + w_kO + \sum_{t\in T} y_{kt}G_{kt}), && (4.17)\\
\text{subject to:} \quad & \sum_{k\in N_l\setminus\{i,j\}} x_k \geq \left\lfloor \frac{D_l}{R-A} \right\rfloor \quad \forall l \in L, && (4.18)\\
& \sum_{k\in N_l} w_k \geq \left\lceil \frac{\tau_l}{\kappa} \right\rceil \quad \forall l \in L, && (4.19)\\
& w_k = \sum_{t\in T} z_{kt} \quad \forall k \in N, && (4.20)\\
& 0 \leq \sum_{k\in N} z_{kt} \leq B_t \quad \forall t \in T, && (4.21)\\
& w_k \leq x_kM \quad \forall k \in N, && (4.22)\\
& z_{kt} \leq y_{kt}M \quad \forall k \in N, t \in T, && (4.23)\\
& x_k \in \{0,1\} \quad \forall k \in N, && (4.24)\\
& y_{kt} \in \{0,1\} \quad \forall k \in N, t \in T, && (4.25)\\
& w_k \in \mathbb{Z}_+ \quad \forall k \in N, && (4.26)\\
& z_{kt} \in \mathbb{Z}_+ \quad \forall k \in N, t \in T. && (4.27)
\end{aligned}$$

4.3 Minimum covering model considering traffic with restricted connections to electrical substations

As an alternative to the approach in Section 4.2, where each node can be supplied with electricity from multiple substations, we now introduce a restriction to this. The constraint

$$x_k = \sum_{t\in T} y_{kt} \quad \forall k \in N, \tag{4.28}$$

is added to make sure that a node can only be supplied from a single transformer station. A station can however supply multiple nodes if it has the capacity. This is more in accordance with the practical implementation of charging facility construction in use.

The model as a whole is now identical to (4.17)-(4.27) with the addition of the new constraint (4.28), but we include it for the sake of completeness:

$$
\begin{aligned}
\text{minimize} \quad & \sum_{k \in N} (x_k C_k + w_k O + \sum_{t \in T} y_{kt} G_{kt}), && (4.29) \\
\text{subject to:} \quad & \sum_{k \in N_l \setminus \{i,j\}} x_k \geq \left\lfloor \frac{D_l}{R - A} \right\rfloor \quad \forall l \in L, && (4.30) \\
& \sum_{k \in N_l} w_k \geq \left\lceil \frac{\tau_l}{\kappa} \right\rceil \quad \forall l \in L, && (4.31) \\
& w_k = \sum_{t \in T} z_{kt} \quad \forall k \in N, && (4.32) \\
& 0 \leq \sum_{k \in N} z_{kt} \leq B_t \quad \forall t \in T, && (4.33) \\
& w_k \leq x_k M \quad \forall k \in N, && (4.34) \\
& z_{kt} \leq y_{kt} M \quad \forall k \in N, t \in T, && (4.35) \\
& x_k = \sum_{t \in T} y_{kt} \quad \forall k \in N, && (4.36) \\
& x_k \in \{0, 1\} \quad \forall k \in N, && (4.37) \\
& y_{kt} \in \{0, 1\} \quad \forall k \in N, t \in T, && (4.38) \\
& w_k \in \mathbb{Z}_+ \quad \forall k \in N, && (4.39) \\
& z_{kt} \in \mathbb{Z}_+ \quad \forall k \in N, t \in T. && (4.40)
\end{aligned}
$$

Chapter 5

Data collection and generation of input data

As we stated in Chapter 3, the practical use of publicly available Norwegian data is a main focus of this project. In this chapter, we will discuss the challenges with data gathering and how the data are used to generate the input needed for the implementation of the model. Experiments carried out with these data are described in Chapter 6.

5.1 Data on grid capacity

This project uses Trøndelag county in Norway as an example case. The choice of geographic area is purely based on the availability of data for the capacity of electrical substations. The network company *Tensio AS* provided the data. At the beginning of this project, this was one of the few network companies that had the opportunity to share data on the capacity of the grid. The willingness and opportunity of network companies to share such data seems to be changing, and some of these changes are described later in this section.

Initially, a considerable amount of time was spent trying to establish a dialogue with different actors within the energy industry in Norway to obtain relevant information on the grid. The main focus was to extract information from the network companies responsible for specific parts of the electrical grid in Norway. The network companies have a monopoly on maintaining and expanding the electricity grid that has a voltage of 22 *kilovolt* (kV) or lower within their designated geographical area. There were 95 network companies at the end of 2021 [32]. The data that network companies have on capacity and geographical locations of relevant grid infrastructure form part of the basis for an evaluation on where to place the charging infrastructure, as close proximity to parts of the grid with free capacity can reduce the overall cost of such a project drastically.

Depending on the company, it varies how one can contact them. Some utilize forms on their web pages, and some have a general email address. They also use different vocabularies and they are structured differently from each other. This means that a request to one company might be sent over email to a specific department, while the same request to a different company is sent by a form on their web site with limited opportunity to specify who should receive the request. Some have limits on how much text one can write when making an inquiry. This makes it difficult to be specific enough to minimize the effort required of the receiving part to understand and process the request. All these factors seem to lead to a high probability that a request goes unanswered.

It is also challenging to reach the right person(s) within a network company, since a request for data for use in research is not a standard one. Network companies have a wide range of responsibilities, and their ability to contribute to research is often restricted. Alternative routes for approaching and getting in touch with key people were explored with the help of *Norconsult Digital*. The experience from this project is that if one manages to reach the right person who sees the potential value in a project, the data are available and can be obtained for use in research and electrification projects.

The network companies have data on free capacity in the grid and other data that might be necessary for a project similar to this thesis, but the norm is that the network companies respond mainly to concrete requests to connect to the network. These requests specify how much capacity the party needs from the grid. The network company can then determine whether the requested amount of capacity is available and the financial contribution that the requesting party has to contribute to provide the necessary upgrades to provide the requested electricity. The network companies are wary of answering more general questions about available capacity. This can have multiple reasons. Some of the data is restricted, such as the placement of some types of underground cable and other infrastructure. The capacity data must be calculated to be accurate, a process that is time-consuming and reserved for more concrete requests for connection to the grid. A third reason could be that giving out capacity information can in some instances give a competitive edge. A speculative party can request all the available capacity if they know exactly how much is available.

This search for data led to interesting discussions about data sharing with representatives of *Lede AS* and *Elvia AS*, two of the largest network companies in Norway. In connection with this thesis, we have had the opportunity to contribute some suggestions to the *Wattapp* project, where both of these network companies are stakeholders. The *Wattapp* project aims to share data on the electrical grid efficiently and openly [8]. The project has per now led to a website where much of the information necessary to do a project like this is available.

The suggestions we provided in the discussion around the *Wattapp* project are mainly centered on what data should be available from a planning and modeling perspective, the level of detail necessary to make informed decisions without contacting the network company, and some comments on the use of the platform.

A positive attitude toward data openness is noticeable in several of the network companies, and this sentiment seems to be growing throughout the industry. A clear example of this is the formation of *Elbits*, a company owned by multiple network companies that provide digital services, where multiple of these revolve around information about capacity and simplifying the process of connecting to the grid [7]. There is also a project that considers how to create a grid availability map in the context of establishing fast charging infrastructure for BEVs in a Norwegian setting [26]. These efforts will with time lead to a simpler data gathering phase for electrification projects that require similar data as this thesis.

5.2 Road network data collection and generating a graph

The process of generating a representative graph of the road network is challenging. The graph established in our project is based on data from *Nasjonal veidatabank* (NVDB) for the locations of the intersections and the distance between each pair of nodes [45]. *GeoNorge AS* has developed an interface to retrieve information from, among other databases, NVDB directly to *ArcGIS Pro*, which is a geographical processing tool [9, 12]. Both geographical information about the road network and traffic data are available here. Traffic is continuously measured in a few selected places, manually counted sporadically, or computed. [40].

The data are pre-processed in *ArcGIS Pro*. *Norwegian Public Roads Administration* (NPRA) uses the categories private roads, municipal roads, county roads, national roads, and E-roads to separate the road network by size and organization responsible for maintenance. The E-roads are part of the *International E-road network* [44]. County roads, national roads, and E-roads are used as a basis for the road network in this project. These roads are then joined with traffic data for each road segment.

The road network information is then processed using a graph making tool, *NetworkX* (version 3.1) [14]. A graph is created by connecting the nodes (road intersections) with the roads between them. These roads become the edges in the graph. An intersection is in our case defined as a geographic location where three or more roads meet. Roundabouts are also considered road intersections. A road between two intersections is in many cases divided into several segments in NVDB. This leads to pseudo-nodes that only connect two road segments and does not represent an actual intersection. Therefore, we process this data set by removing nodes that do not meet our criteria of connecting three or more roads by removing all nodes with a degree of two. If the degree is exactly two, then the arcs the node connects are merged to one arc with the combined weight of the two merged arcs. The distance between the remaining nodes becomes the weight for each edge in the graph. The node is then removed. Nodes closer than 10 meters from one another is also merged to one node.

Then several paths, or routes, are generated between each pair of nodes. The number of paths generated is based on the computational capacity available. In this case, the shortest paths are generated between all pairs of intersections. The routes of this set of shortest paths that are longer than or equal to what we define as the practical range of a BEV, $R - E$, are stored in a pickle file [35]. This means that the objects are serialized and then saved in the file. This considerably reduces the file size and makes it possible to export and import larger structures. The different paths are then imported to be used in the implementation of the model.

Chapter 6

Experiments

This chapter includes various experiments conducted with the mathematical models introduced in Chapter 4 along with a running time analysis. The experiments aim to address the following questions:

- What is the minimum number of charging facilities required to cover Trøndelag county while still being connected to the grid?
- What is the minimum number of charging facilities and chargers needed to cover Trøndelag county while accounting for the amount of traffic?
- How does varying the parameter values related to the cost of establishing a charging facility and the cost of a charger affect the objective function value and the number of nodes chosen as locations for charging facilities, the number of chargers placed at each facility and the number of transformers used for grid connectivity and electricity supply?
- How does limiting the number of transformer stations that can supply a single charging facility affect the solution and the total cost?
- Is Trøndelag county covered by charging infrastructure by today's existing charging facilities? If not, what is needed to close this gap?
- How does the size of the input in the form of the number of paths affect the running time and the ability of the solver to reach an optimal solution?

We will first give an introduction to the framework of our experimental work. We then explain each experiment before showcasing the results. The experimental part of this thesis is concluded with a running time analysis.

6.1 Methodology: Optimal charging facility location in Trøndelag county

The range of a BEV, R, is set to 400 km in the following experiments if no other range is explicitly stated. This is considered a realistic range based on the fact that new electric cars coming to market in 2023 have an average range of almost 480 km [37]. The value representing the anxiety range experienced by a driver, A, is set to 50 km. The threshold for the routes included in the data set is therefore set at 350 km. This results in 110494 routes. The chargers are given a power of 300 kW. This is in accordance with the newer chargers available on the market, as mentioned in Section 1.1. In our calculations, one charger is equivalent to one charging point, even though chargers often have two or more points and can split their power between these. A description of the parameters held constant in the following experiments and their values are included in Table 6.1. Traffic and the cost of establishing an electrical cable from a node to a transformer are not given in the table. Traffic is specific to the given route, and the price of laying a cable is specific to the node-transformer pair.

The locations of the transformer stations will not be shown on the maps included in this chapter. This is because their location is not publicly available, and we do not have explicit permission from *Tensio AS* to share these. However, the coordinates of the transformer stations used for electricity supply and the charging facilities they supply are nevertheless an output of the optimization process.

The implementation of the model consisting of equations (4.5) - (4.10) is first run without taking traffic into account. This is to establish a base case of a minimum covering of Trøndelag county with charging facilities. This application can be useful in planning and policy-making, as it shows the minimum number of charging facilities and their location that is necessary to cover the shortest paths from one intersection to another intersection in the county.

After this base case is established, a series of experiments are run with the model also considering traffic. This refers to the model based on equations (4.17) - (4.27). The traffic volume is used to determine how many chargers are needed at each facility. The first of these experiments runs the model with the same parameter values as used to establish the minimum coverage without traffic. A series of experiments are then conducted to investigate the variation of parameter values and their impact on the objective function value and solution. A total of nine experiments are run with this model. Then, the same

Table 6.1: Description of the parameters used in the models from equations (4.5)-(4.10), equations (4.17)-(4.27) and equations (4.29) - (4.40) and their value.

Parameter	Explanation	Value	Unit
R	Range of BEV	400	km
A	Value for range anxiety	50	km
τ_l	Traffic on route l	Varies per route l	Cars per 24 hours
κ	Bound on cars per chargers	300	Cars per charger
G_{kt}	Price of establishing a electrical cable from node k to electrical substation t	Dependent on distance from node k to electrical substation t	NOK

nine experiments are run with the model where the number of connection points each node can have to the grid is restricted. This model is formulated with equations (4.29) - (4.40). A final series of experiments is run to answer if the existing charging facilities and chargers are enough to cover the routes generated.

We then conduct a running time analysis to look at the solver's running time and its correlation to input size. The input size is, in this context, the number of paths that are given to the solver and the number of constraints and variables this leads to.

The routes used in the experiments described in Sections 6.2, 6.3, 6.4 and 6.5 are plotted in Figure 6.1. The blue points are intersections, and the red lines are routes. The nodes not covered by the routes are nodes that do not have any nodes long enough away from themselves to result in a shortest path over the 350 km threshold and that are not included in any other routes. As can be seen in Figure 6.1, these nodes are located near the geographical midpoint of the county.

All experiments are run until the solver reaches a relative optimality gap of less than or equal to two percent. This means that the difference between the incumbent solution and the best-known bound is less than or equal to two percent. The experiments are run on a PC equipped with an AMD Ryzen 7 3700U with Radeon Vega Mobile Gfx processor with a base frequency of 2.30 GHz. The installed RAM is 16 GB (13,9 GB usable). The PC runs on a 64 bits Windows 10 operating system. In this project, *Gurobi* (version 10.0.1) is used to implement the model [13]. Pycharm professional (version 2022.1) is used as an IDE running Python 3.10.

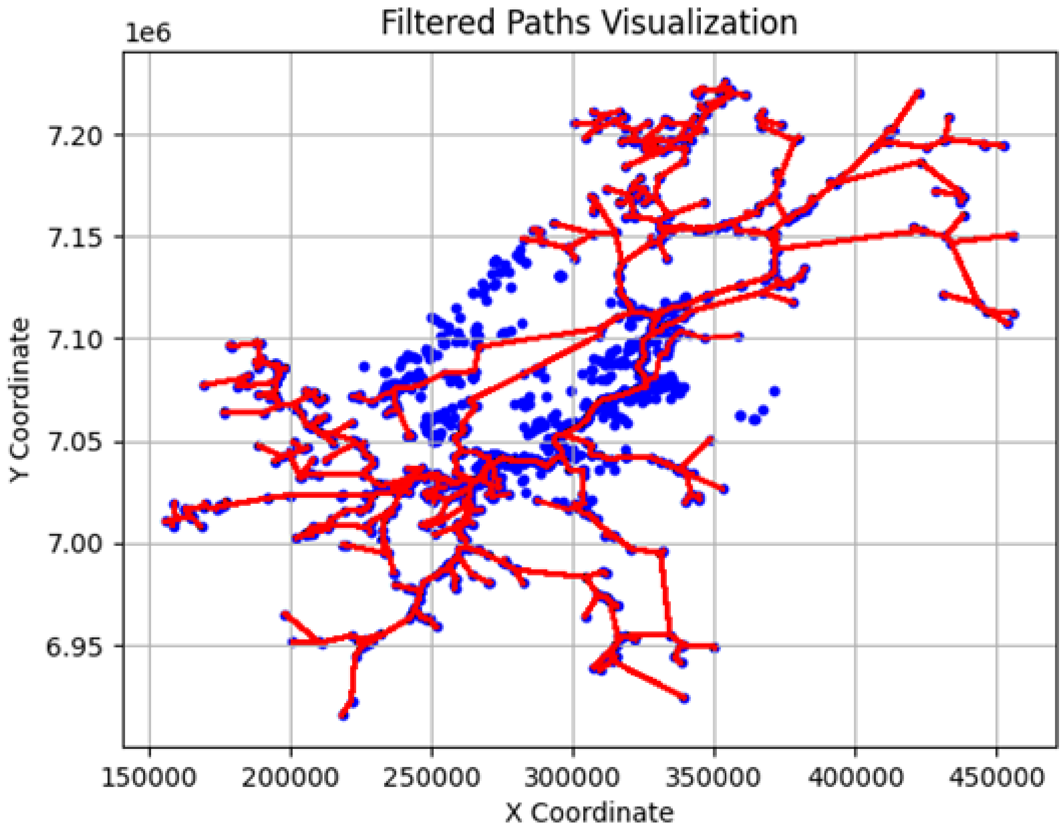

Figure 6.1: Plot of the intersections/nodes in the road network used in the experiments in Section 6.2 and Section 6.3. Red lines represent the routes between node pairs that have a shortest route between them that is longer than the threshold of 350 km mentioned in Section 6.1. The figure shows 110494 paths.

6.2 Infrastructure location ignoring traffic

We refer the reader to equations (4.5) - (4.10) for the model that is used in this experiment. We use this model to establish a base case where the geographical area is covered without considering traffic and the number of chargers needed. The cost of establishing a new location is set at two MNOK. This is extrapolated from reports on charging infrastructure in Norway [36, 27]. The cost of digging and laying cable from the chosen nodes to an electrical substation is given a value of 3493 NOK per meter. This cost is the summation of the cost given in *Norsk prisbok* of one meter of electricity cable for a large building (1400 NOK per meter) and the cost of a cable trench for said cable (2093 NOK per meter) [31]. The Euclidean distance between the node and the transformer station is used. The cost is, however, dependent on the distance one has to dig, the terrain, and so on. We will use a static parameter value in all experiments. The reality is that these costs are assessed on a case-by-case basis by the network companies. Therefore, the amounts used are example values and should be replaced with more accurate numbers when available.

6.3 Infrastructure locations considering traffic

The model used in the experiments in this section is an implementation of equations (4.17) - (4.27). There are two main objectives for these experiments. The first is to establish a minimum covering similar to the one in Section 6.2, but now also taking into account the volume of traffic. The traffic volume is the dimensioning factor for the number of chargers installed at a charging facility. The second objective is to see how a variation in the values of the parameters in the model affects the solution in terms of objective function value and the solution in terms of the number of charging facilities and chargers at each charging facility.

The parameters used in experiment 1 are from reports on fast charging infrastructure in Norway that include sections on the cost of establishing such charging facilities [36, 27]. The bound on the number of cars per charger, κ, is set at 300 in all experiments [29]. These values serve as a baseline. Subsequent experiments are performed to see the impact of variations in the values of C_k and O on the objective function value. The values used for the parameters that are varied are included in Table 6.2. Each of these two parameters is varied with 20 % from the baseline used in experiment 1.

Table 6.2: Values in MNOK used in experiments to test the sensitivity of the objective function value. Recall that C_k is the cost associated with establishing a charging facility at node k, O is the cost of one charger. The parameter values are varied 20 % from the baseline that is experiment 1.

	C_k (MNOK)	O (MNOK)
Experiment 1	2.0	1.0
Experiment 2	2.0	0.8
Experiment 3	2.0	1.2
Experiment 4	1.6	1.0
Experiment 5	1.6	0.8
Experiment 6	1.6	1.2
Experiment 7	2.4	1.0
Experiment 8	2.4	0.8
Experiment 9	2.4	1.2

6.4 Infrastructure locations with restricted number of grid connections

Equations (4.29) - (4.40) are in this section used as the mathematical model. The same objectives presented in Section 6.3 apply here as well, but with the added constraint that a node can only be supplied with electricity from a restricted number of transformer stations. This is done to reflect the way new infrastructure is connected to the grid in today's system. The parameter values presented in Table 6.2 are used to perform nine experiments to once again investigate the impact of varying cost parameters.

6.5 Evaluating existing coverage in Trøndelag county

The existing charging infrastructure in Trøndelag county is already quite developed. Existing charging facilities with one or more 150 kW chargers are shown in blue in Figure 6.7. The model consisting of equations (4.17) - (4.27), with modifications to equation (4.18) and equation (4.19), is used to evaluate the coverage of these charging facilities. Equation (4.18) is modified from

$$\sum_{k \in N_l \setminus \{i,j\}} x_k \geq \left\lfloor \frac{D_l}{R - A} \right\rfloor \quad \forall l \in L,$$

to

$$\sum_{k \in N_l \setminus \{i,j\}} (x_k + p_k) \geq \left\lfloor \frac{D_l}{R - A} \right\rfloor \quad \forall l \in L,$$

where the constant p_k is 1 if there exists a charging facility within 300 meters of node k and 0 otherwise. Equation (4.19) is modified in a similar manner as equation (4.18) from

$$\sum_{k \in N_l} w_k \geq \left\lceil \frac{\tau_l}{\kappa} \right\rceil \quad \forall l \in L,$$

to

$$\sum_{k \in N_l} (w_k + m_k) \geq \left\lceil \frac{\tau_l}{\kappa} \right\rceil \quad \forall l \in L,$$

where the constant m_k is the number of chargers already installed at charging facility p_k. These new parameters are not included in the objective function, and they do not contribute to the overall cost of establishing new charging infrastructure.

The location and the number of chargers for each location are downloaded using *Geodata online* and used as input into the model [12]. Chargers with a power output of 150 kW or greater are included in this input data set. The choice to include chargers in a radius of 300 meters around an intersection is made to not exclude chargers located in parking lots, service stations, and other areas close to the intersection, which still serve the said intersection. This distance is calculated using the Euclidean distance.

6.6 Running time analysis

To get an impression of what smaller and bigger instances of the problem would do to the running time and solvability using the commercial solver chosen for this project, a series of instances varying in size in terms of the number of paths included is tested on the model consisting of equations (4.17) - (4.27). These instances are generated by setting the practical range of the car, $R - A$, to 500 km and starting with including paths equal to or longer than this threshold. Then, the number of included paths is increased by lowering this threshold with 20 km if the solver can reach a solution. The practical range of the car is kept unchanged. The number of paths per threshold is given in Table 6.3 and plotted in Figure 6.2. The number of constraints per threshold is plotted in Figure 6.3. The practical range is set to 500 km to get a solution that is not empty for a threshold of included paths that is over 500 km.

Table 6.3: Number of included paths when the threshold for including a path is decreased. The threshold means that all paths of this distance or longer are included.

Threshold for included paths (km)	No. paths	No. of constraints	No. of Variables
500	64	435250	867600
480	628	588418	1171260
460	2410	680310	1347672
440	9022	744214	1448892
420	20452	814858	1544328
400	39126	919538	1678806
380	60884	1028938	1810392
360	91270	1311254	2252868
340	133580	1718054	2896338
320	207776	2240030	3642474

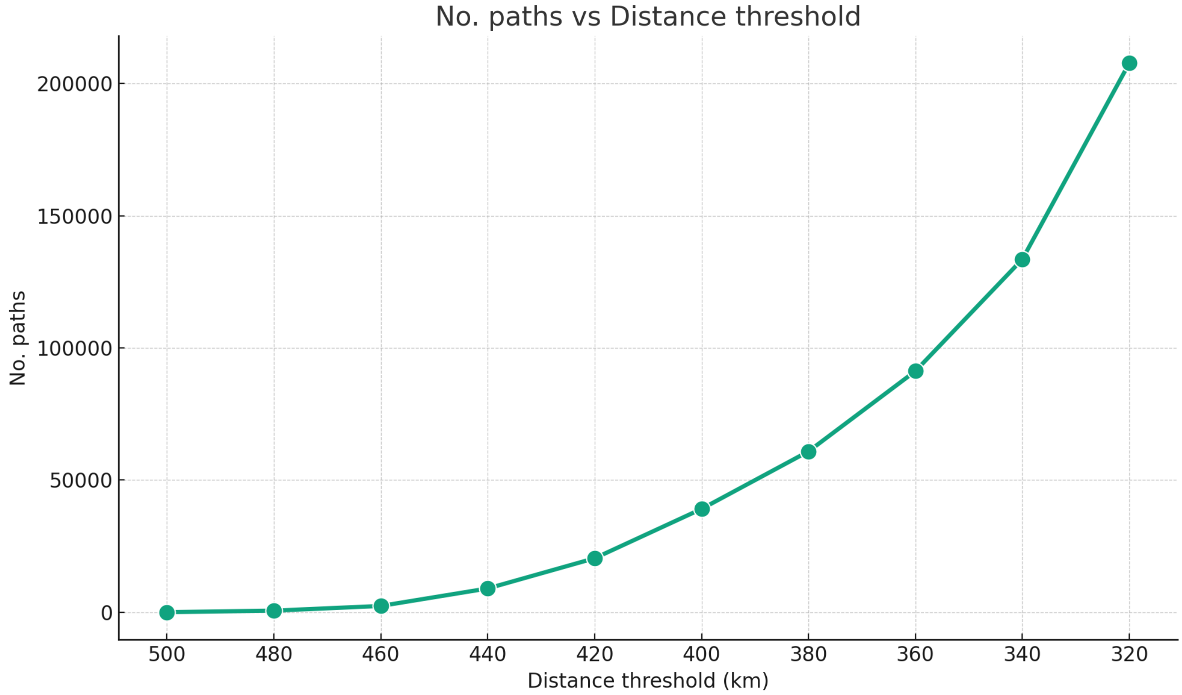

Figure 6.2: Number of paths generated based on the threshold for an included path. The threshold means that all paths of this distance or longer are included.

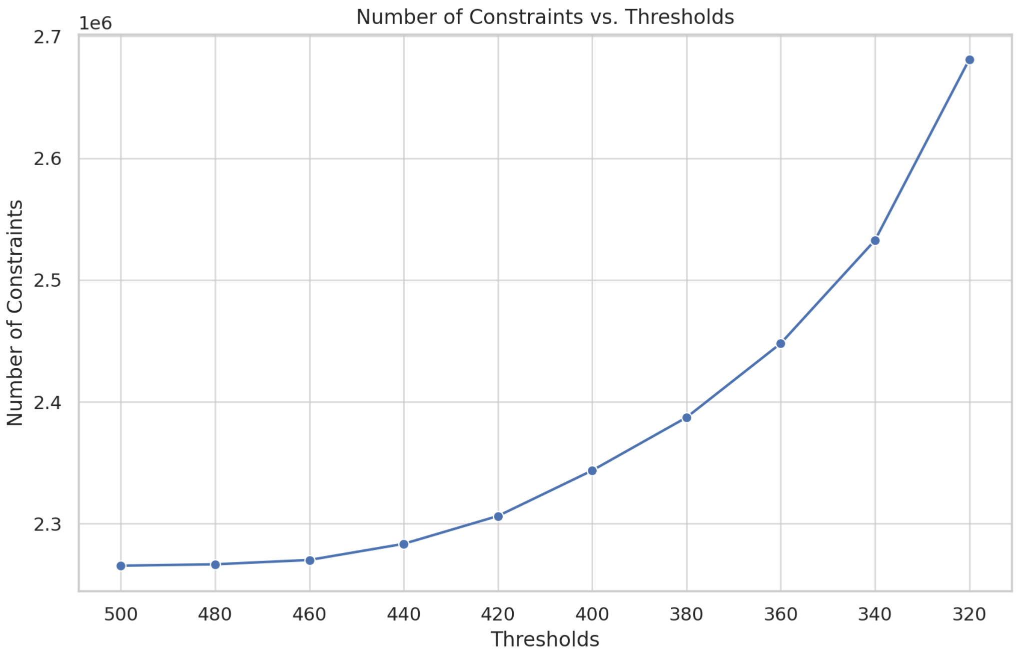

Figure 6.3: Number of constraints generated based on the threshold for an included path. The threshold means that all paths of this distance or longer are included.

6.7 Results: Infrastructure locations ignoring traffic

When considering the minimum cover of the routes longer than 350 km in Trøndelag county, only four nodes are chosen for charging facilities, as seen in Figure 6.4 as blue circles. Four transformer stations supply these locations. The number of facilities is closely related to the range of the vehicle. This becomes evident if we reduce the range of the car to 250 km with a 50 km range anxiety buffer. The number of paths rises to 1588050. Then 14 facilities are needed to cover all the shortest routes over 200 km. This is shown in Figure 6.4, marked with red circles. 13 transformer stations are used to supply these charging facilities. These results are, of course, most relevant if all transformer stations can supply enough electricity to charge every vehicle that stops at each charging facility. This is, however, not the case, and the cost of connecting these few facilities to transformer stations with free capacity, but that are located at a greater distance from the charging facilities, has to be compared to the cost of opening more facilities that are closer to electrical substations with free capacity.


Kartverket, Geovekst, kommuner og OSM - Geodata AS

Figure 6.4: Charging facilities needed to cover Trøndelag county when not considering the impact of traffic. The locations marked with four triangles cover all routes when the range of a BEV is set to 400 km. The 14 circles are the needed facilities when the range is reduced to 250 km.

6.8 Results: Infrastructure locations considering traffic

When performing experiment 1 as described in Section 6.3 with the values from Table 6.2, 13 nodes are chosen as locations for charging facilities. This is nine more than the model in Section 6.7 chooses to establish. The number of chargers at each facility ranges from five at the low end to 52 at the high end. 51 electrical substations are used to supply the electricity needed. The objective function value is 1383 MNOK. The 13 locations are visualized in Figure 6.5. The variations of parameter values laid out in Table 6.2 result in variation in both the objective function value and the number of nodes and transformer stations used. The result is presented in Table 6.4. There are, however, no significant changes in the solution in terms of the number of nodes, transformer stations, and chargers used in each solution. The model seems to be stable within these variations of the cost parameters. There is a 6.8 % increase from the lowest objective function value of 1345 MNOK to the highest value of 1436 MNOK.

Compared to the result of the base case in Section 6.7, we see a drastic increase in the number of nodes and transformers used. Similar to the locations found in Section 6.7 when covering routes longer than or equal to 350 km, is a node in the north of Fosen in proximity to Åfjord chosen, along with nodes near Trondheim city center. A node north of Stjørdal is also chosen in both experiments. It is notable that even though only four nodes are needed to cover all paths, the model chooses to establish charging facilities on 13 nodes. This is to minimize the cost of supplying the required number of chargers with electricity. The total cost of opening more charging facilities and supplying them from electrical substations in close proximity is lower than that of only establishing charging infrastructure on the four nodes chosen in Section 6.7.

This solution deviates considerably from today's construction practice, where each charging facility has one single connection point to the grid. The results point to an alternative approach to the integration of charging facilities into the grid. An analysis of the practical feasibility of this approach is not within the scope of this project.

Figure 6.5: Charging facilities needed to cover Trøndelag county when accounting for traffic. A total of 13 nodes are chosen as charging facilities. The charging facilities are supplied with electricity from a total of 51 electrical substations.

Table 6.4: Results of Section 6.8. The *Ex* column specifies the experiment carried out. The *OFV* column displays the variation in objective function value throughout the experiments.

Ex	OFV (MNOK)	No. nodes	No. substations	No. Chargers per node
Ex 1	1383	13	51	10, 3, 11, 5, 8, 2, 4, 12, 3, 28, 17, 52, 6
Ex 2	1345	13	54	4, 3, 11, 5, 12, 2, 3, 7, 15, 7, 24, 20, 52
Ex 3	1415	14	51	13, 3, 11, 5, 8, 2, 3, 7, 5, 8, 3, 28, 13, 52
Ex 4	1395	13	51	18, 6, 3, 11, 5, 2, 3, 3, 9, 3, 28, 17, 53
Ex 5	1345	14	53	18, 4, 3, 11, 5, 8, 2, 4, 8, 7, 24, 13, 52, 6
Ex 6	1427	13	53	14, 6, 3, 11, 5, 8, 2, 3, 3, 28, 17, 8, 53
Ex 7	1404	12	52	18, 3, 11, 5, 2, 3, 6, 3, 28, 20, 9, 53
Ex 8	1353	12	53	18, 10, 4, 3, 11, 5, 2, 12, 24, 7, 17, 52
Ex 9	1436	12	52	18, 3, 11, 5, 2, 7, 12, 3, 2, 28, 17, 53

6.9 Results: Infrastructure locations with restricted number of grid connections

When using the model from equations (4.29) - (4.40), the results are somewhat different. For the parameter values of experiment 1, the model chooses 43 nodes and 43 transformer stations. The 43 nodes are shown in Figure 6.6. The different experiments result in slight variations in the number of nodes and transformers used. The results are shown in Table 6.5.

Although the area occupied by the chargers installed at each facility is not taken into account in this project, a side effect of introducing this constraint is that the chargers are spread out. At most, a single charging facility contains 13 chargers. This is a significant reduction in the area demand of 52 chargers in a single facility found in Section 6.8. It does, however, result in an objective function value that is 507 MNOK higher for experiment 1 than the objective function value found in Section 6.8. This is an increase of 36.6 % and suggests that supplying a charging facility from multiple transformer stations results in an overall lower cost than restricting the number of connecting points for a charging facility to the grid.

If we let a charging facility be supplied by up to two transformer stations by modifying equation (4.28) from

$$x_k = \sum_{t \in T} y_{kt} \quad \forall k \in N,$$

to

$$2x_k \geq \sum_{t \in T} y_{kt} \quad \forall k \in N,$$

Figure 6.6: Charging facilities needed to cover Trøndelag county when accounting for traffic. A total of 43 nodes are used for charging facilities. Each node is only supplied by one electrical substation. The charging facilities are supplied with electricity from a total of 43 electrical substations.

we now get 27 nodes chosen for charging facilities and 48 substations used to supply electricity for the values of experiment 1 in Table 6.2. This result is notable because the number of charging facilities is drastically reduced.

6.10 Analysis: Trøndelag county's existing coverage

Trøndelag county is close to being covered for a car with a range of 400 km. It is required to establish four new locations to cover all 110494 paths representing the shortest paths between nodes within the county. The new nodes do, however, only cover 50 paths not already covered by the existing charging facilities equipped with chargers with a power output of 150 kW or more. Seven electrical substations are used to supply the electricity necessary for these charging facilities. A total of 11 chargers must be installed. These new additions to the charging network would have a price tag of 73 MNOK.

Table 6.5: Results from Section 6.9. The *Ex* column specifies the experiment carried out. The *OFV* column displays the variation in objective function value throughout the experiments.

Ex	OFV (MNOK)	No. nodes	No. substations	No. chargers per node
Ex 1	1890	43	43	4, 5, 3, 2, 1, 2, 2, 13, 1, 4, 4, 3, 2, 3, 1, 3, 5, 4, 5, 3, 4, 5, 5, 5, 5, 4, 3, 5, 5, 1, 2, 4, 5, 4, 5, 5, 5, 6, 3, 4, 5, 4, 3
Ex 2	1852	44	44	3, 4, 3, 1, 1, 2, 2, 2, 1, 13, 1, 1, 4, 5, 3, 2, 3, 3, 5, 4, 5, 3, 4, 5, 5, 5, 5, 4, 3, 5, 5, 3, 4, 5, 4, 5, 5, 5, 6, 3, 4, 5, 4, 3
Ex 3	1923	45	45	3, 3, 5, 1, 3, 2, 1, 2, 1, 2, 13, 1, 1, 4, 4, 3, 2, 1, 3, 3, 5, 4, 5, 3, 4, 5, 5, 5, 5, 4, 3, 5, 5, 4, 5, 4, 5, 5, 5, 6, 3, 4, 5, 4, 3
Ex 4	1871	43	43	3, 3, 5, 3, 1, 2, 2, 2, 13, 1, 4, 4, 3, 2, 3, 2, 5, 4, 5, 3, 4, 5, 5, 5, 5, 4, 3, 5, 5, 1, 2, 4, 5, 4, 5, 5, 5, 6, 3, 4, 5, 4, 3
Ex 5	1839	43	43	3, 4, 5, 3, 1, 2, 2, 2, 13, 1, 4, 4, 3, 2, 1, 3, 4, 4, 5, 3, 4, 5, 5, 5, 5, 4, 3, 5, 5, 1, 3, 4, 5, 4, 5, 5, 5, 6, 3, 4, 5, 4, 3
Ex 6	1907	43	43	4, 5, 2, 2, 1, 2, 2, 13, 1, 4, 4, 3, 2, 3, 3, 5, 4, 5, 3, 4, 5, 5, 5, 5, 4, 3, 5, 5, 1, 2, 2, 4, 5, 4, 5, 5, 5, 6, 3, 4, 5, 4, 3
Ex 7	1908	43	43	4, 5, 1, 3, 1, 2, 2, 2, 13, 1, 4, 4, 3, 2, 3, 5, 4, 5, 3, 4, 5, 5, 5, 5, 4, 3, 5, 5, 1, 2, 4, 5, 4, 5, 5, 5, 3, 6, 3, 4, 5, 4, 3
Ex 8	1875	43	43	2, 4, 5, 1, 3, 1, 2, 2, 2, 13, 1, 4, 4, 3, 2, 3, 3, 5, 4, 5, 3, 4, 5, 5, 5, 5, 4, 3, 5, 5, 1, 4, 5, 4, 5, 5, 5, 6, 3, 4, 5, 4, 3
Ex 9	1937	42	42	3, 3, 5, 2, 2, 2, 1, 13, 1, 4, 4, 3, 2, 3, 2, 5, 4, 5, 2, 4, 5, 5, 5, 5, 4, 3, 5, 5, 2, 3, 5, 5, 4, 5, 5, 5, 6, 3, 4, 5, 4, 3

Figure 6.7: Existing charging facilities with one or more 150 kW chargers in Trøndelag county (blue markers) and additional charging facilities (green markers) needed to cover the whole county. The new charging facilities cover 50 paths, of the total 110494, that are not already covered by chargers with a power output greater than or equal to 150 kW chargers.

6.11 Results: Running time analysis

The running time starts at 30.5 seconds for 64 paths and decreases to 19.2 seconds for 628 paths. It then increases again to 67.7 seconds for 2410 paths. The running time more than doubles to 181.5 seconds for 9022 paths and rises to 334.1 seconds for 20452 paths. Then, it decreases to 301.7 seconds for 39126 paths before rising again to 521.4 seconds for 60884 paths. It then jumps to 1637.4 seconds for 91270 paths and rises to 2646.8 seconds for 133580 paths. This is the biggest instance the solver is able to solve to optimality, with 1718054 constraints and 2896338 variables. It is notable that the solver is able to solve this to a two percent optimality gap in around 45 minutes despite the high number of constraints and variables. These are lowered after a presolving step to 630140 constraints and 1602402 variables. The solver solves this problem by relaxation at the root node. No other nodes are explored. The solver performs 4127 simplex iterations and improves the dual bound by, among other techniques, adding Gomory cuts.

At 207776 paths, the solver runs out of memory after the solver has run for 2929.4 seconds. The relative optimality gap is 27.7 % when this occurs. This instance has 2240030 constraints and 3642474 variables. The evolution in running time is shown in Figure 6.8.

The efficiency of the optimization process seems to vary with different complexity levels. It is notable that the last instance with 2240030 constraints and 3642474 variables from 207776 paths makes the solver time out. The largest jump in running time in seconds occurs when the number of paths is increased from 60884 paths to 91270 paths. The running time increases by 214 % for this step in the threshold. The largest increase in running time in percentage occurs when the threshold is decreased from 480 km to 460 km. This increase in running time is as high as 252 % from 19.2 to 67.7 seconds. This is, however, after the running time decreases from 30.5 seconds for a threshold of 500 km. It is notable that the running time decreases for two of the instances compared to the previous running time.

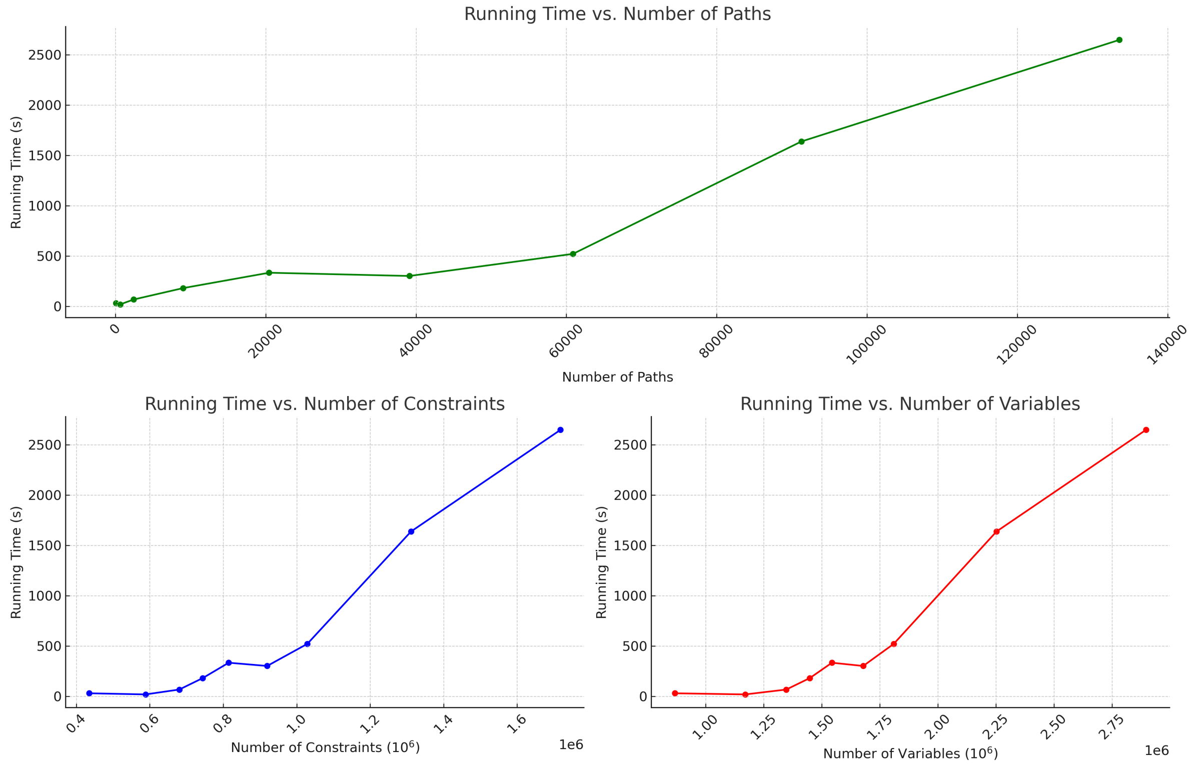

Figure 6.8: Running time in seconds against number of paths (green), number of constraints (blue) and number of variables (red).

Chapter 7

Conclusion

As the electrification of the transportation sector continues, the infrastructure required by the switch to AFVs must be planned and constructed at a rate high enough to not become a limiting factor. Proper planning at an early stage is important for a satisfactory result for all parties. This is also true for charging facilities for BEVs. The planning of these facilities and their integration into the power grid can benefit from improved strategies and methods for finding their potential locations. Good locations for charging facilities can help reduce the overall cost of the infrastructure needed both at the charging facilities themselves and in the grid.

In this project, we have concentrated our efforts on the problem of locating charging facilities for BEVs in a road network. We summarized some important previous work in the field of location-allocation problems, specifically in the context of refueling AFVs.

We then presented three mathematical formulations of the problem of locating charging facilities, where the goal of the models is to minimize the cost of covering a certain set of paths. The first model does not account for the traffic volume. The two others do but vary in how the charging facilities are connected to the grid. The models are tested on a case based on Trøndelag county. We showcase the lengthy and complicated process of collecting data from network companies. We also point to the change in attitude toward openness around power grid data.

The models were tested in a series of experiments. We showcase the different solutions of the three models for a base case and the impact of varying certain parameters on said solutions. We then use the model to evaluate the existing charging infrastructure in Trøndelag county in Norway to see if this is sufficient to cover our problem instance.

Finally, a running time analysis is done to see how the model tackles variation in problem sizes.

As we see it, the most important contribution of this thesis is to showcase a practical implementation of mathematical programming and optimization in the context of infrastructure planning in Norway. We hope that as the trend of more open sharing of data from the network companies continues, this research will be further expanded.

A possibility for further work within the planning of charging infrastructure in Norway would be to look at a larger area than we consider here. The planning and construction of infrastructure do not happen in a closed system, and the larger the area one looks at, the more applicable the results would be in a real-world setting. It would therefore be natural to consider expanding the boundaries of the case. This could require the implementation of heuristic solution methods to solve the problem to near optimality within a reasonable time frame when the amount of input data increases.

The electrification of road freight that we see the start of now adds additional challenges to the problem of locating charging facilities. The power of the chargers is increasing and will thus represent an increased demand on the electricity grid. The area required to maneuver a truck is also significantly bigger than that of a car. This might lead to a limitation on the placement of charging facilities to rest areas for truckers and service stations.

A more sophisticated simulation of the exerted load on the grid could also be included. It could be natural to look at this in connection with a refined traffic flow estimation method. This could be used to adjust the number of chargers needed, take into account factors such as peak load, and more realistically represent the impact a charging facility has on the power grid.

Even though multiple avenues of further research exist, we would once again like to point out that this project has showcased how stakeholders and planners can use optimization to their benefit when planning infrastructure.

List of Acronyms and Abbreviations

AC *alternating current.*

AFV *alternative fuel vehicles.*

BEV *battery electric vehicles.*

DC *direct current.*

EU *European Union.*

FCEV *Fuel cell electric vehicles.*

FCLM *Flow Capturing Location Model.*

FRLM *Flow Refueling Location Model.*

Gt *Gigaton.*

km *kilometers.*

kV *kilovolt.*

kW *kilowatt.*

MNOK *million NOK.*

NOK *Norwegian kroner.*

NPRA *Norwegian Public Roads Administration.*

NVDB *Nasjonal veidatabank.*

RNC *Route Node Coverage.*

SoC *state of charge.*

TWh *Terrawatt hour.*

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