MULTIOBJECTIVE TRANSPORTATION PLANNING FOR WASTE HAULING

By Li-Hsing Shih and Kuang-Jer Cheng

ABSTRACT: In the transportation planning for some industrial wastes, in addition to hauling cost, environmental impact must frequently be considered. A notable example is transporting waste soil generated by major construction projects. Adequate transportation planning is particularly important for construction in a metropolitan area. In this study, we present a novel two-phase approach to address the multiple-criteria decision problem. The first phase applies the fuzzy analytic hierarchy process to obtain a “composite impedance” for each road sector where transportation costs, environmental impact, and traffic congestion are considered in the evaluation. The second phase employs fuzzy mathematical programming to find the optimal transportation network based on the fuzzy impedance. An illustrative example is provided for the transportation planning for waste soil of the Kaohsiung mass rapid transit system construction project. The optimal solutions using the proposed approach are compared with the solutions using the conventional shortest-path approach where minimizing the transportation cost is the only objective.

INTRODUCTION

In the transportation planning for some nonhazardous industrial wastes, in addition to hauling cost, environmental impact must frequently be considered. Although the impact and associated risk are not as high as the impact of transporting hazardous waste, transportation of some waste may still pose a potential risk owing to its significant amount. A notable example is the transporting of waste soil generated by major construction projects. Such transportation causes noise, dust, and traffic congestion in the area near the hauling routes, with an inevitably negative impact when the construction is located in densely populated metropolitan areas. Highway construction and construction of a mass rapid transit system are common examples.

When considering environmental impact or transportation risk in addition to transportation cost, transportation planning becomes a multicriteria decision problem. Previous literature generally offers two means of solving multicriteria transportation problems. The first category initially estimates the risk, impact, or cost for passing through the possible paths in the transportation network and then formulates the problem as a multiobjective mathematical programming one. Notable examples of this category include Abkowitz and Cheng (1991), Bit et al. (1993), Tzeng and Lee (1993), Chang and Wang (1994), Chang et al. (1996), and Verma et al. (1997). The second category evaluates each candidate transportation route using multiattribute decision making methods since the number of candidate routes is relatively limited. This approach is frequently applied when transporting hazardous wastes such as radioactive or toxic chemicals. In this case, a prior screening criterion screens most road sectors so that only a limited number of routes become promising candidates for transporting these goods. Multiattribute methods are used to evaluate the candidate routes so that an optimum route can be chosen. Recent examples of this second category include Hong (1992), Chang (1995), Chen (1996), and Su (1996).

In light of the above discussion, this study presents a novel two-phase approach to solve the multicriteria transportation planning problem for nonhazardous waste, viz. waste soil. The first phase estimates the composite impedance for each possible road sector. The impedance represents the “cost” including environmental impact, traffic congestion impact, and transportation cost that must be paid to haul the waste through the road sector. Because this is a multiattribute evaluation problem, we apply the fuzzy analytic hierarchy process (FAHP) to incorporate the decision maker’s judgment. The analytic hierarchical process (AHP) developed by Saaty (1982) has been widely used in solving multicriteria, decision-making problems. AHP constructs a hierarchy by breaking down the decision problem into interrelated criteria and determines the weights of criteria by incorporating the decision maker’s judgment. The method involves paired comparisons down through the level of alternatives and allows some qualitative elements in the decision alternatives. The results include the rank order of alternatives as well as their relative standings. In this study, fuzzy numbers are allowed for the ratio values in the pairwise comparison. The second phase employs the fuzzy impedance of each road sector as the composite cost in the minimized cost network flow problem. In addition, fuzzy mathematical programming is used to determine the optimal transportation quantities and routes based on the fuzzy composite impedance of each road sector.

The rest of this paper is organized as follows. The next section describes the FAHP approach used herein to determine the fuzzy impedance value for each road sector. The solution procedures for fuzzy weights and the consistency check are based on the work of Buckley (1985, 1990) and Hsu and Chen (1994). The following section introduces an approach for solving a fuzzy mathematical programming problem based on Herrera and Verdegay’s (1995) work. The penultimate section presents an illustrative example that finds an optimal transportation network for waste soil generated in a mass rapid transit construction project. Conclusions are made in the last section.

FUZZY COMPOSITE IMPEDANCE EVALUATION

The analytic hierarchic process has been extensively applied to evaluate alternatives under multiple attributes (Saaty 1982, 1988; Shih 1999). In this study, we evaluate a composite impedance of each road sector. This number represents the general penalty incurred by traveling the sector and can incorporate the traffic load, environmental impact, and transportation cost. FAHP is used to resolve the multiattribute evaluation problem and incorporate the decision maker’s subjective judgments. The method of Buckley (1985, 1990) is adopted herein to solve for the fuzzy weights in the hierarchy. Attribute values are multiplied by the weights to find the fuzzy impedance value. A fuzzy consistency index proposed by Hsu and Chen (1994) is also used to perform the consistency check. The procedures of FAHP can be divided into five steps.
Construct a Hierarchy

Multiple levels are constructed in the hierarchy to evaluate the overall impedance of road sectors. The top level contains the overall goal of evaluating a composite impedance/penalty for hauling waste through the road. The second level may consist of different interest groups expressing different perspectives on the impact incurred by transporting a material like waste soil. This level could involve multiple decision makers such as the transportation agency, local residents, and government officials. The third level contains the major criteria for overall impedance evaluation, e.g., traffic congestion, transportation cost, and environmental impact. The fourth level consists of some attributes with respect to the criteria at the third level. Examples of the attributes include the average speed, hauling distance, hauling time, number of schools and hospitals, type of district along the road, and population near the road sector.

Obtain Fuzzy Pairwise Comparison Matrices

At each level in the AHP, paired comparisons are made to determine the relative weights of the criteria. For each paired comparison, a fuzzy ratio representing the subjective judgment of a decision maker is obtained to express the relative importance between the pair of criteria. For example, when a decision maker feels that criterion A1 is much more important than A2, the ratio could be equal to 7/1, 8/1, or 9/1. A triangular membership function is generally assumed for the fuzzy ratios. Using fuzzy numbers allows the decision maker to determine that the ratio is between 7:1 and 9:1. Moreover, using these fuzzy numbers also allows one to write the fuzzy paired comparison matrix as follows:

\[ \bar{A} = [\bar{a}_{ij}] \quad i, j = 1, 2, \ldots, n \]  

where \( i \) and \( j \) denote the alternative criteria in the paired comparison. When multiple decision makers are involved, the geometric means of the fuzzy numbers are used to aggregate the group decision (Buckley 1985). Correspondingly, the elements of the fuzzy paired comparison matrix can be written as

\[ a_{ij}^u = (a_{ij}^l \cdot a_{ij}^m \cdot a_{ij}^u)^{1/k} \]  

\[ a_{ij}^l = (a_{ij}^m \cdot a_{ij}^n \cdot a_{ij}^u)^{1/k} \]  

\[ a_{ij}^n = (a_{ij}^m \cdot a_{ij}^l \cdot \cdots a_{ij}^u)^{1/k} \]

where \( k \) denotes the number of decision makers. When the triangular membership function is used, subscripts \( l, m, \) and \( u \) represent the lower bound, mode value, and the upper bound of the fuzzy number, respectively. In addition, superscript \( n \) denotes the comparison on subcriteria being conducted under the \( n \)th criterion.

Calculate Fuzzy Weights

Since the paired comparison matrices are nonnegative irreducible matrices, Buckley (1990) obtained the fuzzy eigenvector (fuzzy weights) by initially solving for the crisp weights under certain \( \alpha \)-cuts on the fuzzy number. The meaning of an \( \alpha \)-cut can be illustrated in Fig. 1 where a left and a right value denote the range of a cut at the membership equal to \( \alpha \). Then the complete fuzzy weight and its membership can be obtained by using an interpolation method. For example, the lower, medium, and upper bounds of the fuzzy ratios are collected to obtain paired comparison matrices \( A^l, A^m, \) and \( A^u \) under different \( \alpha \)-cuts (e.g., \( \alpha = 1 \) and \( \alpha = 0 \)) and the maximum eigenvalues \( \lambda_{\alpha}^{\text{max}}, \lambda_{\alpha}^{\text{med}}, \) and \( \lambda_{\alpha}^{\text{max}} \) respectively of these matrices are calculated. The corresponding cuts of the criteria weights can be obtained by solving for the eigenvectors

\[ \sum_{j=1}^{n} a^*_{ij} \omega_j^a = \lambda_{\alpha}^{\text{max}} \omega_i^a \quad 1 \leq i < n \]  

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where \( \lambda_{\alpha}^{\text{max}} \) denotes the maximum eigenvalue using the \( \alpha \)-cut values of the comparison matrices. Subscripts \( l \) and \( u \) represent the lower and upper bounds of the \( \alpha \)-cut, respectively. For each \( \lambda_{\alpha}^{\text{max}} \), the corresponding eigenvector \( \omega^a \) can be obtained since the weight vectors \( \omega^l \) and \( \omega^u \) representing the left cut and the right cut of the fuzzy weights, respectively, can be solved using expression (3).

The fuzzy weights must be normalized since the weights should have their support in \([0, 1]\). Buckley (1985) suggested that the fuzzy weights are normalized by dividing all fuzzy numbers by the largest right-cut value under \( \alpha = 0 \), i.e.,

\[ \max(\omega^a_i) = 1, 2, \ldots, n \]

where \( \omega^a_i \) denotes the right cut at \( \alpha = 0 \) of the \( i \)th weight.

Conduct Consistency Check

In the AHP, a crisp consistency index is used to check for the consistency of the decision maker’s responses (Saaty 1982). Buckley (1985, 1990) did not address the consistency check for the fuzzy analytic hierarchic process. Hsu and Chen (1994) proposed a method to verify the consistencies of the decision maker’s judgments. The idea is as follows.

Define a fuzzy consistency index \( FCII \) similar to the crisp consistency index

\[ FCII = (\hat{\lambda}_{\text{max}} - n)/(n - 1) \]

where \( \hat{\lambda}_{\text{max}} \) = maximum eigenvalue and a fuzzy number that can be denoted by \( \lambda_{\text{max}}^l, \lambda_{\text{max}}^m, \) and \( \lambda_{\text{max}}^u \) under different \( \alpha \)-cuts. Hence, \( FCII \) is also a fuzzy number with a triangular membership function. Three numbers \( (f_1, f_2, f_3) \) representing the left bound, mode, and right bound of \( FCII \) can be calculated by using expression (5). Hsu and Chen (1994) proposed three criteria for the consistency check:

1. The judgments are not consistent when \( f_1 > 0.1 \).
2. The judgments are consistent when \( f_3 < 0.1 \).
3. When \( f_1 < 0.1 < f_3 \), a consistency degree (CD) is defined to check for consistency.

The CD represents the ratio of the area \( A \) to the left of \( f = 0.1 \) and the total area of the entire triangular membership function in Fig. 2. The CD can be calculated using...
flow conservation constraints. The fuzzy linear programming problem is solved using the approach proposed by Herrera and Verdegay (1995) where the problem with fuzzy objective coefficients can be transformed to a multiple criteria linear programming one
\[
\begin{align*}
\min (c^1x, c^2x, \ldots, c^p x) \\
\text{subject to } Ax &\leq b \\
& x \geq 0 \\
& c^k \in E(\alpha) \\
& \alpha \in [0, 1] \quad k = 1, 2, \ldots, p
\end{align*}
\]
where \(c^k\) denotes a vector that combines the upper and lower \(\alpha\)-bounds of the fuzzy coefficients; \(c^k\) and \(p\) denote the number of the fuzzy objective coefficients. In addition, \(E(\alpha)\) represents the set of the vectors consisting of bounds of \(\alpha\)-cuts. Since each element of the vector \(c^k\) has two possible values (i.e., the upper and lower \(\alpha\)-bounds of the fuzzy coefficients), there are totally \(2^p\) possible values of \(c^k\). For example, \(c^k\) contains all the lower \(\alpha\)-cuts of the fuzzy coefficients while \(c^k\) contains all the upper \(\alpha\)-cuts of the fuzzy coefficients. The multiple criteria problem can be solved using a weighting method through assigning weights \((ww, w_2, \ldots, w_e)\) to various criteria with \(\sum w_e = 1\). The problem formulation becomes as follows:
\[
\begin{align*}
\min (ww_1 c^1x + ww_2 c^2x + \cdots + w_{w_e} c^p x) \\
\text{subject to } Ax &\leq b \\
& x \geq 0
\end{align*}
\]
Notably, decision makers can assign the values of weights. For example, an optimistic combination is obtained by assigning \(ww = (1, 0, \ldots, 0)\), implying that the lower \(\alpha\)-bounds of all the impedances are adopted in the objective function. In other words, only the first term of the objective function in (9) exists, the other terms are equal to zero. When \(ww = (1, 0, \ldots, 0)\), since the left cuts of the impedances are adopted and the impedances tend to be underestimated, we call it an optimistic case. In contrast, the pessimistic combination is obtained by assigning \(ww = (0, 0, \ldots, 1)\). After assigning the weights, the fuzzy linear programming model can be solved by using ordinary linear programming solvers.

ILLUSTRATIVE EXAMPLE: WASTE SOIL TRANSPORTATION FOR KAOSHIUNG MASS RAPID TRANSIT SYSTEM CONSTRUCTION

The illustrative problem addresses waste soil transportation planning for the Kaohsiung mass rapid transit system (KMRT) construction project in Taiwan. Kaohsiung is the second-largest city in Taiwan with more than 3 million inhabitants. Construction of the KMRT is expected to commence shortly and includes a 42.7-km-long railroad and 37 stations. The system consists of two lines; the Orange line is south–northbound and the Red line is east–westbound. The project is mainly conducted under ground using open excavation and shield tunneling. As estimated, the amount of waste soil generated during construction in the Orange line exceeds 4.1 million m³, while the waste soil generated in Red line construction surpasses 3.9 million m³. Except for 0.74 million m³ of waste soil transported to the main maintenance plant construction site, the rest is sent to the Nan-Sing tidal land project.Transporting this large amount of waste soil generated from various construction sites can negatively impact the local residents. For example, the total daily amount of waste soil will surpass 13,000 m³, implying a daily traffic load of 1,300 trucks during the construction period.
Phase I: Fuzzy AHP

A fuzzy hierarchical structure is constructed to evaluate the fuzzy composite impedance for each road sector. The hierarchical structure consists of four levels: overall goals, actors, main criteria, and subcriteria. Twenty-one decision makers, including seven local residents, seven transportation agencies, and seven government officials, are involved to determine the criteria weights in the fuzzy AHP. Average speed according to the service level rating is adopted to represent the traffic load. The criterion of transportation cost considers the travel distance, travel time, and the number of bridges and underground tunnels along the route. The criterion of environmental impact considers the type of districts, number of schools and hospitals, and the population along the road.

Responses to pairwise comparison questions are collected to obtain the fuzzy paired comparison matrices. The approach described in the Fuzzy Composite Impedance Evaluation section is used to obtain the weights in the fuzzy analytic hierarchic structure. The weights from multiple decision makers are aggregated using a geometric mean as in (2). Fig. 3 shows the resulting fuzzy weights where R, G, and A denote the results based on the responses of local residents, governmental officers, and transportation agencies, respectively. The right-hand-side of this figure contains the composite weights that were used to calculate the overall impedance.

The attribute values of each road sector including average speed, length of the road, number of bridges and tunnels, district type, number of schools and hospitals, and population density are adopted from the Kaohsiung City Government and Institute of Transportation, Ministry of Transportation, and Communications. Since the data are geographical, we utilize a geographical information system to store and manage the attribute data of the roads.

Table 1 displays an example of calculating the fuzzy impedance, where the fuzzy composite weights in columns 1 and 2 are multiplied by the fuzzy attribute data in columns 3 and 4 to obtain the fuzzy impedance values for both directions of each road sector. The fact that the attribute values of distance, number of bridges and tunnels, type of districts, and number of schools and hospitals are crisp accounts for why we use three identical values in this table. Since more than one type of district could be along the road sector, the attribute values are obtained by summarizing the multiplication of the lengths of the districts by some weights that were set to be 5 for the residential area, 3 for the commercial district, and 1 for the industrial district. The attribute values of average speeds and the travel time are fuzzy numbers where the peak, average, and off-peak speed are used to determine the upper, medium, and lower bounds of the fuzzy numbers. The population near the road sector is estimated by multiplying the population density by the area within a 50 m distance from the road. Twenty percent of the estimated population is taken as the range of the fuzzy bounds. Notably, each attribute value in Table 1 was normalized by dividing by the maximal value of the attribute values of all road sectors.

Phase II: Fuzzy Mathematical Programming

After the fuzzy impedance of the roads is obtained, the fuzzy mathematical model can be built. The method discussed in the Fuzzy Mathematical Programming Models section is used to solve for the optimal transportation quantities and routes. Because the transportation in both directions for most of the roads is considered, the problem contains as many as 918 decision variables and 280 constraints. The linear programming problem is solved using CPLEX (1994) in IBM-RISC6000 workstation.
First, an optimal route is solved for the waste soil generated from a single station excavation site (O-4). The waste soil is hauled to the main maintenance plant located in southeastern Kaohsiung. The fuzzy impedances (α-cut at α = 1) of all the roads are used as the objective coefficients to find the optimal shortest route. In other words, there is only one term of the objective function in (9) that exists, and the coefficients are equal to the composite impedance values at α = 1. This is a simplification of (9) where the impedances are denoted by two values (when 0 < α < 1) and the objective function could have 2α terms. The decision variables xij in formulation (7) are 0/1 variables in the model. For comparison, the optimal route using the proposed approach and the shortest path by minimizing the travel distance are presented. Fig. 4 depicts the optimal route (S-A) using the proposed approach while Fig. 5 shows the shortest path (S-B) for the waste soil transportation.

Table 2 compares the two resulting routes. The optimal route using the proposed approach has a larger transportation distance and longer transportation time while passing less-sensitive facilities and fewer residential and commercial districts.

![FIG. 4. Optimal Route Using Proposed Approach (α = 1)](image1)

![FIG. 5. Shortest Path by Minimizing Physical Distance](image2)

![FIG. 6. Optimal Transportation Network Using Proposed Approach (α = 1)](image3)

Table 3 compares the two resulting networks. Transportation through network M-A has a longer transportation distance and more travel time but goes through fewer bridges and tunnels and a smaller percentage of residential and commercial areas. Because the routes in network M-B have less average travel distance than those in network M-A, the average number of schools and hospitals on network M-B is less than that in network M-A. However, network M-A takes more diverse routes going through some less densely populated areas to avert environmental and traffic load impact. Moreover, the fact that network M-B relies on a single route for transporting all the waste soil accounts for why the route would suffer from a severe traffic load (1,300 trucks daily).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Network S-A</th>
<th>Network S-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance, km</td>
<td>14.00</td>
<td>12.06</td>
</tr>
<tr>
<td>Number of schools and hospitals</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Number of bridges and tunnels</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Average speed, km/h</td>
<td>19.1, 30.5, 34.9</td>
<td>16.5, 28.1, 35.6</td>
</tr>
<tr>
<td>Average time, min</td>
<td>24.1, 27.6, 44.0</td>
<td>20.3, 25.8, 43.9</td>
</tr>
<tr>
<td>Residential district, %</td>
<td>14.29</td>
<td>33.33</td>
</tr>
<tr>
<td>Commercial district, %</td>
<td>14.29</td>
<td>38.89</td>
</tr>
<tr>
<td>Industrial district, %</td>
<td>35.71</td>
<td>11.11</td>
</tr>
</tbody>
</table>
CONCLUSIONS

This study presents a novel two-phase approach to address the multiple criteria transportation planning problem for industrial waste. First, fuzzy impedance representing the composite penalty including transportation cost, traffic load, and environmental impact for hauling waste through each road sector is evaluated using the fuzzy AHP method. Group decision makers are involved in determining criteria weights used in the process. In the second phase, fuzzy mathematical programming models are solved to obtain the optimal transportation network for the waste where objective function coefficients are fuzzy.

An illustrative example using the proposed approach is applied to transportation planning for waste soil generated by the Kaohsiung mass rapid transit system construction project. The solutions using the proposed approach are compared with solutions that simply minimize the total distance traveled. The FAHP solutions can consider environmental impact and therefore include multiple routes that pass through rural and industrial areas while the least-costly solutions contain the routes with a heavy traffic load passing through the highly populated areas of the city. Because a multiattribute decision process is used in the proposed approach, the resulting optimal routes tend to cause less traffic congestion and environmental impact upon the local residents.

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