공학석사학위논문

Charging Station Location Problem for Electric Vehicles in a Mixed Duopoly

혼합 복점 시장에서의 전기자동차 충전소 입지선정 문제

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Abstract

Charging Station Location Problem for Electric Vehicles in a Mixed Duopoly

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This thesis studied a charging station location problem (CSLP) in a mixed market on a network space. The research was motivated by the increasing interest in electric vehicles (EVs) and publicly accessible charging stations. Diverse situations are presented, and the corresponding mathematical formulations are modeled by implementing the optimization approach. The relationships between the models are then analyzed mathematically, showing the existence of complementarity and dominance. Computational experiments follow this in order to validate the presented models and verify the analyses. The trade-off between the stakeholders' objectives is demonstrated, providing policy implications for the public sector and managerial insights for private investors.

Keywords: Facility location, Charging station location, Mixed market, Multiple decision makers, Competition, Cooperation

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Chapter 1

Introduction

In the past, electric vehicles (EVs) emerged as a solution to the depletion of fossil fuels, and interest in them has risen again because of environmental concerns. While interest in EVs has been growing for quite some time, it dipped temporarily because of technical problems and the lack of available charging stations. As EV-related technology has developed, however, tremendous progress has been made in recent years, and interest in EVs has emerged again. According to Bloomberg NEF (`https://about.bnef.com/electric-vehicle-outlook/`), the global EV market has proliferated and will continue to do so. However, more technical developments for EVs are necessary.

One of the most critical considerations relates to EV batteries. Conventional internal combustion engine vehicles (ICEVs), with their gas tanks, only take a few minutes to refuel, even if the tank is empty. Contrary to this, EVs require about 30 minutes to recharge if quick chargers are supported, and take hours to recharge with standard chargers. An additional drawback to EVs is that, even with this long charging duration, EVs have shorter driving ranges than ICEVs. While longer driving ranges, mostly made possible by bigger battery capacities, and faster charging options are continuously being researched, advances are still insufficient to spur con-

sumers to completely replace their ICEVs with EVs. Given this, the greatest concern for EV users appears to be the 'charging capabilities for EVs'.

Many studies on EVs have emphasized the importance of charging stations [39, 25, 6]. These studies showed that the availability of public charging stations, such as gas stations which can be used by anyone, play a significant role not only in boosting convenience for EV owners but also in inducing potential customers to purchase EVs. On the other hand, some studies argue that public charging stations are actually not crucial to the EV users [59, 61, 63, 23, 6, 43, 42]. Unlike ICEVs, which are difficult to refuel at home, EVs can be recharged at home whenever as long as a charger is installed. In surveys of actual EV users, including trial participants, public charging stations were not used much, and most of the charging events took place at home. These results obviously assume that a private charger is equipped at home. It is easy to provide private chargers in a residential environment composed of houses with garages. However, the availability of home charging is a highly valued attribute in cities with a high percentage of residents living in multi-units without garages (for example, Seoul, South Korea). In the end, public charging stations are essential not only for EV users but also for prospective owners [7, 61, 55]. For this reason, governments worldwide are allocating a considerable budget for the expansion of charging facilities, while automakers themselves are also actively investing in such facilities. Considering the significance of publicly accessible charging points, we focus in this thesis on a charging station location problem (CSLP) between a public firm and a private firm. We present several situations with corresponding mathematical models. Mathematical analyses are performed based on the optimization of the presented models.

The facility location problem (FLP) has received much attention after the work of Alfred Weber, which considered the location of a warehouse to minimize the total travel distance between the warehouse and the customers [64]. Many researchers have dealt with FLPs, and naturally, extensive reviews and surveys were inevitable. Because of insufficient publications in the past, comprehensive review papers were published that covered the widespread use of FLPs, such as papers by Brandeau and Chiu [5] or Owen and Daskin [54]. However, as the number of publications has increased significantly in the last few decades, there has been a tendency to narrow the scope of reviews or surveys.

Farahani et al. [18] presented a literature review for set covering problems in facility locations, which the models we present in this thesis originate from. Set covering location problems have been used to identify the optimal locations of facilities to serve demand points within a previously defined distance of time.

The problem may be completely different depending on the purpose of the facility. In particular, Revelle et al. [56] distinguishes the public firm from the private firm and demonstrates the difference between the two. The public sector usually focuses on non-economic benefits (e.g., social welfare), whereas the private firms typically focus on monetary gain. This distinction mainly appears in the objectives. Current et al. [15] reviewed the studies that examined the multi-objective aspects of FLPs, as well as classified the objectives most frequently used for FLPs. They considered the most popular 23 objectives categorized into four types: cost objectives, demand-oriented objectives, profit objectives, and environmental objectives. Furthermore, Farahani et al. [20] investigated multi-criteria decision-making problems in the location analysis, where multi-criteria decision-making problems are

composed of multi-objective decision-making problems and multi-attribute decision-making problems.

Beyond problems that focus on a single decision maker, there are also problems that focus on multiple decision makers. When more than one decision maker exists, interactions inevitably occur between them, which take the form of either competition or cooperation. The competitive location problem originated with the study of Hotelling [32]. He considered a case in which two firms simultaneously made decisions on a finite linear space with uniformly distributed customers. After this groundbreaking study, much work has been carried out on the competitive location problem. Aboolian et al. [1] thoroughly investigated simultaneous situations, whereas Kress and Pesch [38] presented a rich literature review on the sequential case setup, especially on networks. On the other hand, research into cooperation has also been extensively conducted. Goemans and Skutella [24] studied the fair cost allocation of several variants of facility location problems based on the cooperative game theory.

It is easily observable that the multiple decision makers of the previously mentioned papers have the same objectives, respectively. Unfortunately, there may be multiple decision makers with different or conflicting objectives, as we show in this thesis through our consideration of both a single public firm and a single private firm that pursued different purposes. A market in which both public and private firms participate is called a mixed market, which is challenging to analyze because of the complex situation caused by several different objectives. Due to the complexity inherent in the setup, studies dealing with the FLP in a mixed market were limited to a linear space [50, 53, 30, 31, 57, 58, 3, 67, 22, 51, 66, 21, 29, 49] or a circular space

[44, 52]. Extensions to more complex spaces should be extensively studied.

As the significance of the charging stations has been emphasized, related studies, including studies for the CSLP, have increased in practical and academic importance. Asamer et al. [2], Huang and Kockelman [35], Lee et al. [42], and Kchaou-Boujelben [36] have solidly introduced the characteristics of charging stations. Except for offering battery swapping, charging stations can be broadly classified into three categories according to their technology: level 1, level 2, and level 3. The charging time decreases as the level gets higher, while the installation cost for the station increases. In particular, levels 1 and 2 chargers require hours for a complete charge, while a level 3 charger will not take even an hour. Hence, it is reasonable that levels 1 and 2 chargers are preferable in locations with long dwell times or for private purposes (e.g., home charging), while level 3 chargers are normally used for long-distance trips.

One major part of the CSLP that has been extensively studied is the flow-based model [36]. EV drivers taking long-distance trips must recharge the battery on their way, and indeed, on the return trip, too. To satisfy such demands, charging stations, mostly level 3, should be located adequately to make sure that the distance between two consecutive stations is within the driving range, taking into account the origin-destination trips [40, 65, 45, 17, 28, 9, 13, 37].

Another part considers the node-based models, to which our models belong [36]. These are the cases in which the demands simply arise at the nodes. The node-based models are usually used for demonstrating the charging events that take hours while the users are resting at home, working, or shopping [2, 34, 69, 14, 16, 62, 33]. As mentioned previously, home charging is a highly valued attribute, not only in Seoul,

but also in most of the cities of South Korea in general [55]. This problem has also been a challenge for other countries [2, 35]. To this point, the South Korean government has announced that by 2025, it will build more than 500,000 levels 1 and 2 chargers in areas within 5 minutes' walking distance from residences or workplaces. Given this, we focus on the problem of locating publicly accessible charging stations with level 2 chargers in areas near the demand that offer services similar to home charging.

In contrast to previous studies handling the node-based models, we study the case where multiple facility builders participate with different objectives. Only a few studies have been published that integrate multiple decision makers into a CSLP. Even papers dealing with multiple decision makers only dealt with competition among profit maximizers [48, 4, 26, 68, 12] or with a game composed of a charging station builder and the users [27, 4, 26, 10, 46, 47].

To the best of our knowledge, no attempts have been made to integrate a mixed market into the FLP on a network or to handle a CSLP with multiple facility builders with different objectives. The motivation for this study is to tackle such issues.

The remainder of this study is organized as follows: In Chapter 2, we describe our problem, including the assumptions. The mathematical formulations are presented in Chapter 3. Based on these formulations, some research questions are raised in Chapter 4. In addition, mathematical analyses based on four propositions are provided to answer the research questions. Computational experiments are reported in Chapter 5, and conclusions are offered in Chapter 6.

Chapter 2

Problem description

We consider an FLP, especially a CSLP, at a network formed market, based on the mixed duopoly model for a single period. The terms "facility'' and "station'' are used interchangeably throughout this thesis. As we handle a network space, the optimal solutions could not be expressed in a closed form, or generally. Therefore, we implement the mixed-integer linear programming optimization with mathematical analyses instead of the game theoretic approach, which the previous works have applied to a linear or circular space. The duopoly consists of a public firm attempting to maximize the total coverage within a given budget and a private firm that maximizes its own profit. The firms, hereafter "public'' and "private'' respectively, are willing to locate charging stations that belong to ordinary service facilities [19, 8]. Although we are taking into account both private and public as the decision makers, we adhere to the position of the public. In order to successfully implement the charging station expansion plan for the public, we investigate how the public should act with the consideration of the existence of the private. In addition, any transportation costs are not considered because the presented models belong to set covering problems. The demands are assumed to be deterministic. According to Bunce et al. [6], 49 percent of drivers recharged at regular intervals, usually at home overnight

or at work during the day. In addition, Langbroek et al. [41] found that 60 percent of EV owners charge every day, rather than only when it is necessary. Therefore, we can assume that the majority of people charge their EVs regularly, which leads to deterministic demands and predictable profits. The stations are located at the nodes of the network, and only one station, at most, can exist at any node. We also assume that every charging station is uncapacitated and identical, which leads every customer to visit only the nearest station. As we assumed deterministic demands also, the demands that will be served are fixed once the locations of the stations are decided. Then, the number of the cords could be chosen after choosing the locations, and a scheduling problem could be conducted afterward to manage all the demands to be served. More demands require more cords. In Chapter 5, we have considered this impact by generating the cost with respect to the demands. The problem can be categorized into six cases, as shown in Table 2.1.

Table 2.1: Categorization of the Problem

	Sequential		**Simultaneous**
	Public $\longrightarrow$ Private	**Private $\longrightarrow$ Public**	
Competition	Model 1	-	-
Cooperation	-	Model 2	Model 3

First, simultaneous competition can take place between the two firms. However, considering that an FLP is being handled at a mixed market, simultaneous competition is not likely to occur in the real world.

Next, the competition can arise sequentially, branching again into two cases: the private decided first, followed by the public, and vice versa. For the former case, the public might intrude into the coverage by the private to maximize its own objective.

Then the private might lose some of its revenue and might file a civil complaint, which the public would not countenance, because of its publicity. Thus, the public would attempt to preserve the coverage of the private. This situation is more likely to represent cooperation and will be introduced again later. The latter situation seems to be more realistic. After the public chooses its locations myopically, the private can enter the market only for profitable spots. Because the entry of the private allows only the total coverage to benefit, the public has no reason to inhibit it.

Cooperation can take place instead of competition, leading to another three cases. Among them, the private leading in cooperation corresponds to the previous case. The private decides first to maximize its profit, and then the public chooses the locations while maintaining the market share of the private. As a result, the public will cover the lonesome nodes left by the private. Public facilities located in the countryside, with negligible populations are an example. When the public decides preemptively, the situation barely shows any characteristics of cooperation.

The two firms could decide simultaneously as well. Cooperation, then, can be regarded as a bi-objective decision-making problem. Classical approaches for solving the multi-objective optimization problem, including the bi-objective problem, try to convert such problems into a single-objective problem. One of the most popular approaches is to modify all except one objective as a constraint. To apply such an approach to this case, we consider one of the firms as the main decision maker and optimize its objective function while guaranteeing the other for a certain level as a constraint. Consequently, we consider the more realistic three cases: (i) sequential competition starting from the public (Model 1), (ii) sequential cooperation starting from the private (Model 2), and (iii) simultaneous cooperation (Model 3).

Chapter 3

Mathematical formulation

3.1 Notations

The model sets and parameters are defined as follows:

I : set of customer zones

J : set of potential facility locations

B : annual budget allocated to the public firm

r : fixed coverage radius

h_i : annual demand of customer zone $i \in I$

d_{ij} : distance between customer zone $i \in I$ and candidate location $j \in J$

a_{ij} : 1 if $d_{ij} \leq r$, 0 otherwise

f_j : annual amortized total cost to open, operate and maintain a facility at candidate location $j \in J$

α : annual earnings gained by serving a unit demand

The opening of facilities usually costs a big lump sum, but this expense arises only once. However, operating costs and maintaining costs occur regularly but are relatively small. We assume the opening costs to be annually amortized, to consider all costs together. Consequently, the total cost, including operating costs, maintenance costs, and amortized opening costs, is assumed to arise annually. The interest rate is not introduced because we are not handling multiple periods. Because we assume regular charging intervals and deterministic demands, the profit is predictable and can be estimated if the coverage is specified. Hence, we deal with the annual earnings gained by serving a unit demand instead of dealing with the charging fee imposed for a one-time charge.

Also, four decision variables are used to construct the mathematical models, as follows:

x_j : 1 if a public facility is located at candidate location $j \in J$, 0 otherwise

y_{ij} : the fraction of demand of customer zone $i \in I$ served by public facility $j \in J$

z_j : 1 if a private facility is located at candidate location $j \in J$, 0 otherwise

w_{ij} : the fraction of demand of customer zone $i \in I$ served by private facility $j \in J$

3.2 The sequential competition model (Model 1)

The sequential competition model (Model 1) is as follows:

$$
\begin{aligned}
\max \quad & \sum_j \sum_i h_i y_{ij} & & \\
\text{s.t.} \quad & y_{ij} \leq a_{ij} x_j & i \in I,\, j \in J & \quad (3.1) \\
& \sum_j y_{ij} \leq 1 & i \in I & \quad (3.2) \\
& y_{ik} \leq 2 - (a_{ij} x_j + a_{ik} x_k) & i \in I,\, j, k \in J : d_{ik} > d_{ij} & \quad (3.3) \\
& \sum_j f_j x_j \leq B & & \quad (3.4) \\
& x_j \in \{0, 1\} & j \in J & \quad (3.5) \\
& y_{ij} \geq 0 & i \in I,\, j \in J & \quad (3.6)
\end{aligned}
$$

$$
\begin{aligned}
\max \quad & \alpha \sum_j \sum_i h_i w_{ij} - \sum_j f_j z_j \\
\text{s.t.} \quad & y_{ij} \leq a_{ij} x'_j && i \in I,\, j \in J && (3.7) \\
& w_{ij} \leq a_{ij} z_j && i \in I,\, j \in J && (3.8) \\
& \sum_j (y_{ij} + w_{ij}) \leq 1 && i \in I && (3.9) \\
& x'_j + z_j \leq 1 && j \in J && (3.10) \\
& y_{ik} + w_{ik} \leq 2 - (a_{ij}(x'_j + z_j) + a_{ik}(x'_k + z_k)) && i \in I,\, j,k \in J : d_{ik} > d_{ij} && (3.11) \\
& z_j \in \{0, 1\} && j \in J && (3.12) \\
& y_{ij}, w_{ij} \geq 0 && i \in I,\, j \in J && (3.13)
\end{aligned}
$$

$$
\begin{aligned}
\max \quad & \sum_j \sum_i h_i (y_{ij} + w'_{ij}) \\
\text{s.t.} \quad & y_{ij} \leq a_{ij} x'_j && i \in I,\, j \in J && (3.14) \\
& \sum_j (y_{ij} + w'_{ij}) \leq 1 && i \in I && (3.15) \\
& y_{ik} + w'_{ik} \leq 2 - (a_{ij}(x'_j + z'_j) + a_{ik}(x'_k + z'_k)) && i \in I,\, j,k \in J : d_{ik} > d_{ij} && (3.16) \\
& y_{ij} \geq 0 && i \in I,\, j \in J && (3.17)
\end{aligned}
$$

Model 1 consists of three stages. The first and the second stages represent the decision of the public and the profit-seeking choice of the private with the decision of the public given, respectively. The objective function of Stage 1 maximizes the public's coverage. Constraints (3.1) prohibit a customer from being covered by a facility that has not been opened, or that is not within a given radius, r. Constraints (3.2)

state that customers can be disregarded. Note that altering the inequality to strict equality necessitates covering every customer, which might be infeasible because of the budget constraint. Constraints (3.3) represent the customers' preferences for the nearest facility. In detail, if facilities j and k are open and j is relatively closer, customers will not visit facility k. Constraint (3.4) indicates the budget limitation over the costs. Constraints (3.5) define the domain of variable x, and Constraints (3.6) require variable y to be non-negative. Restricting x to a binary state satisfies the assumption that, at most, only one station can exist at any given node. Note that customers always visit the nearest station, and all stations are uncapacitated. Therefore, despite y being defined as continuous, there always exists an optimal solution in which $y_{ij} \in \{0, 1\}, \forall i \in I, \forall j \in J$. In fact, it is reasonable to designate y as being continuous rather than binary, because the customers of a single node can be partitioned into several facilities at the same distance. The public's decision in Stage 1 (x) is fixed as a parameter in Stage 2 (x'), but the coverage is still represented by a variable (y), because it can change by the private's choice.

The objective function of the second stage maximizes the private's profit, which is composed of the revenue earned from covering the customers and the costs. Note that the private's revenue is proportional to its coverage. The variables z and w of the private correspond to the public's variables x and y, respectively. Constraints (3.10) restrict any node from having more than one facility, regardless of the owner. Other constraints are comparable to the first stage.

The last stage has no conceptual meaning but guarantees the maximum total coverage among several optimal solutions retrieved from the second stage.

3.3 The sequential cooperation model (Model 2)

The sequential cooperation model (Model 2) is as follows:

$$
\begin{aligned}
\max \quad & \alpha \sum_j \sum_i h_i w_{ij} - \sum_j f_j z_j \\
\text{s.t.} \quad & w_{ij} \leq a_{ij} z_j && i \in I,\, j \in J && (3.18) \\
& \sum_j w_{ij} \leq 1 && i \in I && (3.19) \\
& w_{ik} \leq 2 - (a_{ij} z_j + a_{ik} z_k) && i \in I,\, j,k \in J : d_{ik} > d_{ij} && (3.20) \\
& z_j \in \{0,1\} && j \in J && (3.21) \\
& w_{ij} \geq 0 && i \in I,\, j \in J && (3.22)
\end{aligned}
$$

$$
\begin{aligned}
\max \quad & \sum_j \sum_i h_i (y_{ij} + w'_{ij}) \\
\text{s.t.} \quad & y_{ij} \leq a_{ij} x_j && i \in I,\, j \in J && (3.23) \\
& \sum_j (y_{ij} + w'_{ij}) \leq 1 && i \in I && (3.24) \\
& x_j + z'_j \leq 1 && j \in J && (3.25) \\
& y_{ik} + w'_{ik} \leq 2 - (a_{ij}(x_j + z'_j) + a_{ik}(x_k + z'_k)) && i \in I,\, j,k \in J : d_{ik} > d_{ij} && (3.26) \\
& \sum_j f_j x_j \leq B && && (3.27) \\
& x_j \in \{0,1\} && j \in J && (3.28) \\
& y_{ij} \geq 0 && i \in I,\, j \in J && (3.29)
\end{aligned}
$$

Model 2 consists of two stages. The first stage represents the decision of the private with a profit-maximizing objective function. All the constraints of Model 2, including the second stage, have been described previously.

Stage 2 represents the public's decision with the choice given by the private. The objective function maximizes the total coverage. The private's decision of Stage 1 (z) is fixed as a parameter in Stage 2 (z'), as in Model 1. The coverage (w) is also fixed (w'), because Model 2 handles the situation of the public that preserves the private's market share. Therefore, the private's coverage should remain static. Integration of Constraints (3.24) and (3.26) inhibits the public's intrusion and renders any solution permitting the private's loss as infeasible.

3.4 The simultaneous cooperation model (Model 3)

We can formulate two models by considering which firm has the main decision. The simultaneous cooperation model with the main decision maker of the private (Model 3-1) is as follows:

$$
\begin{aligned}
\max \quad & \alpha \sum_j \sum_i h_i w_{ij} - \sum_j f_j z_j \\
\text{s.t.} \quad & \sum_j \sum_i h_i (y_{ij} + w_{ij}) \geq \beta \sum_i h_i && (3.30) \\
& y_{ij} \leq a_{ij} x_j && i \in I,\, j \in J \quad (3.31) \\
& w_{ij} \leq a_{ij} z_j && i \in I,\, j \in J \quad (3.32) \\
& \sum_j (y_{ij} + w_{ij}) \leq 1 && i \in I \quad (3.33) \\
& x_j + z_j \leq 1 && j \in J \quad (3.34) \\
& y_{ik} + w_{ik} \leq 2 - (a_{ij}(x_j + z_j) + a_{ik}(x_k + z_k)) && i \in I,\, j, k \in J : d_{ik} > d_{ij} \quad (3.35) \\
& \sum_j f_j x_j \leq B && (3.36) \\
& x_j, z_j \in \{0, 1\} && j \in J \quad (3.37) \\
& y_{ij}, w_{ij} \geq 0 && i \in I,\, j \in J \quad (3.38)
\end{aligned}
$$

On the other hand, the simultaneous cooperation model with the public having the main decision (Model 3-2) is as follows:

$$
\begin{aligned}
\max \quad & \sum_j \sum_i h_i(y_{ij} + w_{ij}) \\
\text{s.t.} \quad & \alpha \sum_j \sum_i h_i w_{ij} - \sum_j f_j z_j \geq P && (3.39) \\
& y_{ij} \leq a_{ij} x_j && i \in I,\, j \in J \quad (3.40) \\
& w_{ij} \leq a_{ij} z_j && i \in I,\, j \in J \quad (3.41) \\
& \sum_j (y_{ij} + w_{ij}) \leq 1 && i \in I \quad (3.42) \\
& x_j + z_j \leq 1 && j \in J \quad (3.43) \\
& y_{ik} + w_{ik} \leq 2 - (a_{ij}(x_j + z_j) + a_{ik}(x_k + z_k)) && i \in I,\, j,k \in J : d_{ik} > d_{ij} \quad (3.44) \\
& \sum_j f_j x_j \leq B && (3.45) \\
& x_j, z_j \in \{0, 1\} && j \in J \quad (3.46) \\
& y_{ij}, w_{ij} \geq 0 && i \in I,\, j \in J \quad (3.47)
\end{aligned}
$$

Both versions of Model 3 contain a single stage each, with each showing the simultaneous circumstance. Note that no variables are fixed and are considered as parameters because of the simultaneousness of the model. The objective function of Model 3-1 maximizes the private's profit, because the private is the main decision maker, whereas the objective function of Model 3-2 maximizes the total coverage considering mainly the public.

The only difference in the constraints between the two models is Constraints (3.30) and (3.39). These two constraints represent the guarantee for the secondary firms. For example, the main decision maker of Model 3-1 is the private, which makes the public the secondary participant. Therefore, the total coverage is guaranteed to

be higher than a certain level, β. The private's profit is guaranteed in Model 3-2 because the public carries the main decision. All the other constraints have been described previously.

Note that the objectives of the secondary firms for each model are not guaranteed as being maximized. In other words, several optimal solutions can exist with the same objective function value but with different total coverage (Model 3-1) or with different profit outcomes of the private (Model 3-2) because both models contain a single stage, unlike Model 1. This latent problem will be handled in the next chapter.

Chapter 4

Problem analysis

A simple experiment has been conducted based on the presented models, and the details will be introduced in the next chapter.

Table 4.1: Results of the Small-Size Instance

Model	**Total coverage**	**The private's profit**
1	79.5%	73.3265
2	82.9%	219.9895
3-1	82.9%	219.9895
3-2	100.0%	115.9871

Based on the results shown in Table 4.1, four research questions have been raised and investigated. They are as follows:

- Will Model 3-1 and Model 3-2 retrieve the same results, and if so, under which conditions?
- Will Model 2 and Model 3-1 always retrieve the same results?
- Is there a trade-off between the total coverage and the private's profit?
- Will Models 2, 3-1, and 3-2 dominate Model 1?

The optimal results are denoted as $(\tilde{P}, \tilde{\beta})$, (P^*, β^*), $(P_1^*(\beta), \beta_1)$ and $(P_2, \beta_2^*(P))$

for Models 1, 2, 3-1, and 3-2, respectively. Before answering the above questions, we will clarify the definitions of the terms "dominate'' and "Pareto optimal''.

Definition 4.1. *Model A strictly dominates Model B if the outcomes of Model B are all worse than Model A. Model A weakly dominates Model B if the outcomes of Model A are all at least as good as the outcomes for Model B. Model A dominates Model B if Model A either strictly dominates or weakly dominates Model B.*

Definition 4.2. *A situation is called "Pareto optimal'' if some improvements of an outcome always lead to a strict decline of any other outcome.*

Proposition 4.3. *Assuming feasibility of Model 3-1 for a given $\bar{\beta}$,*

1) $\beta_2^*(P_1^*(\bar{\beta})) \geq \bar{\beta}$ *and* $(P_1^*(\bar{\beta}), \beta_2^*(P_1^*(\bar{\beta})))$ *is Pareto optimal*

2) *For* $P < P_1^*(\bar{\beta})$; $\beta_2^*(P) \geq \beta_2^*(P_1^*(\bar{\beta}))$ *and* $\beta_2^*(P) > \beta_2^*(P_1^*(\bar{\beta})) \implies P_2 < P_1^*(\bar{\beta})$

3) *For* $P > P_1^*(\bar{\beta})$; $\beta_2^*(P) < \beta_2^*(P_1^*(\bar{\beta}))$, $P_2 > P_1^*(\bar{\beta})$ *for every feasible solutions of Model 3-2*

Proof.

1) The optimal solution of Model 3-1 for a given $\bar{\beta}$ is also feasible for Model 3-2 with $P = P_1^*(\bar{\beta})$.

$\therefore \beta_2^*(P_1^*(\bar{\beta})) \geq \beta_1 \geq \bar{\beta}$

Assume the existence of a solution for Model 3-2 with $P = P_1^*(\bar{\beta})$ resulting $(P_2, \beta_2^*(P_1^*(\bar{\beta})))$ where $P_2 > P_1^*(\bar{\beta})$. Then, this solution is also feasible for Model 3-1 with given $\bar{\beta}$, and thus makes a contradiction to the optimality of $P_1^*(\bar{\beta})$.

$\therefore P_2 \leq P_1^*(\bar{\beta})$

Because $\beta_2^*(P_1^*(\bar{\beta}))$ is optimal for Model 3-2 with $P = P_1^*(\bar{\beta})$, there is no solution resulting (P_2, β_2) where $P_2 \geq P_1^*(\bar{\beta})$, $\beta_2 > \beta_2^*(P_1^*(\bar{\beta}))$ or $P_2 > P_1^*(\bar{\beta})$, $\beta_2 = \beta_2^*(P_1^*(\bar{\beta}))$.

$\therefore (P_1^*(\bar{\beta}), \beta_2^*(P_1^*(\bar{\beta}))$ is Pareto optimal

2) The solution resulting $(P_1^*(\bar{\beta}), \beta_2^*(P_1^*(\bar{\beta})))$ from 1) is also feasible for Model 3-2 with $P < P_1^*(\bar{\beta})$.

$\therefore \beta_2^*(P) \geq \beta_2^*(P_1^*(\bar{\beta}))$

Assume the existence of a solution resulting (P_2, β_2) where $P_2 \geq P_1^*(\bar{\beta})$ and $\beta_2 > \beta_2^*(P_1^*(\bar{\beta}))$. Then, this solution is also feasible for Model 3-2 with $P = P_1^*(\bar{\beta}))$, and thus makes a contradiction to the optimality of $\beta_2^*(P_1^*(\bar{\beta}))$.

$\therefore \beta_2^*(P) > \beta_2^*(P_1^*(\bar{\beta})) \implies P_2 < P_1^*(\bar{\beta})$

3) For an arbitrary feasible solution of Model 3-2 with $P > P_1^*(\bar{\beta})$, $P_2 \geq P > P_1^*(\bar{\beta})$. If $\beta_2^*(P) \geq \beta_2^*(P_1^*(\bar{\beta}))$, then $\beta_2^*(P) \geq \bar{\beta}$ by 1). This solution is also feasible for Model 3-1 with given $\bar{\beta}$, and thus makes a contradiction to the optimality of $P_1^*(\bar{\beta})$.

$\therefore \beta_2^*(P) < \beta_2^*(P_1^*(\bar{\beta}))$

□

Proposition 4.4. *Assuming feasibility of Model 3-2 for a given $\bar{P}$,*

1) $P_1^*(\beta_2^*(\bar{P})) \geq \bar{P}$ *and* $(P_1^*(\beta_2^*(\bar{P})), \beta_2^*(\bar{P}))$ *is Pareto optimal*

2) *For* $\beta < \beta_2^*(\bar{P})$; $P_1^*(\beta) \geq P_1^*(\beta_2^*(\bar{P}))$ *and* $P_1^*(\beta) > P_1^*(\beta_2^*(\bar{P})) \implies \beta_1 < \beta_2^*(\bar{P})$

3) *For* $\beta > \beta_2^*(\bar{P})$; $P_1^*(\beta) < P_1^*(\beta_2^*(\bar{P}))$, $\beta_1 > \beta_2^*(\bar{P})$ *for every feasible solutions of Model 3-1*

Proof.

Omitted. Symmetric to the proof of Proposition 4.3.

□

Corollary 4.5. $P_1^*(\beta_2^*(P_1^*(\beta))) = P_1^*(\beta),\ \beta_2^*(P_1^*(\beta_2^*(P))) = \beta_2^*(P)$

The first question can be answered by Corollary 4.5 and Propositions 4.3 and 4.4. Models 3-1 and 3-2 will retrieve the same results when $\bar{\beta} = \beta_2^*(P_1^*(\beta))$ for Model 3-1 and $\bar{P} = P_1^*(\beta)$ for Model 3-2 with a given β or $\bar{\beta} = \beta_2^*(P)$ for Model 3-1, and $\bar{P} = P_1^*(\beta_2^*(P))$ for Model 3-2 with a given P.

As mentioned previously, Models 3-1 and 3-2 may have several optimal solutions. Note that $(P_1^*(\bar{\beta}),\ \beta_2^*(P_1^*(\bar{\beta})))$ and $(P_1^*(\beta_2^*(\bar{P})),\ \beta_2^*(\bar{P}))$ are Pareto optimal each, which indicates that these results are the best among those multiple optimal solutions. Consequently, using the two models sequentially is the key to ensuring the best outcome for the secondary firm in a given circumstance. This demonstrates the complementarity of the two models, despite the fact that they are presented to describe different situations.

Proposition 4.6. *Assuming feasibility of Model 2,*

1) $P^* \geq P_1^*(\beta),\ \forall \beta$

2) $\beta \leq \beta^* \iff P_1^*(\beta) = P^*$

3) *For* $\beta = \beta^*;\ (P_1^*(\beta), \beta_1) = (P^*, \beta^*)$

4) *For* $\beta < \beta^*;\ \beta_2^*(P_1^*(\beta)) = \beta^*$

5) *For* $\beta > \beta^*;\ P_1^*(\beta) < P^*,\ \beta_1 > \beta^*$ *for every feasible solutions of Model 3-1*

Proof.

1) All feasible solutions of Model 3-1 regardless of the value of β are also feasible for the first stage of Model 2 and the objective functions are the same, which implies that the first stage of Model 2 is a relaxation of Model 3-1.

$\therefore P^* \geq P_1^*(\beta),\ \forall \beta$

2) ($\Longrightarrow$) If $\beta \leq \beta^*$, the optimal solution of Model 2 is also feasible for Model 3-1, which implies $P_1^*(\beta) \geq P^*$. Because $P^* \geq P_1^*(\beta),\ \forall \beta$ by 1), $\beta \leq \beta^* \implies P_1^*(\beta) = P^*$.

($\Longleftarrow$) Assume the existence of a solution for Model 3-1 with an arbitrary β resulting $(P_1^*(\beta), \beta_1)$ where $P_1^*(\beta) = P^*$ and $\beta_1 > \beta^*$. This solution is also feasible for Model 2, and thus makes a contradiction to the optimality of β^*.

$\therefore P_1^*(\beta) = P^* \implies \beta \leq \beta_1 \leq \beta^*$

$\therefore \beta \leq \beta^* \iff P_1^*(\beta) = P^*$

3) Because $\beta = \beta^*$ satisfies $\beta \leq \beta^*$, $P_1^*(\beta) = P^*$ by 2). Also, $P_1^*(\beta) = P^* \implies \beta_1 \leq \beta^*$ as shown in the proof of 2). On the other hand, $\beta_1 \geq \beta = \beta^*$.

$\therefore (P_1^*(\beta), \beta_1) = (P^*, \beta^*)$

4) The optimal result (P^*, β^*) of Model 2 is also an optimal result for Model 3-1 with $\beta < \beta^*$, but there could also exist additional optimal results (P^*, β_1) where $\beta \leq \beta_1 < \beta^*$. The optimal solution of Model 2 is also feasible for Model 3-2 with $P = P^*$ which implies $\beta_2^*(P^*) \geq \beta^*$.

Assume the existence of a solution for Model 3-2 with $P = P^*$ resulting $(P_2, \beta_2^*(P^*))$ where $\beta_2^*(P^*) > \beta^*$. Note that $P_2 \geq P^*$. If $P_2 > P^*$, a contradiction to the optimality of P^* occurs because all feasible solutions of Model 3-2 regardless of the value of P are also feasible for the first stage of Model 2. Therefore, $P_2 = P^*$. Then, the proposed solution is also feasible for Model 2, and thus makes a contradiction to the

optimality of β^*.

$\therefore \beta_2^*(P^*) \leq \beta^*$

Because $\beta < \beta^*$ satisfies $\beta \leq \beta^*$, $P_1^*(\beta) = P^*$ and $\beta_2^*(P_1^*(\beta)) = \beta_2^*(P^*)$ by 2).

$\therefore \beta_2^*(P_1^*(\beta)) = \beta_2^*(P^*) = \beta^*$

5) For an arbitrary feasible solution of Model 3-1 with $\beta > \beta^*$, $\beta_1 \geq \beta > \beta^*$.

Note that $P^* \geq P_1^*(\beta)$ by 1). Assume the existence of a solution for Model 3-1 with $\beta > \beta^*$ resulting $(P_1^*(\beta), \beta_1)$ where $P_1^*(\beta) = P^*$. This solution is also feasible for Model 2, and thus makes a contradiction to the optimality of β^*.

$\therefore P_1^*(\beta) < P^*$

□

The second question can be answered "no" by Proposition 4.6. It is easily shown that Model 2 is a relaxation of Model 3-1. Therefore, the two models are not precisely equivalent and may not retrieve the same results. In detail, Model 3-1 will always result in the same outcome as the outcome for Model 2 if the given β is equal to β^*. If the given β is smaller than β^*, the private's profit in Model 3-1 is the same as that of Model 2, but the total coverage is not guaranteed to be the same because of the existence of multiple optimal solutions. For this case, additionally applying Model 3-2 after Model 3-1 will ensure that the results of Model 2 are achieved. The two models cannot have the same results if β is given as being bigger than β^*.

By combining the three propositions, we can conclude that a trade-off between the total coverage and the private's profit exists, and we can answer the third question. In particular, Proposition 4.6 shows that the maximum profit among any circumstances is achieved by Model 2 and gives the bound for the trade-off curve. In

detail, the result of Model 2 (P^*, β^*) will be placed at one end of the curve having the highest profit of the private and the lowest total coverage. The other points of the curve can be found by increasing the input β of Model 3-1 starting from β^* until 100 percent, and applying Model 3-2 consecutively. Decreasing the input P of Model 3-2 starting from P^* could be another way to achieve this end. For this case, P decreases until the resulting total coverage of the subsequent model, Model 3-1, reaches 100 percent. Either approach will give the same results in the same order, and we implement the first procedure for the experiments. The complementarity of the models is enhanced by accompanying Model 2, considering that it sets the starting point when drawing the trade-off curve.

Note that the private's profit also contains a part of the coverage, given that the private's revenue is expressed as a linear function of its own coverage. The interesting part of the third question is that the total coverage and the private's profit present a trade-off despite the common factor. In fact, it is quite apparent mathematically, because Propositions 4.3 and 4.4 guarantee the Pareto optimality. However, it is slightly more complex logically. Recall that locating more facilities never drops the total coverage. Model 3-1 does not particularly inhibit the overlapped demands heading to the public, whereas immediately following Model 3-2 assures the private's profit to be achieved. Considering a solution having the Pareto optimality, there are only two cases that can increase the total coverage: (i) the public locating additional facilities, regardless of however the private changes its decision, and (ii) the private locating more facilities while the public does not add more.

The first case denotes that there was enough left in the budget to place more facilities. However, the public did not utilize the remaining budget, although Model

3-2 maximizes the total coverage, indicating that the private's profit would have suffered. On the other hand, the private covers the most profitable nodes after Model 3-1, while assuring a certain level of the total coverage. If any valuable nodes remained, the private should have already covered them. Consequently, all remaining nodes are genuinely unprofitable, signifying that the private has to take a loss to locate more facilities. Therefore, either case necessitates cutting off the private's profit in order to increase the total coverage.

Proposition 4.7. *Assuming feasibility of Model 1,*

$$1)\ P^* \geq P_1^*(\tilde{\beta}) \geq \tilde{P}$$

$$2)\ \beta_2^*(\tilde{P}) \geq \tilde{\beta},\ \beta_2^*(\tilde{P}) \geq \beta^*$$

Proof.

1) The optimal solution of Model 1 is also feasible for Model 3-1 with $\beta = \tilde{\beta}$, which implies $P_1^*(\tilde{\beta}) \geq \tilde{P}$.

Additionally, $P^* \geq P_1^*(\tilde{\beta})$ because $P^* \geq P_1^*(\beta),\ \forall\beta$ by Proposition 3.

$\therefore P^* \geq P_1^*(\tilde{\beta}) \geq \tilde{P}$

2) The optimal solution of Model 1 is also feasible for Model 3-2 with $P = \tilde{P}$, which implies $\beta_2^*(\tilde{P}) \geq \tilde{\beta}$.

Additionally, the optimal solution of Model 2 is also feasible for Model 3-2 with $P = \tilde{P}$ because $P^* \geq \tilde{P}$ by 1), which implies $\beta_2^*(\tilde{P}) \geq \beta^*$.

$\therefore \beta_2^*(\tilde{P}) \geq \tilde{\beta},\ \beta_2^*(\tilde{P}) \geq \beta^*$

□

The dominance of Models 3-1 and 3-2 over Model 1 can be easily established by Proposition 4.7. There always exists a case in which the two models weakly dominate Model 1. One of the objectives is guaranteed to be no worse than Model 1 by Constraints (3.30) and (3.39), while the other is ensured by Proposition 4.7 for both models. Furthermore, Model 1 could be strictly dominated in practice, as shown in the next chapter. However, the dominance of Model 2 is uncertain. The private's profit is always at least better than Model 1, as shown in Proposition 4.7, but the total coverage is not assured. The total coverage can either be higher or lower, which is also demonstrated in the next chapter.

We can conclude that the first three propositions indicate the main contribution of this study, which shows that a trade-off between the total coverage and the private's profit exists. Meanwhile, the last proposition implies that cooperation always guarantees a better solution than competition. These findings are illustrated and verified via computational experiments in the next chapter.

Chapter 5

Computational experiments

5.1 Experiments for the small-size instance

The mathematical models were solved with FICO Xpress version 8.12. To validate the models presented in Chapter 3, a simple experiment has been conducted. The data were taken from Snyder and Shen [60], which was named "10-node facility instance''. The set of customer zones and potential facility locations are equal (i.e., $I = J$). The coordinate values of the nodes have been scaled up 10 times, and the distances between nodes are calculated as the Euclidean distance, assuming a complete graph. The fixed costs were substituted to amortized total costs. Table 5.1 summarizes the data.

Table 5.1: Data of the Small-Size Instance

Index	**x-coordinate**	**y-coordinate**	**Annual demand**	**Annual amortized total cost**
1	2	1	60	200
2	9	7	27	200
3	2	4	29	200
4	9	2	26	200
5	5	9	33	200
6	6	3	15	200
7	8	4	17	200
8	5	3	97	200
9	3	6	97	200
10	2	6	19	200

Other parameters have been generated on the basis of work by Chu et al. [11], Franke and Krems [23], and Huang and Kockelman [35]. Chu et al. [11] noted that EV users in South Korea charged their vehicles 14.07 times per month, while Franke and Krems [23] figured out that users in Berlin, Germany, charged their EVs 3.1 times per week. Consequently, we assumed that people charge their EVs around 161∼169 times per year, on average. The financial parameters refer to Huang and Kockelman [35] and are organized in Table 5.2.

Table 5.2: Assumptions for Financial Parameters

	Assumption
Average charging duration	30minutes/charge
Charging price per minute	\$ 0.125/minute
Average charging price	**\$ 3.75/charge**
Amortization period	5 years
Land acquisition cost	\$ 300,000 ∼ \$ 500,000
Cord installation cost	\$ 20,000
Variable cost including maintenance	\$ 10,000/year
Annual amortized total cost	**\$ 74,000/year ∼ \$ 114,000/year**

Aggregating the charging frequency and the charging price, the revenue gained by serving one demand per year (α) is between \$603.75 and \$633.75. Because the amortized total cost (f) is in the range of \$74,000 to \$114,000, f/α varies from 116 to 189. Therefore, we assumed the value of f/α to be fixed as 150. Because the costs are all equal to 200, α will take the value of 4/3. In addition, the public's budget, B, is assumed to be 10 percent of the sum of the costs, while the coverage radius, r, is set so that 2.8 nodes, on average, are within r, resulting in a B of 200 and an r of 4, respectively. The numerical results were summarized in Table 4.1.

Figure 5.1 visualizes the results of the first stage and the third stage of Model 1,

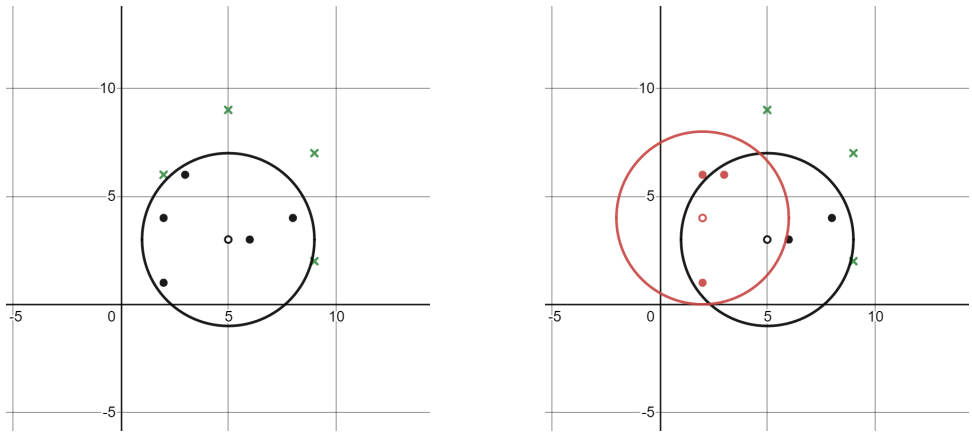

Figure 5.1: Results of Model 1

respectively. Black and red represent the public and the private, respectively. The big circles show the coverage radius, and the green crosses indicate the nodes uncovered. The small circles denote the locations where the facilities are placed, and the dots signify the covered nodes.

The public can locate exactly one station, because all costs are equal to 200, and the budget is also 200. To maximize its own coverage, the public set its placement at (5,3), which offers the most coverage. After the public made its decision, the private located a facility at (2,4). Because Model 1 describes a competitive situation, we might have found that the private felt free to intrude into the public's coverage. The result also indicates that other points are not profitable enough for the private to place additional facilities, considering that it placed only one.

Figure 5.2 shows the results of the two stages of Model 2. The private also chose the point that the public chose in Model 1. However, the public could not make the same decision as the private made in Model 1. Points (5,9) and (9,7) were the only feasible nodes the public could have chosen in order to preserve the private's

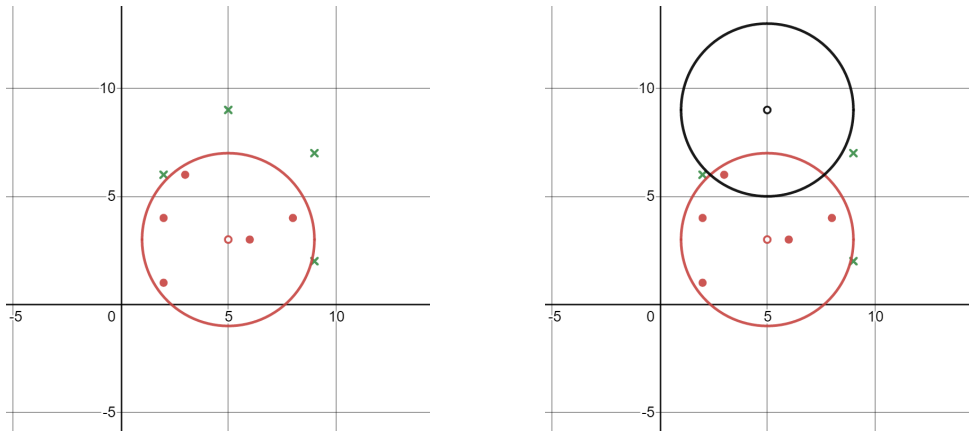

Figure 5.2: Results of Model 2

coverage, thereby maintaining the cooperation. The public placed its facility at (5,9), which garners more demand. The overlapping point (3,6) is located at the same distance from the two facilities. Still, the private fully covers that point because the capacities are infinite, and the public will not care, given that the total coverage is the same, no matter who covers it.

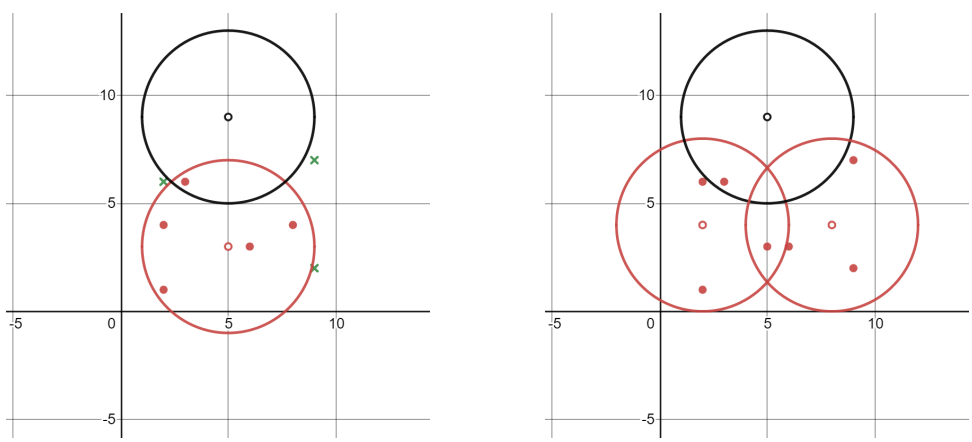

Figure 5.3: Results of Model 3

Figure 5.3 demonstrates the results of Model 3-1 and Model 3-2. The results

of Model 1 were used as the assurance levels for Model 3-1 and Model 3-2. These were 79.5 percent for Model 3-1 and 73.33 for Model 3-2. As shown in Table 4.1, the results of Model 3-1 are the same as those for Model 2, and it is not surprising that the solutions are also the same. Model 3-2 shows that even 100 percent coverage could be achieved while still guaranteeing that the profit is higher than it is in Model 1.

5.2 Experiments for the large-size instance

A larger-size experiment also has been conducted to illustrate the theoretical results established in Chapter 4. The large-size instance was generated according to the instance on the Euclidean plane of simple location problems from the Benchmark Library (`http://www.math.nsc.ru/AP/benchmarks/english.html`). Because our contribution is neither algorithmic nor based on computations, we have not attempted to solve large or various instances. Instead, a single instance from the Benchmark Library, Code 111, was implemented to verify the theoretical results and the answers to the research questions. The given transportation costs between nodes in the instance were substituted with distances between nodes.

The demands and the costs were generated following the small-size instance. The mean and the standard deviation of the demands in the small-size instance were 42 and 31.6, respectively. Excluding the biggest and the smallest demand for each, the mean and the standard deviation become 38.5 and 27.09. The demands (h_j) were randomly generated from a normal distribution with the parameters of 38.5 and 27.09.

$$f_j = \left(\frac{H_j + 2}{\text{Amortization period}(= 5)} + 1 \right) \times 100 \text{ (unit: \$100)} \tag{5.1}$$

The costs were calculated as Equation (5.1), where H_j corresponds to the land acquisition cost in Table 5.2. Considering a node with a bigger demand as being more profitable, we assumed the cost to be affected by the demand. To implement such influence, every H_j is randomly generated from a normal distribution with mean h_j

and standard deviation $(h_j/5)^2$ (i.e., $N(h_j, (h_j/5)^2)$), respectively.

$$\mathbb{E}\left[f_j\right] = \frac{\mathbb{E}\left[H_j\right] + 7}{5} \times 100 = \frac{h_j + 7}{5} \times 100 \tag{5.2}$$

$$\mathbb{E}\left[\overline{\mathbb{E}\left[f_j\right]}\right] = \frac{\mathbb{E}\left[\overline{h_j}\right] + 7}{5} \times 100 = 910 \tag{5.3}$$

Equation (5.2) shows the expectations of the costs, which are also random variables. Note that the expectation of the sample mean of the costs becomes 910, as calculated as Equation (5.3), which moderately fits within 740 and 1,140, the range investigated previously (Table 5.2). As a result, costs with an average of 1,043 were generated, and this data was used throughout this chapter.

Other parameters nearly follow the assumptions of the small-size instance. The value of $\bar{f}/\alpha$ instead of f/α is approximated to 150, resulting in α having the value of 7. The public's budget, B, is again assumed to be 10 percent of the sum of the costs. The coverage radius, r, is set so that 2.82 nodes are within r, on average, because there was no r that carried out exactly 2.8 nodes, on average. Consequently, the standards were set to be B of 10,430 and r of 663. Based on these settings, five values of r and B each were considered, with B and r being fixed as the standards, respectively. In detail, the value of r was changed from 500 to 600, 663, 750, and 900, with B fixed as 10,430. Then the value of B was changed from 2,086 to 5,215, 10,430, 20,860, and 52,150, which corresponds to changing n of 1,043$\times n$ from 2 to 5, 10, 20, and 50, with r fixed as 663. Models 1 and 2 have been applied in each case, followed by an iteration of Models 3-1 and 3-2, with the input β increasing from β^* to 100 percent while only having integer percentages.

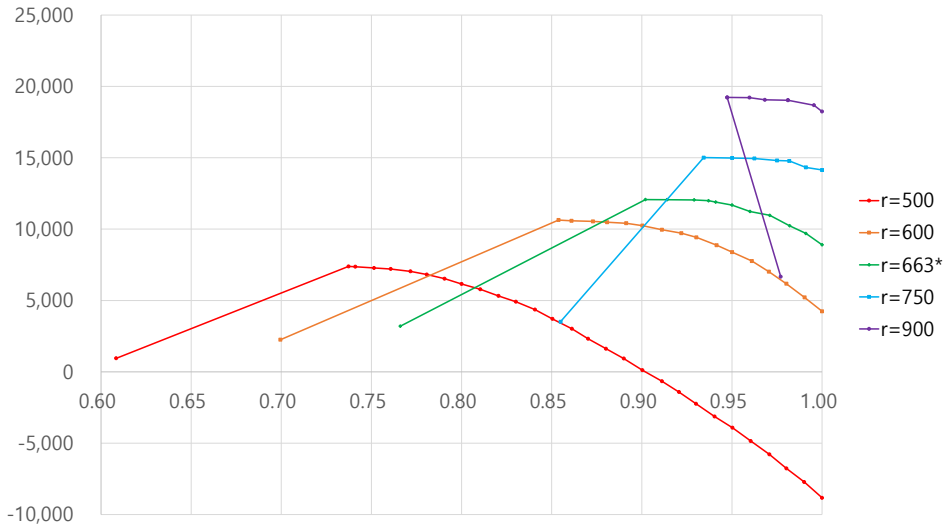

Figure 5.4: Aggregated results of each r

Figure 5.4 shows the total coverage and the private's profit of the models for each r. The isolated points for each case correspond to the results of Model 1. Except for the points of Model 1, it is clear that Models 2, 3-1, and 3-2 demonstrate the trade-off between the total coverage and the private's profit, regardless of the value of r, and form a trade-off curve. Also, it is noticeable that only until r=750 are the isolated points located at the bottom left of the trade-off curve. This indicates that for r=900, the total coverage of Model 1 is higher than that of Model 2, which leads to the fact that Model 2 cannot dominate Model 1. The public locates its facilities within a given budget. For Model 1, when r gets bigger, the public could cover a bigger area by itself in the first stage. However, the facilities would be located sparsely to offer efficient coverage. This leads to more favorable circumstances for the private to intrude, resulting in higher coverage. On the other hand, the private will now locate its facilities sparsely in the first stage in Model 2. When r gets bigger,

only a few nodes will remain feasible in the next stage for the public, because the private's coverage should be preserved. Consequently, the total coverage could not rise sufficiently in Model 2, while it rises steeply in Model 1, and thus, a reversal takes place. Note that the graphs generally move to the upper right. Figure 5.5 demonstrates such movement by emphasizing the shifts of the points for Models 1 and 2, as well as the points representing total coverage of 100 percent, caused by the change of r.

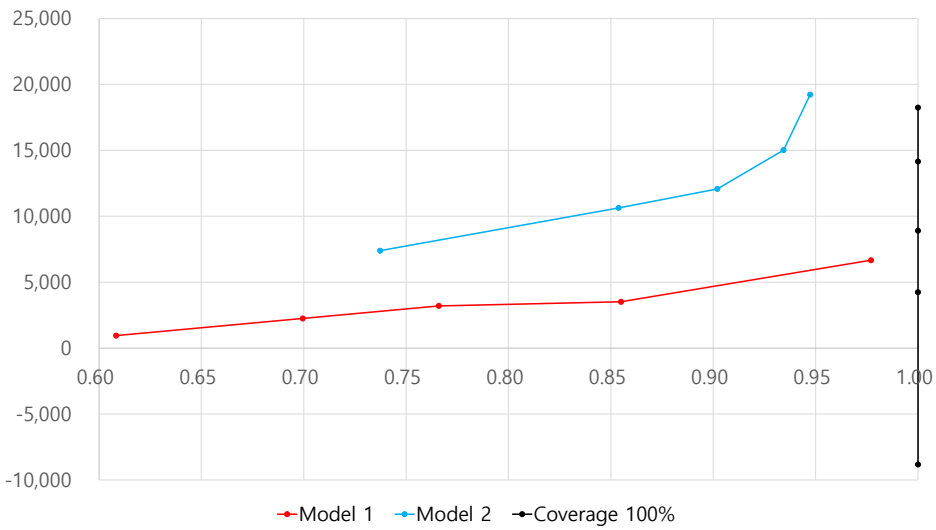

Figure 5.5: Results of changing the value of r

Model 1 draws a gentle upward curve. Considering that the private faces an easier market in which to intrude and that the total coverage increases as r gets bigger, this still does not mean that the private will place many facilities. Arranging facilities sparsely may in fact increase the number of lost opportunities when competing on scales of distance with the public. In contrast, if the facilities are placed densely, the overlapping areas will increase, leading to inefficient and unprofitable coverage.

As a result, the increase of the private's profit is insignificant compared to the total coverage, which indicates that a vulnerable market (i.e., a market that is easy to intrude upon), does not always guarantee high profits. Such a market will work positively if the private bears a cutthroat competition to secure more market share, but this is not the case, and thus, it would be more prudent to expand cautiously.

Model 2 also draws an upward curve. As r gets bigger, the private could cover the nodes more efficiently, resulting in higher profits and coverage. Consequently, the total coverage grows together but faces a wall when r gets excessive.

The private's profit also increases for the points having 100 percent of the total coverage. To cover all the demands when r is restricted, the private must take a loss, because it is responsible for all the nodes that the public could not cover due to the budget constraint. As r increases, the public could cover more nodes by itself. Considering that more of the unprofitable nodes are taken away by the public and that the private covers the nodes more efficiently, the private's profit grows as the burden transferred to it is reduced.

Figure 5.6 presents the results that occur when the value of B gets changed. Note that the isolated points correspond to the results of Model 1 and that the trade-off curves are well illustrated, regardless of the value of B, as is the case when r is changed. It is again noticeable that the isolated point appears at the bottom right of the trade-off curve only for B=52,150. Model 2 also failed to dominate Model 1 in the case of increasing the budget. The public only focuses on expanding its coverage within a given budget, irrespective of its profit. Therefore, the public would simply build more facilities as the budget increases, and it could achieve high-level coverage even by itself in the first stage of Model 1. This implies that the public

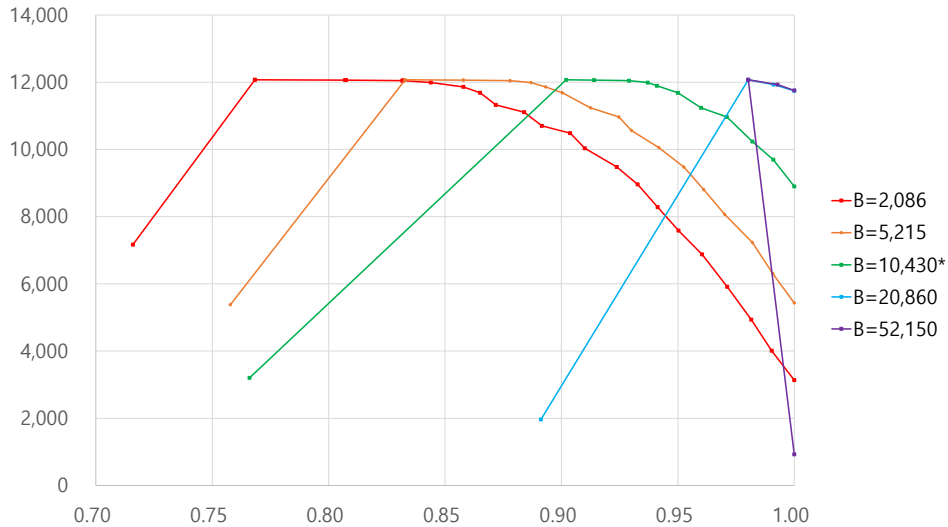

Figure 5.6: Aggregated results of each B

fully utilizes the budget in Model 1, which is not happening in Model 2. In Model 2, the private moves first, and thus, always makes the same decision, because the only changing part is the budget, which belongs to the public. For this reason, all points corresponding to Model 2, the left side starting points of the trade-off curves, display the same level of the private's profit. However, the public must preserve the private's coverage. Eventually, the public should leave some of the budgets idle when they are given immoderately, while the results of the first stage remain, regardless of the budget. Consequently, a sufficient budget is underutilized in Model 2, and the total coverage could not rise enough compared with Model 1, resulting in an overtaking as was the case with r. Note that the graphs generally move to the right. Figure 5.7 shows the results of Models 1 and 2, as well as the cases of the total coverage reaching 100 percent, similar to Figure 5.5.

Model 1 draws a downward curve as opposed to the case of r. As the budget

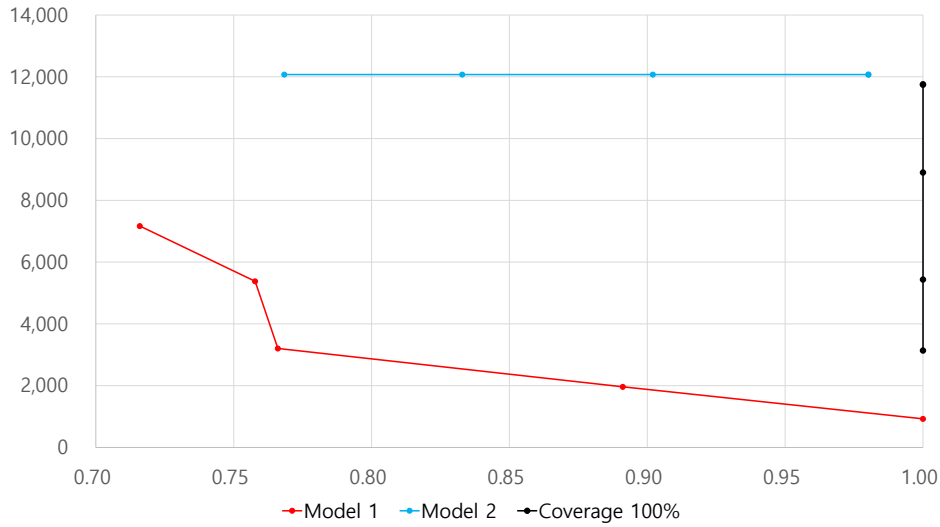

Figure 5.7: Results of changing the value of B

increases, the public simply builds more facilities. Accordingly, the achievable nodes for the private competing on the platform of distance against the public will decrease, and thus, the profit will reduce, too.

Model 2 presents a horizontal line, indicating constant profit and increasing total coverage as the budget grows. Note that only four points are illustrated on the line. The last two cases retrieve the same total coverage, magnifying the underutilization of a sufficient budget. It is also noticeable that the constant profit is less than the profit gained by a bigger r, because the facilities' covering capabilities are unchanged.

The private's profit increased again for the points with 100 percent of the total coverage, as in the case of r. To fully cover the demands for a fixed r and an insufficient budget, the private must give up its profit again. As the budget grows, the public could handle more of the nodes by itself, just as in the case of r. The difference is that the covering efficiency of the private is consistent. Consequently, the

private retains gainful nodes and gets emancipated from covering the unprofitable ones as the budget increases. The profit eventually rises in general as the budget grows but ceases when only the most profitable nodes are left, specifically when the budget is excessive. It is evident that only four points are presented again for this reason, indicating that the last two points overlap. Additionally, it is again conspicuous that the profit gained from the most significant budget is lower than that from the biggest r, for the same reason as in Model 2.

Chapter 6

Conclusions

To support the replacement of ICEVs with EVs, publicly accessible charging stations are necessary. For this reason, the public sector, as well as private firms, are actively investigating the expansion of charging stations. In this thesis, we studied a CSLP in a mixed market on a network space. To the best of our knowledge, this study is the first to graft a mixed market to an FLP on a network, or to consider multiple participants with different objectives in locating charging stations. We presented diverse situations and modeled the corresponding mathematical formulations by implementing the optimization approach. We mathematically analyzed the relationships between the models and showed that complementarity and dominance exist. We conducted computational experiments in order to validate the presented models and verify the analyses. Consequently, we demonstrated the trade-off between the total coverage and the private sector's profit, despite a common factor being shared.

To disseminate EVs harmoniously, not only technical developments but also policies should be carefully considered, because a public charging infrastructure is especially essential for cities with a high percentage of residents living in multi-unit housing, without garages. Our research supports the decision makers, regardless of

their sectors. In detail, we provided policy implications in this thesis for the public sector (e.g., the policymakers or the budget allocators), and we provided managerial insights for private investors. We suggest that cooperation among the public and private sectors is beneficial for both parties, compared to a competitive situation, and we supported this theory through analyses and verification with the computational experiments. Moreover, we believe that the shown trade-off could shed light on how best to negotiate conflicting interests between stakeholders.

For researchers, we hope that our research will serve as a base for future studies of the FLP in a mixed market on a network, or in the CSLP with multiple decision makers. The objectives of each sector vary widely, and there might be conflicting viewpoints about the objectives we proposed in this thesis. In addition, some researchers may not accept the assumptions raised by our research (for example, the deterministic demands or the identical uncapacitated facilities or the single period of focus). Adopting spatial interaction models or market share attraction, applying a stochastic approach for probabilistic demands, or implementing a game theoretic approach might be considered in future research. Further consideration for the extensions and variations of our work can yield meaningful conclusions and enrich the growing body of literature on the FLP.

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국문초록

전세계적으로 환경에 대한 관심이 증가함에 따라 전기자동차에 대한 관심과 수요 또한 지속적으로 증가하고 있다. 하지만 대한민국과 같이 개인 충전시설을 구비하기 어려운 상황에서는 이러한 동향을 따라가기 위해 충분한 수의 공용 충전소를 확보하는 것이 필수이다. 이에 본 연구는 네트워크 상에서 혼합 시장의 전기자동차 충전소 입지선정 문제를 다루었다. 본 연구에서는 경쟁과 협력을 바탕으로 다양한 상황을 고려하였으며, 각 상황에 대응하는 최적화 수리 모형을 제시하였다. 각 모형 간의 관계를 수학적으로 분석하여 이들간의 상호보완성과 우열을 보였으며, 제시한 모형들과 분석 결과들을 검증하기 위한 실험을 진행하였다. 이해관계자들의 목표 사이에 트레이드-오프(trade-off)가 존재함을 보임으로써 정책적 시사점과 경영적 통찰력을 모두 제공하였다.

주요어: 설비 입지선정, 충전소 입지선정, 혼합 시장, 다중 의사결정자, 경쟁, 협력

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