A LOCATION MODEL OF PUBLIC DISTRIBUTION CENTERS CONSIDERING NO_x EMISSIONS

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ABSTRACT
Distribution centers managed by public authorities have been designed to achieve global optimization for efficient logistics and to maintain the urban environment. From the standpoint of social logistics, global optimization should be pursued considering both the environment and the efficiency of business logistics. In this study, we adopt the amount of NO_x emitted by trucks as an environmental measure and propose a mathematical programming model minimizing both NO_x emissions and logistics costs for obtaining the optimal number and locations for the public distribution centers. This model is applied to the Tokyo metropolitan area and an appropriate policy for the number and locations of public distribution centers in the Tokyo metropolitan area can be proposed.

INTRODUCTION
Recently, the concepts of social logistics or green logistics have been generalized for environmental management. In metropolitan areas, a most crucial issue is nitrogen oxide (NO_x) that is emitted by vehicular traffic, which is the main cause of air pollution such as photochemical smog. Diesel engines are especially heavy polluters. Various attempts have been made to minimize NO_x emissions by trucks. Examples include promoting modal shift and joint trucking; securing of cargoes for round trips; eliminating engine racing; enforcing travel at a steady speed; using more low-pollution vehicles; and thorough checking and maintenance of vehicles. Moreover, distribution centers managed by public authorities have been designed to achieve global optimization for efficient logistics and to maintain the urban environment. Public distribution centers are expected to have a positive impact on the urban environment because their use results in a reduction of NO_x emissions from trucks. The achievements may be attributed to fewer vehicles and shorter delivery distances. In order to reduce trucking delivery distances, it might be necessary to increase the number of distribution centers, which would in turn cause an increase in facility-operating costs. From the standpoint of social logistics, global optimization should be pursued considering both the environment and the efficiency of business logistics, or, in other words, reduce the volume of NO_x emitted by trucks, while simultaneously minimizing logistics costs. Logistics costs are made up of transportation costs from supply points to distribution centers, delivery costs from distribution centers to customers, and operating costs at the centers.

In this study, we propose a mathematical programming model minimizing both NO_x emissions and logistics costs for obtaining an optimal number of public distribution centers in strategic locations servicing the Tokyo metropolitan area. Trucks discharge NO_x during transport and delivery activities within the area. This amount of discharged NO_x is proportional to vehicle-kilometers of trucks. In addition to that, idling trucks caught in traffic jams near distribution centers also emit a large amount of NO_x. If the number of centers were fewer, many trucks would crowd round the centers, and traffic jams would be more frequent. In consequence, the amount of NO_x emissions would increase. The goal of this model is to reduce the volume of NO_x emissions. The solutions are evaluated with consideration also given to the costs of logistics.

Though almost all of the existing problems dealing with location emphasize transportation costs or public services, there are few studies dealing with location that focus on the environment including NO_x emissions by trucking and general traffic. We examine those problems and elaborate on an algorithm for determining solutions. The optimum number and ideal locations for the distribution centers from an environmental, logistics, and economics point of view can be obtained with our model. Our model is applied to the Tokyo metropolitan area. The validity of the model is evaluated through simulations.

MODEL AND ALGORITHM

Cost-Minimizing Problem

We first present a mathematical programming model for minimizing total logistics costs.

The following set of assumptions were made in order to formulate the model:

1. Supply points, demand points, and candidate distribution center sites are given as a set of nodes.
2. Distribution centers can handle unlimited amounts of any kind of commodities.
3. The supply and demand of goods at all nodes are given.
4. All goods from supply points are transported to demand points from a distribution center.
5. Transported volume from supply points to demand points is given.
6. Operating costs at distribution centers are increased non-linearly by the amount of goods handled.

Moreover, we define the following notation to formulate our model. K is the commodity set, S is the supply point set, F is the candidate distribution center set, and D is the demand point set. x_{ij}^k is a variable, which is the amount of transport of commodity k from supply node i to center j. z_{jl}^k is a variable, which is the amount of delivery of commodity k from center j to demand node l. Let y_j be a binary variable, which is equal to one if candidate center j is located or zero otherwise. u is the number of public distribution centers. d_{il}^k is the demand of commodity k transported from supply node i to demand node l; c_{ij}^k is the transportation cost per volume, and e_{jl}^k is the delivery cost per volume. f_j is the non-linear operating cost function at center j, and b_j^k is the amount of demand of commodity k handled at center j. M is a very large arbitrary number.

The problem is to determine the number and locations of public distribution centers that will minimize total logistics costs. Using the above-mentioned notation, we can formulate an integer non-linear mathematical programming model as follows:

$$\text{minimize} \quad \sum_{i\in S}\sum_{j\in F}\sum_{k\in K} c_{ij}^k x_{ij}^k + \sum_{j\in F}\sum_{l\in D}\sum_{k\in K} e_{jl}^k z_{jl}^k + \sum_{j\in F} f_j\left(\sum_{k\in K} b_j^k\right) y_j \tag{1}$$

$$\text{subject to} \quad \sum_{j\in F} x_{ij}^k = \sum_{l\in D} d_{il}^k \quad i\in S, k\in K \quad (2) \qquad \sum_{j\in F} z_{jl}^k = \sum_{i\in S} d_{il}^k \quad l\in D, k\in K \quad (3)$$

$$\sum_{i\in S} x_{ij}^k = \sum_{l\in D} z_{jl}^k = b_j^k \quad j\in F, k\in K \quad (4) \qquad x_{ij}^k \le M y_j \quad i\in S, j\in F, k\in K \quad (5)$$

$$z_{jl}^k \le M y_j \quad j\in F, l\in D, k\in K \quad (6) \qquad \sum_{j\in F} y_j = u \quad (7)$$

$$x_{ij}^k \ge 0 \quad i\in S, j\in F, k\in K \quad (8) \qquad z_{jl}^k \ge 0 \quad j\in F, l\in D, k\in K \quad (9)$$

$$y_j \in \{0,1\} \quad j\in F \quad (10) \qquad u \in \mathit{integer} \quad (11)$$

Equation (1) is the objective function, which should be minimized. The first term in this equation represents the transportation cost from supply points to the distribution centers. The second term is the delivery cost from distribution centers to demand points. The third term is the operating cost at these centers, which depends non-linearly on the volume of goods handled. Equations (2), (3), and (4) are the conservation constraints; (2) is the one from supply points to distribution centers; (3) is the one from distribution centers to demand points, and (4) is the one at distribution centers respectively. Equations (5) and (6) are the forcing constraints, which show that any supply or demand must not be transported to center *j* or delivered from center *j*, if the center is not located in node *j*, that is, y_j=0. Equation (7) shows the relationship between y_j and *u*. The rest of the constraints, (8), (9), (10), and (11) denote non-negative, zero-one or integer conditions.

Finding an optimum solution to this problem is not easy because of its integrality and non-linearity. Therefore, we can adopt our Random Multi-start Limited Neighborhood (RMLN) search algorithm to obtain a good approximate solution.

Estimation of the amount of NO_X emissions

Solutions of the cost-minimizing problem are evaluated in terms of the amount of NO_X emissions in order to give consideration to environmental issues. Since the amount of NO_X discharged by trucks during transportation and delivery activities is considered in proportion to the sum of the vehicle-kilometers within the area, we substitute these solutions for the following formula and evaluate the amount of NO_X emissions.

$$\sum_{i\in S}\sum_{j\in F}\sum_{k\in K} m_{ij}^k x_{ij}^k g_{ij}{}^k(x_j, z_j) + \sum_{j\in F}\sum_{l\in D}\sum_{k\in K} n_{jl}^k z_{jl}^k h_{jl}{}^k(x_j, z_j) \ , \tag{12}$$

where, function g_{ij}^k is the volume of NO_X emissions per vehicle from supply node *i* to distribution center *j* of commodity *k,* and function h_{jl}^k is the volume of NO_X emissions per vehicle from distribution center *j* to demand node *l* of commodity *k*. m_{ij}^k is the volume of vehicles per volume transported from *i* to *j* of *k*, and n_{jl}^k is the number of vehicles per volume delivered from *j* to *l* of *k*. x_j is the vector (x_{1j}^k, x_{2j}^k,$\cdots$) and z_j is the vector ,(z_{j1}^k, z_{j2}^k,$\cdots$).

The first term in formula (12) is the amount of NO_X emitted during transportation activities from supply points to distribution centers. The second term is the amount of NO_X emitted during delivery activities from distribution centers to demand points.

In addition to NO_X emissions proportional to the vehicle-kilometers, NO_X is also discharged near the distribution centers by idling trucks. If the number of centers were fewer, the amount of NO_X emissions would increase, as would the size of the

centers. Many trucks would crowd round the centers, and traffic jams would be more frequent. Therefore, g_{ij}^k and h_{jl}^k are functions of vectors x_j and z_j, which indicate the traffic volume in and out of center j.
We can calculate the number of vehicles that would make use of a public distribution center based on the number of centers established. Traffic volume around the center could be estimated based on the number of vehicles. A common approach to modeling the total travel time on a link as a function of traffic volume on that link is the so-called Bureau of Public Roads (BPR) curve.

$$f(v_i) = t\left\{1+\alpha\left(\frac{v_i}{c_i}\right)^{\beta}\right\} \quad , \qquad (13)$$

where, $f(v_i)$ is total travel time for all users on link i, v_i is the volume of traffic on the link, t is free-traffic travel time parameter for a link i, c_i is capacity parameter for link i and α, β are constants. In Japan, a function with α=2.62 and β=5 is experimentally adopted in many studies on road investments. Using this function, we can obtain the average speed per hour within a unit sphere of the center. As the speed of the truck decreases, a large amount of NO_X is discharged due to engine racing and idling. The volume of NO_X emissions can be obtained from the speed per hour of trucks within a unit sphere of the center by using the empirical function derived by the Tokyo Bureau of Environment. Consequently, the relationships between the number of centers, speed per hour, and the amount of NO_X emissions are shown in Figure 1.

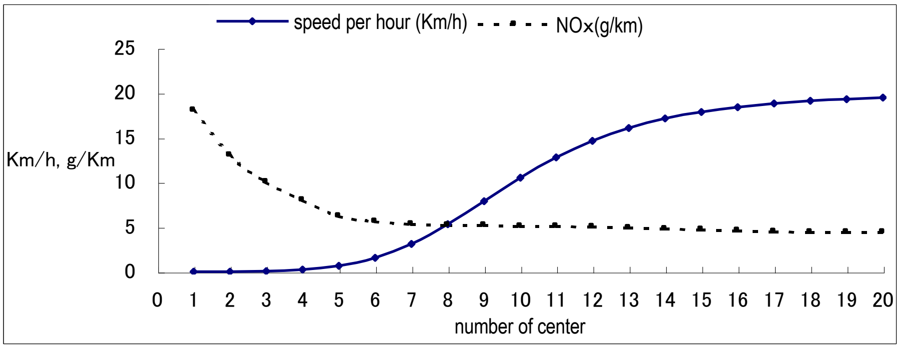

Fig. 1 The relationship between the number of centers and NO_X emissions

NO_X-Minimizing Problem

Given the number of centers as well as the location model for the cost-minimizing problem, we can easily formulate a model for minimizing the volume of NO_X by using an estimation of the amount of NO_X emissions from trucks.
Let the objective function of this problem be the amount of NO_X emissions that should be minimized. This function is the same as in the formula (12) used for evaluating the amount of NO_X emissions in the cost-minimizing problem. The constraints for minimizing NO_X are also the same as those used for the cost-minimizing problem.
We can formulate NO_X minimization as the following integer mathematical programming model:

$$\text{minimize} \sum_{i\in S}\sum_{j\in F}\sum_{k\in K} m_{ij}^k x_{ij}^k g_{ij}{}^k\left(x_j, z_j\right) + \sum_{j\in F}\sum_{l\in D}\sum_{k\in K} n_{jl}^k z_{jl}^k h_{jl}{}^k\left(x_j, z_j\right) \qquad (14)$$

$$\text{subject to} \quad (2)\sim(11)$$

This is the same as the cost-minimizing problem, except for the objective function in which we substitute the amount of NO_X emissions for the total logistics costs.

Therefore, we can adopt the RMLN algorithm to obtain a good approximate solution.

APPLICATIONS

We apply our models to the Tokyo metropolitan area. The Tokyo metropolitan area consists of the Tokyo metropolis and the Kanagawa, Chiba, and Saitama prefectures. The Tokyo metropolitan area is the center of the Japanese economy, transportation, and delivery activities, and more than half of NO_X emissions in Japan are discharged in this area. We divided this area into 283 demand points, which are located at the centers of the cities, towns, and villages comprising the Tokyo metropolitan area. It is assumed that the distribution centers are to be located somewhere among these demand nodes. The number of supply points is nine, and they are located at the entrance nodes outside the Tokyo metropolitan area and in nodes with main sources within that area. We deal with the following eight kinds of commodities: agricultural, marine, forest, metal, machine, chemical, light industrial, other industrial, and special. Demand data, from every supply point to every demand point by commodity, are obtained from a Goods Flow Survey of the Tokyo metropolitan area (1997).

Using these data, we solved the cost-minimizing problem and NO_X-minimizing problem by the RMLN algorithm. Figure 2 shows the comparison of the total logistics costs between both problems. The total costs in cost-minimizing problem decrease until there are three centers and gradually increase from there on. The minimum cost in the NO_X-minimizing problem is obtained when there are four centers. As a matter of course, the total logistics costs in the NO_X-minimizing problem are higher than that in the cost-minimizing problem. In case of three centers, the difference in the total costs accounts for 22.5%, 14.2% in case of four centers and 26.3% in case of 20 centers.

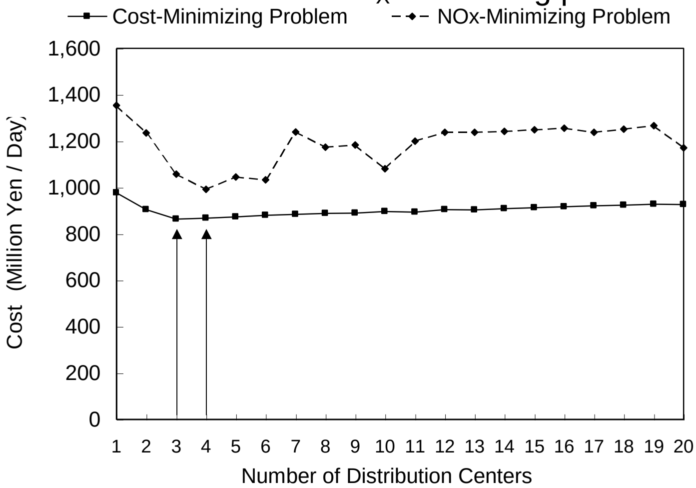

Fig.2 Costs Versus Number of Distribution centers

Figure 3 shows the comparison of the amount of NO_X discharged by trucks between the cost-minimizing problem and the NO_X-minimizing problem. In both problems, it is clear that the amount of NO_X emissions decreases sharply until there are four centers and the amounts seem to remain stable when there are more than four centers. The amounts of NO_X emissions in the NO_X-minimizing problem are lower than that in the cost-minimizing problem. The difference in the amount of NO_X emissions in both problems accounts for 9.1% in case of three centers, 15.9% in case of four centers and 28.6% in case of 20 centers. These results suggest that if all

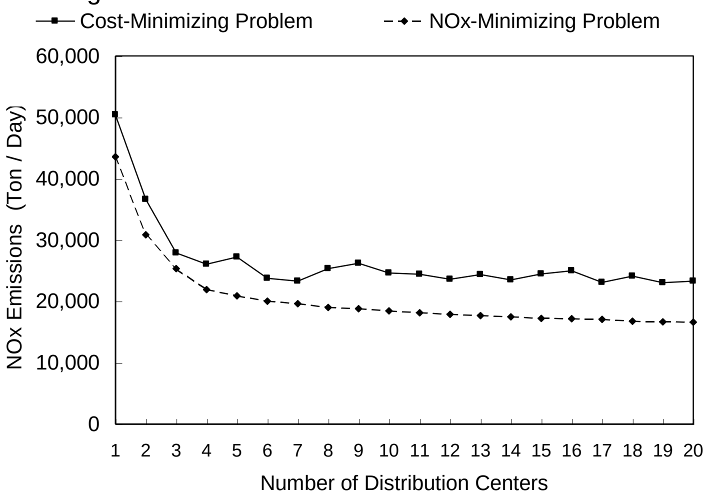

Fig.3 NOx Versus Number of Distribution Centers

companies do their best to reduce NO_X emissions rather than their logistics costs, the amount of NO_X emissions could be reduced by about 16 to 29%.

The number of public distribution centers should be determined based upon both total logistics costs and the amount of NO_X emissions. For the cost-minimizing problem, the difference in the total costs between three and four centers is very small (0.5%), as shown in Figure 2. The difference in the amount of NO_X emissions between three and four centers is 6.6%, as shown in Figure 3. Since the total costs are almost the same in these two cases, and the amount of NO_X emissions can be reduced by about 6.6%, we, therefore, recommend four locations from the environmental standpoint. Figure 4 shows the volume of NO_X emissions of the four centers in the Tokyo metropolitan area.

CONCLUSION

So far, we have outlined our models for the optimal number and location of public distribution centers and showed the applications to the Tokyo metropolitan area. The applications of our model have enabled us to suggest an appropriate policy for public distribution centers in this area. Public distribution centers will be a new attempt to achieve global optimization for the community. However, there are still many problems requiring solution before these distribution centers are widely used, such as the diesel trucks spewing out exhaust fume like NO_X and CO_2, an over-concentration of population and goods into the metropolitan area, etc. These and other problems will have to be solved by the joint efforts of the government, local autonomous bodies, and industries concerned. Enterprises should take the environmental issues into consideration to achieve successful social or green logistics, when planning strategy for logistics.

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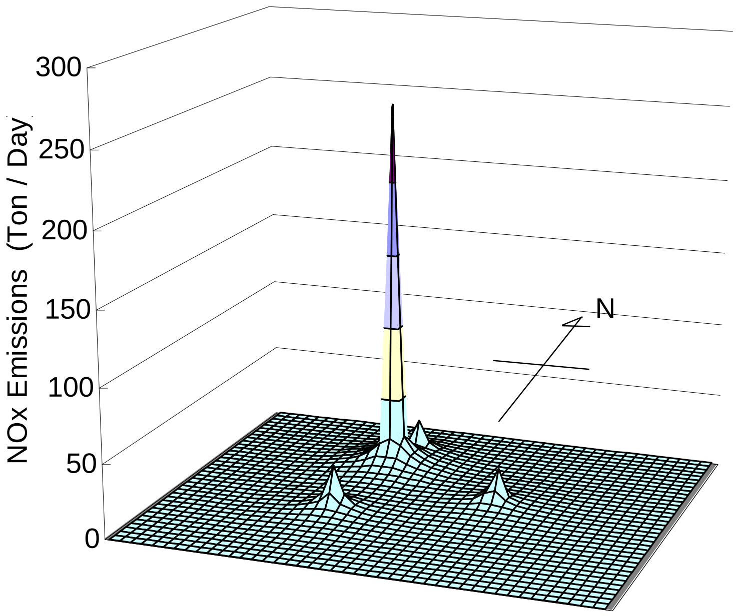

Figure 4. NO_x Emissions in case of Four Centers