A Network-based Set Covering Model for Charging Station Location Problem: A Case Study in Norway

Hao Yu[1] , Xu Sun[1], Diana Santalova Thordarson[2], Kine Solbakken[3], Wei Deng Solvang[1]

Abstract. Due to the worldwide concern about excessive greenhouse emissions and global warming, vehicles with cleaner sources of energy, e.g., electricity, hydrogen, etc., have been increasingly introduced into the market. Apart from the regulations and government incentives, the distance convenience and accessibility to charging stations have become one of the most important success factors to promote the wide adoption of electric or hydrogen vehicles (EVs/HVs). Establishing a charging station network is a complex decision-making problem that cannot be solved with traditional location optimization models. The tradeoff among demands, the density of facilities, and cost-effectiveness needs to be considered holistically. Therefore, we formulate a network-based set covering location problem (NSCLP) in this paper, which considers the coverage of both nodes and arcs in a network. The proposed model is validated with a real-world case study for optimizing the charging stations of electric trucks in the northern part of Norway. The computational results reveal that the location decisions of charging stations are sensitive to the required accessibility of the network.

Keywords: Charging station, network design, optimization, set covering location problem, accessibility

1 Introduction

Today, worldwide concerns have been increasingly given to resource depletion, excessive greenhouse gas emissions, environmental pollution, and global warming [1], which may significantly compromise the UN's sustainable development goals (SDGs). As one of the largest greenhouse gas emitters [2], the decarbonization and greening of the transport sector play a paramount role in the societal transition toward more sustainability [3]. In this regard, cleaner-fueled vehicles, e.g., electric vehicles (EVs) and

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hydrogen vehicles (HVs), as well as hybrid vehicles have been increasingly introduced into the market to replace traditional fossil-fueled vehicles. However, one of the most significant barriers to the mass adoption of cleaner-fueled vehicles is the lack of an infrastructural network of charging stations [4]. Establishing a charging network for EVs and/or HVs is a complex decision-making problem, which needs to consider the tradeoff among demands, accessibility, and cost-effectiveness. Therefore, recent research has been focused on improved optimization models and algorithms for supporting such decisions under various considerations and complex environments [5], e.g., users' perceived anxiety and convenience [4], sharing charging model [6], probabilistic travel range [7], space-time-electricity accessibility [8], etc.

Essentially, establishing an optimal charging network belongs to a classic facility location problem in operations research [9], where covering location problems, *p*-median problems, and *p*-center problems are widely studied. Both the *p*-median problem and the *p*-center problem were proposed by Hakimi [10] in 1964 to optimize a telecommunication network. Considering the limitation of the number of facilities to be opened, the *p*-median problem minimizes the total weighted travel distance to the facilities, while the *p*-center problem minimizes the maximum distance from the most remote customer to its nearest service facility [11]. The covering location problem was originally proposed by Toregas, Swain, ReVelle, and Bergman [12] in 1971 to optimize the facility locations of an emergency service network, which was further developed into the set covering location problem (SCLP) and the maximal covering location problem (MCLP). With a predefined coverage distance, the SCLP aims at minimizing the number or cost of facilities to cover all the demand nodes, while the MCLP, on the other hand, maximizes the demand coverage with a limited number of facilities [11]. Over the years, several variants of these classic location problems have been developed, which have been used to solve a wide array of real-world challenges [13], for instance, urban post office relocation [14] and the design of baggage dissociation in the future air travel [15], to name a few.

Even though recent research focus has been given to the model development of charging station network design [4], few efforts have been spent to further develop the classic facility location model in order to better adapt the new features of the system. Thus, our paper aims at contributing to the development of a new variant of the SCLP. By adding one set of network constraints to the classic SCLP, our model can help with proper facility location decisions in setting up an infrastructural network for cleaner-fueled vehicles to ensure a driver can find the next charging station within a given distance no matter where the trip is started. Furthermore, a real-world case study is provided for model validation.

The remainder of the paper is organized as follows. Section 2 presents the methodological development including the problem description and a mathematical model. Section 3 validates the model with a real-world case study, and some discussions are also given in this section. Finally, Section 4 summarizes the paper and suggests future research directions.

2 Methodology

In this section, we first introduce a network-based set covering location problem (NSCLP), and then a mathematical model is formulated accordingly.

2.1 Network-based set covering location problem (NSCLP)

Considering the practical challenges faced by the infrastructural network of charging stations, the classic location models are not capable to yield proper decisions on a network-based system. The reason is that, in these mathematical models, only the coverage of nodes is considered, but the coverage of arcs is not taken into account. As shown in Fig. 1, under realistic conditions, a driver needs to consider where the next charging station can be found before starting the journey. Thus, the coverage of arcs must be considered in such a network. To solve this challenge, we define an NSCLP in this paper as "*to effectively and efficiently set up s set of service facilities to cover all the demands from both the nodes and the arcs*".

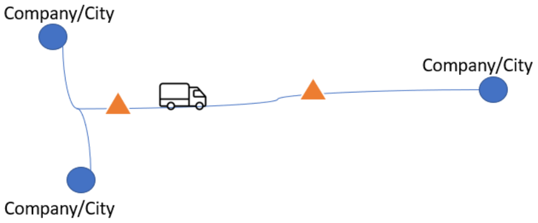

Fig. 1. Network-based set covering location problem.

2.2 Mathematical Model

Based on the classic SCLP, we formulate the NSLPC. The sets, parameters, and decision variables are given as follows:

Sets and parameters	
j	Index of candidate locations in set $\{1, .., N\}$.
i	Index of demand points/cities in set $\{1, .., M\}$.
c_j	Cost of setting up a service facility at candidate location j.
a_{ij}	Binary parameter determining if a demand location is covered by a candidate location.
b_{jk} $\{k \in 1, .., N \backslash k \neq j\}$	Binary parameter determining if a candidate location is covered by another candidate location.
Decision variables	
x_j, x_k	Binary variable determining if a service facility is opened

The objective function Eq. (1) minimizes the total setup cost of the charging stations, e.g., a network of EV/HV charging stations. When cost is not primarily considered, c_j can be set to 1. Then, the problem becomes the minimization of the total number of facilities installed in the network.

$$\text{Minimize } Cost = \sum_{j \in 1,..,N} c_j x_j \tag{1}$$

S.t.

$$\sum_{j \in 1,..,N} a_{ij} x_j \geq 1, \forall i \in 1,..,M \tag{2}$$

$$x_j \leq \sum_{k \in 1,..,N \setminus k \neq j} b_{jk}\, x_k, \forall j \in 1,..,N \tag{3}$$

$$x_j, x_k \in \{0,1\}, \forall j, k \in 1,..,N \tag{4}$$

The model is restricted by constraints (2-4). The first set of constraints (2) ensures that a charging station can be found within a predefined distance. The second set of constraints (3) guarantees when a vehicle has completed charging in one station, the next charging station can be found within the predefined distance. The predefined distance measures the accessibility of the infrastructural network and determines how easy/difficult to find a charging station within the network no matter where the journey is started. The last set of constraints (4) defines the domain of decision variables.

It is noteworthy that, compared with the classic SCLP, the added set of constraints (3) in the NSCLP helps ensure the coverage of demands through the arcs in the network.

3 Case study

In order to validate the proposed NSCLP, a real-world case study in the northern part of Norway is performed. Norway is a pioneer country that has launched an ambitious goal of decarbonizing and greening the transport sector with cleaner EVs and HVs. In 2019, nearly 64.4% of passenger car sales are EVs and hybrid vehicles in Norway, and the targets for zero-emission large vehicles and trucks are 50% and 75% [16]. Thus, setting up an effective charging network is of essential importance to realize this goal. However, on the other hand, Norway is one of the most sparsely populated countries in Europe, especially in the northern part, e.g., 8.53 persons/km^2 in Nordland and 3.23 persons/km^2 in Troms and Finnmark. Due to this reason, the tradeoff between accessibility and cost-effectiveness needs to be balanced when an infrastructural network is planned in this region.

In this study, we considered a charging network planning problem for implementing cleaner electric trucks by several companies between Narvik and Hadsel harbours. Besides, the charging stations can also be used by companies and users from other regions including Lofoten, Sortland, and Senja. Considering the geographical suitableness, 17 locations are selected as candidates for establishing charging stations, as shown in Fig.

2. To simplify the problem, the establishing cost at each candidate location is not considered. Thus, the model aims at minimizing the number of charging stations in the network with a given level of accessibility. Table 1 shows the latitude and longitude of the candidate locations.

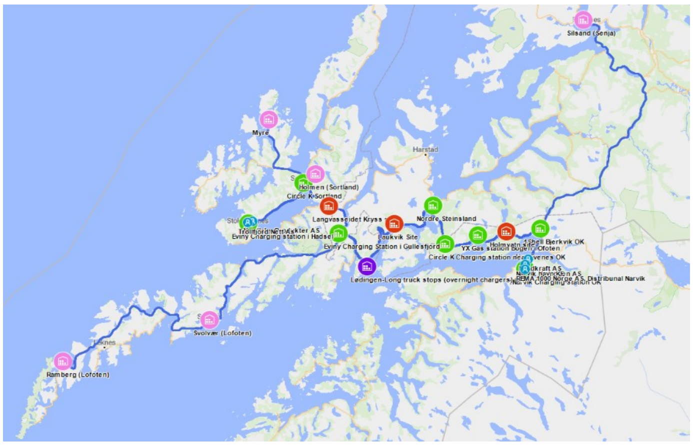

Fig. 2. Knowledge discovery from low correlation data

Table 1. Candidate locations for charging station

No.	Location	Latitude	Longitude
1	Eviny Charging station in Hadsel	68,57	14,91
2	Circle K Sortland	68,70	15,42
3	Langvasseidet Kryss	68,62	15,65
4	Eviny Charging Station in Gullesfjord	68,53	15,73
5	Lødingen-Long truck stops (overnight chargers)	68,42	15,99
6	Laukvik Site	68,56	16,24
7	Nordre Steinsland	68,63	16,59
8	Circle K Charging station near Evenes	68,50	16,70
9	YX Gas station Bogen in Ofoten	68,53	16,99
10	Holmvatn site	68,54	17,26
11	Shell Bjerkvik	68,55	17,56
12	Narvik Charging station	68,41	17,42
13	Myre	68,91	15,10
14	Holmen (Sortland)	68,73	15,52
15	Ramberg (Lofoten)	68,09	13,23
16	Svolvær (Lofoten)	68,24	14,56
17	Silsand (Senja)	69,25	17,95

Based on the location information, the distance matrix can be generated automatically from Bing Maps API. In this study, we considered two scenarios with a coverage distance of 150 km and 130 km, respectively. Then, the coverage matrix (a_{ij}) can be generated accordingly for both scenarios. The model was solved in a PC with Inter Core i5-6400T CPU 2.2GHz and 8 GB RAM under Windows 10 operating system. A professional optimization solver Gurobi 10.0.1 was first used to solve the problem. Due to the small size of the problem, the optimization was also performed with the Problem Solver, which is a free add-on of MS Excel. The optimal locations of the charging stations are given in Figs. 3 and 4, respectively.

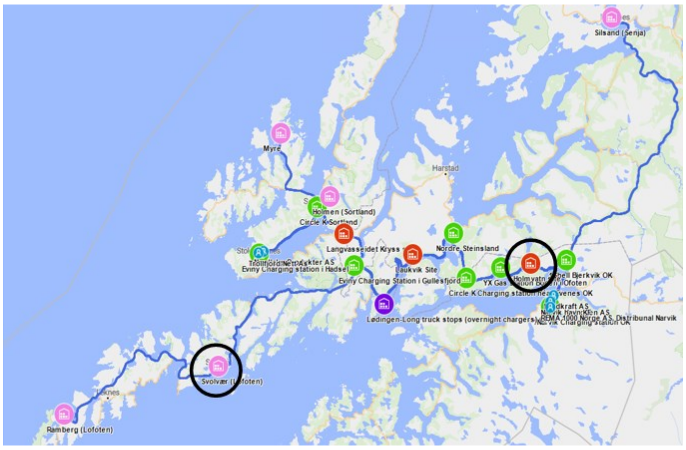

Fig. 3. Optimal results with a coverage distance of 150 km.

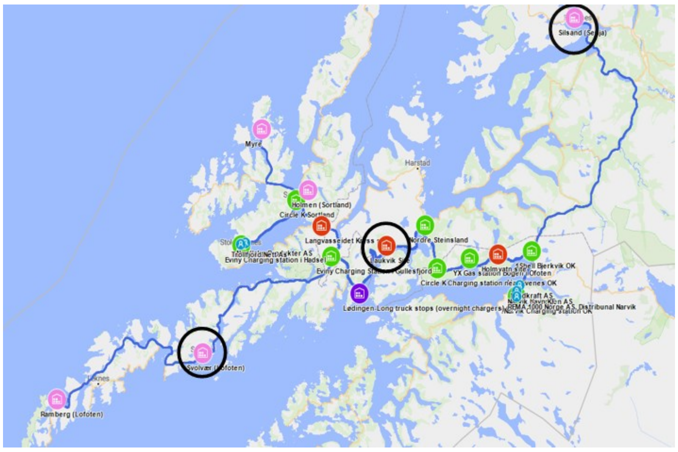

Fig. 4. Optimal results with a coverage distance of 130 km.

As can be seen, the optimal location decisions are sensitive to the coverage distance, say, accessibility. When the coverage distance is set to 150 km, two charging stations are opened at Holmvatn site and Svolvær. However, when the coverage distance is reduced to 130 km, a different decision is made, where three charging stations are opened at Laukvik site, Silsand, and Svolvær, respectively. It is noteworthy that the intracultural network of charging stations is pulled by meeting the demands of remote locations. In this case, the customer demands from Silsand and Ramberg may yield a more significant impact on the location decisions of charging stations. In addition, when a larger coverage distance is used, the charging network becomes more cost-effective, but the accessibility may be compromised. For example, in the first scenario, if a trip starts from Myre toward Silsand, the closest charging station is at Svolær (150 km) but not at Holmvatn site (182 km). Thus, in this case, if the electric truck does not have enough power to travel to Holmvatn site, it needs to first charge at Svolær, which will drastically increase the total driving distance and energy consumption. However, on the other hand, when the coverage distance is reduced to 130 km, this kind of dilemma can be avoided, but one more charging station needs to be established. Therefore, the balance between accessibility and the number of charging stations needs to be properly considered in this case.

4 Conclusions

Today, with an emphasis on emission reduction and sustainable development, the use of cleaner-fueled vehicles, e.g., EVs and HVs, has become increasingly important. One of the success factors is to set up an effective and highly accessible charging network for these vehicles. Based on the traditional SCLP, we define a new NSCLP, based on which a new mathematical model is formulated taking into account not only the coverage of nodes but also the coverage of arcs. The most important contribution of the model is to ensure no matter where the trip is started within the network either from a node or from an arc, the next charging station can be found within the predefined coverage distance. To validate the proposed model, a real-world case study is performed, whose results show the sensitivity of facility location decisions to the coverage distance or required accessibility. To further improve the current research, the following two suggestions are given. First, the model and analysis can further be improved with more data, e.g., the cost of construction of charging stations at different locations and the traffic data at different candidate locations. Second, the analysis can be further improved by considering the sharing of charging stations with other types of users, e.g., electric buses, etc.

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