Optimal location planning of logistics terminals based on multiobjective programming method

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Abstract

This paper focuses on a method for determining the optimal location patterns of logistics terminals constructed by public sector. Since the aim of constructing them is to help establish efficient logistics systems and reduce the total social and environmental costs of transporting goods within urban areas, a variety of objective functions must be considered in the problem formulation. Three objective functions were defined in this study: transport costs, costs of travel time and the CO2 emissions. The values of these objective functions depend on the traffic conditions on road network, so that they will not only differ from each other but also be mutually conflicted. A mathematical model was therefore developed incorporating multiobjective programming method. Vector evaluated genetic algorithms were applied to obtain Pareto optimal solutions which correspond to the alternative location patterns of the logistics terminals. The model was successfully applied to an actual road network in the Kyoto-Osaka area in Japan. A set of Pareto optimal solutions was obtained including the compromise solutions and the optimal solution for each objective function.
1 Introduction

The distribution of goods in urban areas using road-based vehicles has led to many problems such as traffic congestion, negative environmental impact, high energy consumption, and high labour costs. Especially in large cities, environmental problems has become a matter of great concern and traffic congestion is becoming worse, partly because of increasing truck traffic. There is therefore, a need to effectively implement measures which reduce the total social and environmental costs of transporting goods within urban areas.

Some companies in the position of shippers or freight carriers have planned their own logistics systems to minimise their logistics costs: supply chain management procedures and consolidated logistics terminals. These logistics systems may be optimised for a company or a group of companies, but for the whole community, logistics systems within urban areas must be optimised taking into account road congestion, environmental impact, and so on.

To cope with these problems, proposals have been made to construct public logistics terminals in the vicinity of expressway interchanges surrounding large cities in Japan (Taniguchi et al.). Public logistics terminals are multi-company distribution centres and also complex facilities with multiple functions that meet various needs in supply chain management systems using advanced information systems. Similar ideas to public logistics terminals have been proposed in the Netherlands (Janssen and Oldenburger) and in Germany (Ruske). However, the concept of public logistics terminals needs more intensive investigation in several areas such as their function, size, location, management as well as the role of public sector.

This paper describes a model developed for determining the optimal location of logistics terminals that will be required in designing public logistics terminals, and then the model is applied to an actual road network in the Kyoto-Osaka area in Japan. The model takes multiple objective functions into consideration using multiobjective programming method and consequently alternative location patterns of logistics terminals can be obtained.

2 Model for the location of logistics terminals

2.1 Structure of the logistics system investigated

Fig.1 shows the structure of the logistics system investigated in this paper. The goods movement is assumed to be divided into two parts: line-haul which is long-distance transport by large trucks on expressways, and local pick-up/delivery which
is short-distance transport by small trucks on urban streets. Logistics terminals are the connection points between line-haul and local pick-up/delivery, with transhipments being performed there. Inventory in logistics terminals is not considered in this paper.

Figure 1: Structure of logistics system investigated

2.2 Mathematical formulation

The model has following five features: (1) Optimal location of logistics terminals is determined from candidate nodes that are discretely given in advance within road network; (2) Optimal size of each logistics terminal is simultaneously determined taking into account transport costs and facility costs (such as construction, maintenance, land and truck operation costs in the terminals); (3) a planner can determine the optimal size and location of logistics terminal but cannot control the distribution and assignment of truck traffic; (4) distribution of goods movement is given in advance for each pair of centroids for line-haul trucks and pick-up/delivery trucks; (5) each truck can choose a logistics terminal depending on the traffic conditions on urban streets.

The mathematical formulation of this model is described below:

(upper level problem)
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\[
\min_{x \in X, y \in Y} f(x, y, z^*) \tag{1}
\]
subject to
\[
g(x, y, z^*) \leq 0 \tag{2}
\]
(lower level problem)

\[
\min_{z \in Z} f'(x, z) \tag{3}
\]
subject to
\[
g'(x, z) \leq 0 \tag{4}
\]

where,
- \(X\) : vector of location patterns of candidate nodes
- \(y\) : vector of the number of berths of candidate nodes
- \(Z\) : vector of behaviour of trucks
- \(Z^*\) : vector of behaviour of trucks under \(X\) (solution of lower problem)
- \(X\) : sets of vector \(X\)
- \(Y\) : sets of vector \(y\)
- \(Z\) : sets of vector \(Z\)
- \(f\) : vector of objective functions for a planner
- \(f'\) : objective function of a truck (or a company)
- \(g, g'\) : constraint vector for a planner and a truck, respectively

The lower level problem describes the behaviour of each company or each truck in choosing optimal logistics terminal and route, where passenger car traffic and pick-up/delivery truck traffic are treated. Both traffic modes satisfy the user equilibrium condition on road network. The lower level problem corresponds to the doubly constrained combined distribution-assignment model (Evans*), which incorporates the equal travel time principle for assignment and variable demand for distribution between a centroid for pickup/delivery trucks and a logistics terminal.

The upper level problem describes the behaviour of a planner for minimising the values of several objective functions. In this paper, transport costs of line-haul trucks and pickup/delivery trucks, costs of travel time of all vehicles (i.e. passenger cars, line-haul and pickup/delivery trucks) and CO\(_2\) emissions of all vehicles are treated as objective functions. The values of these objective functions depend on the traffic conditions on road network, so that they will not only differ from each other but also be mutually conflicted. Optimal size of each logistics terminal, represented by the number of berths, is also given by the upper problem. The size of logistics terminal is related to the facility costs calculated using queuing theory (Taniguchi et al.*).
Fig. 2 indicates the structure of the model for determining the size and location of logistics terminals.

**Initial location patterns of logistics terminals**

- Generation and attraction traffic volume of PD
- Distribute traffic volume of PC

**Traffic assignment**

- Number of PD and LH that use logistics terminals
- Traffic volume of LH on each link

- Travel time and speed of LH on each link
- Optimal size of logistics terminals

- Total travel time
- Total distance travelled

- Unit costs of logistics terminals
- Costs of constructing logistics terminals
- Transport costs
- Costs of travel time
- CO\(_2\) emissions

**Fitness of each location pattern**

- Simulation using VEGA

- Renewed location patterns of logistics terminals

- Criterion (Number of generations)

PD: Pickup/delivery trucks
LH: Line-haul trucks
PC: Passenger cars

Figure 2: Structure of the model
2.3 Multiobjective programming method

Multiobjective programming method (for example Chancong and Haimes; Sawaragi et al.) can be generally applied to the problem with mutually conflicted objective functions. All objective functions cannot be simultaneously minimised in case they are mutually conflicted and hence Pareto optimal solutions (i.e. noninferior or nondominated solutions) are defined as optimal solutions for multiobjective optimisation problem. Pareto optimal solutions are represented by $x^*$ when there is not any $x$ ($x \in X$) which satisfies $f_i(x) \leq f_i(x^*)$ at $i = 1, \cdots, k$ for $x^* \in X$ and $f_j(x) < f_j(x^*)$ at arbitrary $j$. They are used if the value of at least one objective function must be increased in order to decrease the value of a certain objective function.

The upper level problem has discrete variables representing location pattern of logistics terminals. It requires a very long computation time to obtain exact Pareto optimal solutions and if there are many candidate logistics terminals, it is impossible in practice. Vector evaluated genetic algorithms (for example Schaffer) have been therefore applied here. Vector evaluated genetic algorithms (VEGA) provide an effective method to quickly obtain approximate Pareto optimal solutions.

2.4 Vector evaluated genetic algorithms

Genetic algorithms (for example, Goldberg) are heuristic techniques to obtain approximate optimal solutions in most practical applications within reasonable computational times. Approximate optimal solutions are searched through genetic operators, which involve the generation, reproduction (or selection), crossover and mutation as observed in living things. Individuals correspond to feasible solutions to the problem. Genetic algorithms (GA) start by generating a population that represents the set of individuals. Population in the subsequent generation is determined by procedures where parents are selected and new individuals are produced based on processing characteristics of the parents.

Fig. 3 indicates the calculation steps of VEGA applied in this study. VEGA has the same genetic operators as GA, but the reproduction in VEGA is performed based on the value of each objective function (Step 4). Individuals are divided by the number of objective functions, and subgroups of the population are generated. These subgroups are mixed after reproduction (Step 5), and then crossover and mutation are performed for the reconstructed population (Step 6 & 7). VEGA make use of the GA’s characteristics that a number of individuals search for multiple points at the same time and enable obtaining Pareto optimal solutions at a time.
### Step 1: Initial Setup (Determination of genotype)

<table>
<thead>
<tr>
<th>Individual</th>
<th>Example for location pattern of terminals (2, 4, 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 1 0 1 0 0</td>
<td>Number of individuals: 70</td>
</tr>
<tr>
<td>0 0 0 0 1 0</td>
<td>Fitness obtained by linear normalization of 1/(the value of objective function)</td>
</tr>
</tbody>
</table>

### Step 2: Generation of first population

- Number of individuals: 70
- Fitness obtained by linear normalization of 1/(the value of objective function)

<table>
<thead>
<tr>
<th>Subgroup (based on the value of objective function 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 3: Calculation of fitness for each individual</td>
</tr>
</tbody>
</table>

### Step 4: Performance of reproduction

<table>
<thead>
<tr>
<th>Subgroup (based on the value of objective function 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
</tr>
<tr>
<td>Subgroup (based on the value of objective function k)</td>
</tr>
</tbody>
</table>

### Step 5: Mixture of subgroups

### Step 6: Performance of cross over

### Step 7: Performance of mutation

### Step 8: If number of generations reaches criterion

- Number of elites: 10
- Crossover rate: 1.0
- Uniform crossover
- Mutation rate: 0.05
- Number of generations: 50

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**3 Application to actual road network**

The model described above was applied to an actual road network in the Kyoto-Osaka area in Japan (Fig.4). This network is planned for the year of 2010 and 16 candidates for public logistics terminals are placed along with several planned expressways. The network has two centroids for line-haul trucks in East and West Japan and 36 centroids for pick-up/delivery trucks and passenger cars. For passenger cars, 6 nodes of outside the area are also included in the network. The land price is high for candidate nodes that are close to Osaka and Kyoto. It means that the
construction costs of logistics terminals in these areas are higher. Predicted distribute traffic volume of passenger and freight traffic in the year of 2010 and the present amount of goods were used as inputs.

Three objective functions, used in a subsequent calculation, are as follows:

\[ f_1 = \frac{\text{The difference in total transport costs between with and without public logistics terminals}}{\text{Total construction costs of public logistics terminals}} \] (5)

\[ f_2 = \frac{\text{The difference in total costs of travel time between with and without public logistics terminals}}{\text{Total construction costs of public logistics terminals}} \] (6)

\[ f_3 = \frac{\text{The difference in total CO}_2\text{ emissions between with and without public logistics terminals}}{\text{Total construction costs of public logistics terminals}} \] (7)

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**Figure 4: Road network in the Kyoto-Osaka area**

- expressway
- urban streets (ordinary roads)
- link to nodes outside the area
- centroid
- nodes
- nodes outside the area
- candidate nodes for public logistics terminal
- land price (thousand yen/m²)
The above objective functions are described as maximisation problems, which can be easily transformed into minimisation problems as fitted with eqn (1). The value in the numerator of the above equations corresponds to the benefit. Each of the above equations therefore represents the Cost Benefit Ratio for each evaluation index (i.e. transport costs, costs of travel time and the CO₂ emissions).

Table 1 indicates the optimal solutions. They include the compromise solutions as well as the optimal solution for each objective function. All location patterns shown in Table 1 include terminal 5. This is because terminal 5 is near large cities which have large demands for goods movement and its land price is relatively low.

The value in the numerator was maximised for all objective functions when the location pattern was composed of four nodes (1, 2, 5 and 15). However, the optimal location pattern for each objective function differs from each other (Table 1). This result can be explained by the difference in benefit and that in construction costs of logistics terminals among the optimal location patterns shown in Table 1. As for transport costs and CO₂ emissions, the difference in benefit among them were relatively small. Therefore, the construction costs of logistics terminals had a great impact on the value of objective function. On the other hand, as for costs of travel time, the value of objective function was more strongly affected by the difference in benefit than that in construction costs that was much larger than that in benefit.

<table>
<thead>
<tr>
<th>Location pattern</th>
<th>( f_1 ) (Transport cost)</th>
<th>( f_2 ) (Cost of travel time)</th>
<th>( f_3 ) (CO₂ emissions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2,5,7,10)</td>
<td>10.054*</td>
<td>2.055</td>
<td>5.203</td>
</tr>
<tr>
<td>(1,4,5,7,15)</td>
<td>10.042</td>
<td>3.435</td>
<td>5.254</td>
</tr>
<tr>
<td>(1,5,7,10,15)</td>
<td>10.025</td>
<td>4.057</td>
<td>5.282*</td>
</tr>
<tr>
<td>(1,5,6,7,15)</td>
<td>9.981</td>
<td>4.159</td>
<td>5.280</td>
</tr>
<tr>
<td>(1,2,5,7,15)</td>
<td>9.868</td>
<td>4.588</td>
<td>5.250</td>
</tr>
<tr>
<td>(1,5,10,15)</td>
<td>9.831</td>
<td>4.713</td>
<td>5.221</td>
</tr>
<tr>
<td>(1,2,5,15)</td>
<td>9.686*</td>
<td>5.312*</td>
<td>5.186</td>
</tr>
</tbody>
</table>

*maximum value of each objective function

| 4 Conclusions |

A mathematical model was developed to obtain optimal location patterns of logistics terminals incorporating multiobjective programming method. It determines the approximate optimal location patterns of logistics terminals using vector evaluated genetic algorithms for minimising the value of objective functions associated with transport costs, costs of travel time and the CO₂ emissions. This model was successfully applied to an actual road network in the Kyoto-Osaka area in Japan, and
the Pareto optimal solutions representing alternative location patterns of logistics terminals could be obtained.

It will be better for location planning of public logistics terminals that a planner determine alternative location patterns of public logistics terminals in advance and then select an optimal (or preferred) one from them considering the ease of land purchase and the needs of users (i.e. shippers and freight carriers). Further investigation will therefore be required to obtain a preferred location pattern from alternative ones.

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References