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# ROBUST COLLABORATIVE DELIVERY SERVICE SYSTEM FOR UNCERTAIN DEMAND

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Abstract. *The e-commerce market is growing rapidly with the impact of COVID-19, and the delivery service market is also growing proportionally. With the rapid increase in demand for delivery services, new delivery service companies are also appearing, and they are investing heavily to expand their market share in delivery services. Nevertheless, due to various factors such as inflation and difficulties in managing the logistics site, the rise of delivery service cost remains a problem to be overcome. Recently, studies on the introduction of a collaborative delivery service system as an alternative to solve these problems are being actively conducted. In this study, a design methodology using Robust Optimization (RO) for designing a service network under collaborative delivery considering the uncertainty of demand for delivery services is presented. We proposed a mathematical model for RO for collaborative delivery service. An example problem is carried out to explain RO's approach and verify its feasibility using simulation analysis.*

**Keywords:** E-commerce, Delivery service, Collaboration, Robust optimization, Simulation analysis

1. **Introduction.** The COVID-19 issue is accelerating the growth of e-commerce toward new companies, customers, and product categories. This growth will likely result in a long-term change in the types of e-commerce transactions from luxury goods and services to basic necessities. According to the eMarketer research data, online sales are expected to continue rising and take a larger piece of the retail pie (Figure 1). By 2025, it is estimated that world retail e-commerce sales will exceed $7.3 trillion and the overall e-commerce share of retail sales will hit 23.6 percent.

Large delivery companies such as Amazon in the US, Alibaba in China, and Coupang in South Korea place a greater emphasis on efficiency, cost, and accuracy. Small and medium-sized delivery companies, however, suffer significant survival difficulties in the market for speedy delivery due to severe rivalry among them. It takes new tactics and methods to stay competitive in the delivery industry in the COVID-19 environment. To be more precise, small and medium-sized delivery companies may develop a range of cooperative tactics in order to survive in the fierce market rivalry. To reduce service costs,

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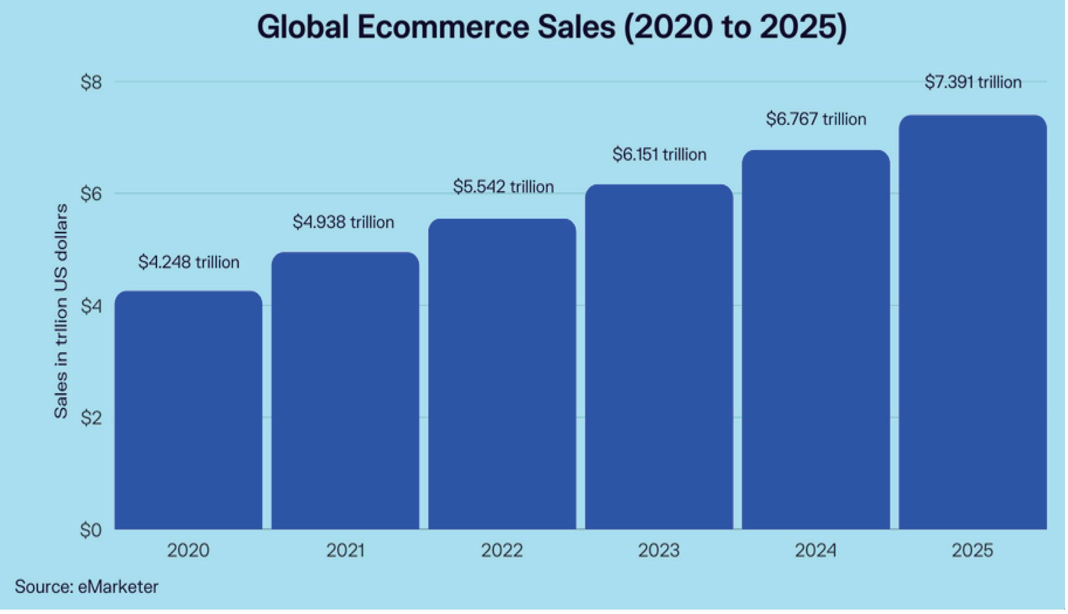

Figure 1. Retail e-commerce sales worldwide from 2020 to 2025 (in trillion U.S. dollars). Source: eMarket, 2022 [1].

enhance service quality, and satisfy clients, they can create partnerships that benefit both parties along the value chain. This can be achieved by aligning company strategies, consolidating available resources and service centers, streamlining material flows, and driving operational excellence. A reasonable profit split from such a collaboration can also enhance consumer relationships, boost partner confidence, and increase customer loyalty. Moreover, one of the major challenges in delivery is uncertainty of demand, mostly approximated through forecasts, that is highly crucial to make accurate decisions. Accordingly, deterministic model with approximation may lead to costly miscalculated decisions. Therefore, uncertainty should be taken into account in decision making process.

This study proposes collaborative delivery network design model with demand uncertainty for delivery, from the perspective of robust optimization and provides new perspectives to respond to survive in competitive market environments. The performance of the collaborative delivery network design model under uncertainty was depicted based on comparison between deterministic and robust model. The key idea behind this model is to operate only one service center shared by various delivery service companies in each merging region. A mathematical model is formulated as a multi-objective programming problem for collaboration model to maximize the incremental profit of each participating company.

## 2. Literature Review.

Comparing the post-crisis period to the pandemic period, e-commerce development had a significant acceleration [2]. Due to the COVID-19, consumers are forced to use the Internet and develop the daily habit of buying goods and services online [3]. Global logistical networks have been significantly impacted by the pandemic issue [4]. The “bring-service-near-your-home” idea was explained by Choi [5], who also covered the financial support measures needed during the pandemic.

To improve delivery services, numerous research has been conducted. Most of these studies concentrate on enhancing the efficiency and competitiveness of individual delivery companies. The primary objectives are to promote customer satisfaction and innovation while maximizing profit and minimizing expenses using terminals, routes, delivery, and pickup procedures as efficiently as possible. As a crucial link between businesses and consumers, the role of express delivery services has considerably risen [6]. Ferdinand et al. proposed a network design model for strategic alliances in express courier services.

Also, they offer a mathematical model for multi-objective decision making and a solution strategy based on genetic algorithms [7]. Coevolutionary algorithm-based approach to the collaborative network design in express delivery services using coalitional game theory was studied by Ferdinand and Ko [8]. Makhmudov et al. introduced network design for time-phased collaboration in delivery service (incorporated collaboration in pre-agreed timeframes: morning and daytime) [9]. Furthermore, fair profit distribution in delivery service collaboration considering service quality (consider 3 types of products: regular, oversized/overweighted and cold, and introduce defective rate in delivery service) was studied by Makhmudov et al. [10].

Deterministic optimization models often assume that all variables, including cost and demand, are precisely known and that the data are error-free [11]. However, deterministic solutions are not enough and are even impossible for real-world issues due to the growing uncertainty of the production system and delivery [12]. Robust Optimization (RO) is a good optimization method to respond to uncertainty. Within a given uncertainty set, the goal of RO is to get a choice that is practical and effective even in the worst-case scenario [13]. RO has a variety of mathematical formulation depending on how uncertainty set is defined such as box set [14], ellipsoidal set [15] and cardinality set [16]. Wei et al. [17] and Alem et al. [18] applied robust optimization model using cardinality uncertainty set about perturbation of demand and production cost. They demonstrated through simulation that their robust solutions are very effective in uncertain demand or production cost.

The contribution of this study is summarized as compared to the previous studies: from the standpoint of robust optimization, this study suggests a collaborative delivery network design model with demand uncertainty for delivery and offers new perspectives to adapt to survive in competitive market conditions. Based on a comparison of deterministic and robust models, the performance of the collaborative delivery network design model under uncertainty was presented.

## 3. Problem Statement and Preliminaries.

We establish a collaborative delivery network design model in this chapter. The model is developed from the previous study in Chung et al. [19]. The problem considered is to decide which company performs a delivery service in each of multiple candidate regions in order to maximize the net profit of each participating company through collaboration.

We define $I = \{1, 2, \ldots, m\}$ as a set of delivery service companies and $J = \{1, 2, \ldots, n\}$ as set of merging regions. All parameters and decision variables are summarized in Tables 1 and 2.

Table 1. Decision variables for collaborative delivery network design model

| Decision variables | Meaning | |
|---|---|---|
| $x_{ij}$ | $x_{ij} = 1$ | if company $i$ performs a delivery service in region $j$ |
| | $x_{ij} = 0$ | otherwise |

Table 2. All parameters for collaborative delivery network design model

| Parameters | Meaning |
|---|---|
| $f_{ij}$ | Fixed cost accruing from operating the service in region $j$ by company $i$ |
| $Q_i$ | Remaining capacity for processing delivery hub of company $i$ |
| $d_{ij}$ | Daily delivery amount of the company $i$ in region $j$ |
| $D_j$ | Daily delivery amount within region $j$. $D_j = \sum_{i \in I} d_{ij}$ |
| $r_{ij}$ | Net profit by one unit of delivery amount of company $i$ within region $j$ |

The objective function of this study is to maximize the summation of profit for each company as Equation (1). Actually, the objective function is expressed a multi-objective function, but in this study, it was transformed by applying the maxsum criterion. Equation (2) means at least one company should be assigned for each region $j$. Equation (3) is capacity constraint about delivery demand that each company can handle. Equation (4) is binary constraint for decision variable.

$$\max \sum_{i \in I} \left[ \sum_{j \in J} r_{ij} \left( D_j x_{ij} - d_{ij} \right) + \sum_{j \in J} f_{ij} \left( 1 - x_{ij} \right) \right] \tag{1}$$

$$\text{s.t.} \quad \sum_{i \in I} x_{ij} = 1 \qquad \forall j \in J \tag{2}$$

$$\sum_{j \in J} \left( D_j x_{ij} - d_{ij} \right) \leq Q_i \qquad \forall i \in I \tag{3}$$

$$x_{ij} \in \{0, 1\} \qquad \forall i \in I,\ \forall j \in J \tag{4}$$

Now, we establish a robust optimization model that makes conservative decisions in situations where delivery demand $d_{ij}$ is uncertain. We assume that uncertain demand $d_{ij}$ is within uncertain set $U$ and the uncertain set is symmetric. Our assumptions can be represented as Equation (5) that $\bar{d}_{ij}$ means nominal value and $\hat{d}_i$ is positive.

$$d_{ij} \in U = \left\{ \bar{d}_{ij} - \hat{d}_i, \bar{d}_{ij} + \hat{d}_i \right\} \quad \forall i \in I,\ \forall j \in J \tag{5}$$

Associated with the uncertain demand $d_{ij}$, we define new decision variable that determines the degree of robustness as $\eta_{ij} = \frac{\left(\bar{d}_{ij} - d_{ij}\right)}{\hat{d}_i}$, and takes values in $[-1, 1]$.

Bertsimas and Sim [16] proposed a methodology for establishing the robust optimization model for cardinality uncertain set and we applied their methodology to deterministic optimization model. Then, Equations (6) to (19) are our robust optimization model developed from the previous study. Objective function (1) and capacity constraint (3) which include uncertain demand are reformulated for robust decision. Equations (7) to (10) are robust constraints that are reformulated from the objective function and Equations (11) to (15) are reformulated from capacity constraints. The parameter $\Gamma$ is protected level, which is the indicator of robustness. For example, if you set the $\Gamma$ as high value, the robust model derives conservative solution which may have the bad objective value but stable in uncertain demand. The new decision variables $z$, $\theta_i$, $q_i$, $\sigma_{i,i}$ are dual variables.

$$\max g \tag{6}$$

$$\text{s.t.} \quad g \leq A + \Gamma z + \sum_{\forall i \in I} \theta_i \tag{7}$$

$$A = \sum_{i \in I} \left[ \sum_{j \in J} r_{ij} \left( \bar{D}_j x_{ij} - \bar{d}_{ij} \right) + \sum_{j \in J} f_{ij} (1 - x_{ij}) \right] \tag{8}$$

$$B_i^1 = \sum_{j \in J} r_{ij} x_{ij} - \sum_{j \in J} r_{ij} \qquad \forall i \in I \tag{9}$$

$$z + \theta_i \leq B_i \hat{d}_i \qquad \forall i \in I \tag{10}$$

$$E_i + \Gamma q_i + \sum_{i' \in I} \sigma_{i,i} \leq Q_i \qquad \forall i \in I \tag{11}$$

$$E_i = \sum_{j \in J} r_{ij} \left( \bar{D}_j x_{ij} - \bar{d}_{ij} \right) \qquad \forall i \in I \tag{12}$$

$$q_i + \sigma_{i,i} \geq y_{i,i'} \hat{d}_i \qquad \forall i, i' \in I \tag{13}$$

$$-y_{i,i'} \leq W_{i,i'} \leq y_{i,i'} \qquad \forall i, i' \in I \qquad (14)$$

$$W_{i,i'} = \sum_{i \in I} x_{ij} - v_{i,i'} |J| \hat{d}_i \qquad \forall i, i' \in I \qquad (15)$$

$$\sum_{i \in I} x_{ij} = 1 \qquad \forall j \in J \qquad (16)$$

$$x_{ij} \in \{0, 1\} \qquad \forall j \in J \qquad (17)$$

$$z \geq 0 \qquad (18)$$

$$\theta_i, q_i, y_{i,i'} \geq 0 \qquad \forall i, i' \in I \qquad (19)$$

4. **Numerical Example.** In this section, the study examines the applicability of the constructed deterministic and robust model in the example of three delivery companies (A, B and C), who enter into collaboration, which allows them to service 10 merging regions by using the infrastructure of each other. Data for delivery demand, and for daily fixed cost are given in Tables 3 and 4.

Table 3. Data for delivery demand

| Company | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 | R9 | R10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 87 | 66 | 138 | 66 | 144 | 105 | 87 | 57 | 60 | 105 |
| B | 135 | 105 | 90 | 78 | 57 | 126 | 42 | 69 | 108 | 150 |
| C | 111 | 87 | 120 | 81 | 126 | 141 | 111 | 54 | 57 | 96 |

Table 4. Data for daily fixed cost

| Company | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 | R9 | R10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 56 | 86 | 66 | 63 | 62 | 80 | 55 | 95 | 81 | 72 |
| B | 92 | 93 | 81 | 96 | 94 | 56 | 57 | 67 | 93 | 98 |
| C | 53 | 76 | 55 | 76 | 53 | 63 | 55 | 68 | 60 | 75 |

4.1. **Solution comparison.** Based on demand and cost data, we derive the optimal solutions by deterministic model (Equations (1)-(4)) and robust model (Equations (6)-(19)) using GAMS/CPLEX on a machine with an Intel(R) Xeon(R) CPU E5-2640 v4 2.40 GHz processor and 64.0 GB of RAM. The optimal solution of deterministic model is shown in Table 5 and the optimal solution of robust model is shown in Table 6. As can be seen, decision-makings are different in regions 9 and 10. This is because conservative decision was established in regions 9 and 10 in response to uncertain demand.

Table 5. Optimal solution derived by deterministic model

| Company | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 | R9 | R10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| B | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| C | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |

Table 6. Optimal solution derived by robust model ($\Gamma = 1, 2, 3$)

| Company | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 | R9 | R10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| B | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| C | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 |

Figure 2 shows the total net profit of each solution according to the indicator $\Gamma$. Since the deterministic model did not consider uncertainty, the same solution was derived regardless of $\Gamma$. However, the robust model considers uncertainty, the total net profit is increasingly bad, but solutions have been more robust depending on the size of $\Gamma$. The net profit of each model was different for $\Gamma$, but the optimal $x_{ij}^*$ of model RO was the same because of binary small size problem.

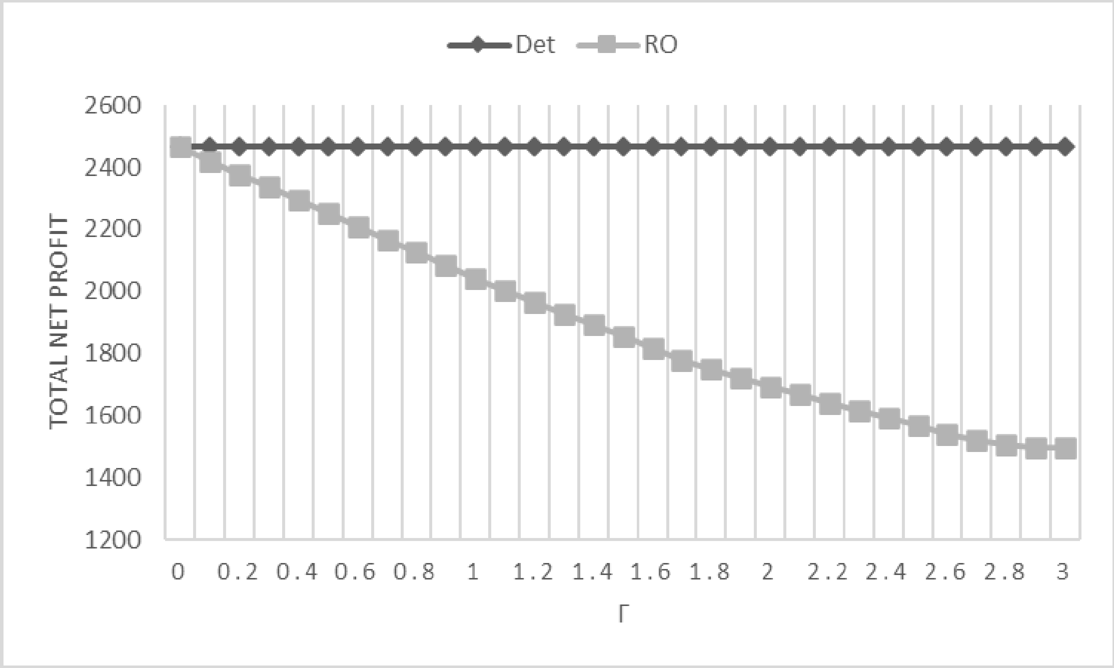

Figure 2. The total net profit of each solution

4.2. **Simulations analysis.** We evaluate the proposed solution shown in Tables 5 and 6. We generated random demand $d_{ij}$ as 48 cases and simulate each solution to see if they actually perform well in 48 random cases. Through simulations, we showed that robust solution seems unreasonable but effective in uncertain situations. Table 7 which is the result of simulation shows the advantages of robust solution well. The model Det recorded an average net profit of less than model RO. Although the standard deviations were similar, RO was better in both the best and worst cases. Therefore, the solution derived from model RO considering uncertainty may be more effective in actual uncertain situations.

Table 7. The result of simulation about Det and RO model

| | Mean | Standard deviation | Max | Min |
|---|---|---|---|---|
| Det | 1,641 | 62 | 1,777 | 1,515 |
| RO ($\Gamma = 1, 2, 3$) | 1,665 | 61 | 1,801 | 1,539 |

5. **Conclusions.** The COVID-19 issue has forced e-commerce to expand to new businesses, consumers, and product categories. Customers now have access to a wide variety of products from the convenience and security of their own homes, while businesses are still able to function despite contact restrictions and other restrictions. Considering these restrictions, there is severe competition with the giant companies with many resources and mid-small size companies. In this paper, strategic decisions of mid-small size delivery companies were studied, where such companies arrange collaboration type of work

in a certain area by combining their resources and making important decisions within the collaboration system to maximize their profits and decrease the costs. Also, we proposed collaborative delivery network design model and expanded robust design model for conservative decision in uncertain demand. Our robust design model can consider the conservativity of the solution based on the protect level chosen by the decision maker. To evaluate the effectiveness of robust design model, we simulated 48 cases of random demand and showed robust solution seems unreasonable but effective in uncertain situations. Our solutions were derived by GAMS/CPLEX on a machine with an Intel(R) Xeon(R) CPU E5-2640 v4 2.40 GHz processor and 64.0 GB of RAM and our experiments were conducted with arbitrary data.

From our point of view, it is yet possible to use and compare stochastic or genetic algorithm methods. Furthermore, from deterministic point we suggest that collaboration models can be extended by means of adding some other real-world constraints.

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