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A MULTIOBJECTIVE PROGRAMMING APPROACH FOR SELECTING NON-INDEPENDENT TRANSPORTATION INVESTMENT ALTERNATIVES

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Abstract—This article presents a new method for **SE**lecting **N**on-independent **T**Ransportation investment **A**lternatives (SENTRA). This method utilizes effective distance heuristic algorithm which attempts to maximize the achieved objectives needed to satisfy available resources. Since transportation investment planning cannot avoid dealing with issues of interdependence among alternatives, this paper will consider four types of investment alternatives: independence, complementarity, substitution and common complementary substitution. Transportation investment alternative selection problem can be formulated in terms of the 0-1 multiobjective multidimensional knapsack problem. Possessing the characteristics of NP-completeness, strict computation is not necessary for the optimal solution, but simple computation for near-optimal solution is expected. The method is proposed in this paper so as to attain the near-optimal solution, which, aside from ranking the selected transportation investment alternatives, can easily perform sensitivity analysis. Finally, an example is presented to illustrate the method. Copyright © 1996 Elsevier Science Ltd

1. INTRODUCTION

Traditional transportation investment decision problems mostly would use Cost-Benefit Analysis (CBA) (Button & Pearman, 1983) to achieve the optimal single objective of profit maximization or cost minimization. To attain to this objective, traditionally three assessment methods, net present worth, benefit/cost ratio and rate of return, would mainly be applied for the evaluation (Stopher & Meyburg, 1976). The major issue of CBA lies in changing all economic and non-economic factors into monetary worth and whether the method of exchange is objective remains controversial; also, CBA cannot accommodate our needs as a diversified society nowadays as it only considers the optimal single objective.

Under this complex social system, transportation investment involves many interested stakeholders and its decisions must be traded off among numerous objectives of conflict. Thus, the agreement cannot be reached by single objective decision-making method; Therefore, the application of multiple criteria decision-making (MCDM) to research cases of transportation investment planning increases, such as Hill (1973), de Neufville and Keeney (1973), Saaty (1977), Friesz *et al.* (1980), Roy and Hugonnard (1982), Leinbach and Cromley (1983), Giuliano (1985), Roy *et al.* (1986), Pak *et al.* (1987), Khorranshahgol and Steiner (1988), Pearman *et al.* (1989), Gomes (1989), Won (1990) and Azis (1990).

Multiple objective mathematical programming (MOMP) is one of the branches of MCDM (Massam, 1988). It focused on constructing transportation investment decision problems into mathematical programming model. And then the solutions will be found

by using such methods as weighting method (Friesz *et al.*, 1980), goal programming (GP) (Leinbach & Cromley, 1983; Khorranshahgol & Steiner, 1988) and compromise programming (CP) (Giuliano, 1985; Won, 1990). When resource constraints are taken into account, transportation investment decision problems will be singled out from several known investment alternatives and investment placed on the desirable ones. As a result, the limited resources can be used to the greatest efficiency so as to achieve objective maximization. Among MultiObjective Transportation Investment Alternative Selection (MOTIAS) problems, decision variables are actually on investment alternatives and the final results are of two types: 0 (unselected) and 1 (selected). Therefore, they are grouped as 0–1 multiobjective multidimensional knapsack problems.

Since the multiobjective multidimensional knapsack problem owns the characteristic of NP-completeness, it might not be able to devise an exact and effective algorithm for the non-inferior solutions or optimal solution. In view of it, the application of heuristic algorithm could be seen as an effective alternative. In the selection of the transportation investment alternatives, in the article, the use of effective distance in heuristic algorithm for a solution substantiates the answer having the same approximate solution (Teng and Tzeng, 1991) as found from effective gradient algorithm by Toyoda (1975). The effective distance algorithm computation proposed in the article is simple and practical, and can be used in selecting the transportation investment alternatives. When the amount of available resource changes, sensitivity analysis can be proceeded effortlessly, overcoming current difficulties in GP, CP, and MOMP methods.

In the past applications of MCDM to transportation investment decision problems for evaluation, only Gomes (1990) had investigated the interdependence of urban transportation system alternatives, while others concentrated on managing the independence of investment alternatives. Actually, in terms of the characteristics of transportation investment decision problems, a certain degree of interdependence does exist among transportation investment alternatives. For instance, some level of substitution prevails between high-speed railroad and freeway; freeway and port are marked by their complementarity. As the article heads onto the selection of transportation investment alternatives, this significant feature will be deliberated.

In the second section of the article MOTIAS problems will be elaborated. In the third section decision methods on the interdependence of transportation investment alternatives will be put forward. In the fourth section the effective distance heuristic algorithms are explained. In the fifth section the numerical example of transportation investment alternative selection will be presented so as to explain the proposed solution method in the article, while those left are the conclusion and some other future research approaches.

2. MULTIOBJECTIVE TRANSPORTATION INVESTMENT ALTERNATIVE SELECTION PROBLEM

Transportation investment alternative selection is a typically discrete multiobjective decision problem, in other words, its transportation investment alternative is a given situation. MOTIAS can be defined as the selected n_1 ($n_1 \leq n$) preferable investment decision problem of transportation investment alternative among n feasible and limited investment alternatives x_1, x_2, \dots, x_n , according to m objectives Z_1, Z_2, \dots, Z_m to be achieved, and under q resource constraints B_1, B_2, \dots, B_q . Mathematically speaking, MOTIAS problem can be denoted as:

$$\text{MOTIAS (1): maximize } Z(x) = (Z_1(x), \dots, Z_m(x)) = Gx \quad (1a)$$

subject to

$$x \in X = \{Ax \leq B; x_j = 0 \text{ or } 1; j = 1, 2, \dots, n\} \quad (1b)$$

$Z(x)$ is the m dimensional vector $\{Z_i(x)\}$ for m objectives, G is the $m \times n$ matrix $\{G_{ij}\}$, whereas its element G_{ij} indicates investment alternative x_j has achieved Z_i objective value ($i=1, 2, \dots, m; j=1, 2, \dots, n$), x is the constructed n dimensional decision vector $\{x_j\}$ for n transportation investment alternatives; if x_j is selected then $x_j=1$, otherwise $x_j=0$. X is the

feasible set; A is the $q \times n$ matrix $\{A_{kj}\}(k=1,2,\dots,q; j=1,2,\dots,n)$ it reveals the needed q resource amount for n investment alternatives, and B is the vector $\{B_k\}$ built under q resource constraints.

MOTIAS decision problem, not only considers the fulfillment of maximization of m objectives, but is also anticipated to fully use the offered resource amount, which is not to be left idle. In other words, the smaller the difference between the needed q resource amount for the selected investment alternatives and the amount able to be provided by q resources, the better it is. Thus, MOTIAS problem needs to add the minimal resource–idleness into the objective formula

$$\text{MOTIAS (2): maximize } Z_i(x) = \sum_{j=1}^n G_{ij}x_j, \quad i = 1, 2, \dots, m \tag{2a}$$

$$\text{minimize } H_k(x) = B_k - \sum_{j=1}^n A_{kj}x_j, \quad k = 1, 2, \dots, q \tag{2b}$$

$$\text{subject to } x \in X \tag{2c}$$

where, $H_k(x)$ indicates the resource-idle situation of k th resource.

If the interdependence of transportation investment alternatives are taken into account, the achieved value by m objectives should include not only the aggregation of a separate value of the selected investment alternative, also the increased value due to complementarity or decreased value due to substitution. So, MOTIAS (2) problem can be rewritten as MOTIAS (3) problem

$$\text{MOTIAS (3): maximize } Z_i(x) = \sum_{j=1}^n G_{ij}x_j + R_i^*(x), \quad i = 1, 2, \dots, m \tag{3a}$$

$$\text{minimize } H_k(x) = B_k - \sum_{j=1}^n A_{kj}x_j, \quad k = 1, 2, \dots, q \tag{3b}$$

$$\text{subject to } x \in X \tag{3c}$$

where $R_i^*(x)$ indicates the increased or decreased achieved value of i th objective due to complementarity or substitution.

If q resources can be supplied sufficiently and n transportation investment alternatives are all chosen, the will-be achieved value by m objectives is the greatest and is shown as $Z_i^*(x)$

$$Z_i^*(x) = \sum_{j=1}^n G_{ij} + R_i^*(x), \quad i = 1, 2, \dots, m \tag{4}$$

where, $R_i^*(x)$ indicates if all n transportation investment alternatives are selected, the achieved value of i th objective is the increased or decreased value due to complementarity or substitution. As a matter of fact, this ideal value is rather uneasy to reach, because the available resource amount is limited. If all possible alternatives are selected, then the needed amount of k th resource for n transportation investment alternatives is L_k , then

$$L_k = \sum_{j=1}^n A_{kj}, \quad k = 1, 2, \dots, q \tag{5}$$

and $L_k > B_k$.

m objectives and q resources have their own weights in each objective and each resource. Let w_i ($i = 1, 2, \dots, m$) and λ_k ($k = 1, 2, \dots, q$) to indicate respectively the weights of

objective i and resource k , then MOTIAS (3) can use scalarization and integrate m objectives and q resource-idle objectives into one single objective. First of all, work on the individual derived degree of m objectives (f_{ij}) of transportation investment alternatives as well as the needed amount of q resources with normalization (h_{ij}):

$$f_{ij} = G_{ij}/Z_i^*(x), \quad \forall i,j \tag{6}$$

$$h_{ij} = A_{kj}/B_k, \quad \forall i,j \tag{7}$$

Then according to the weights $W = \{w_i\}$ of m objectives and $\lambda = \{\lambda_k\}$ of q resources, integrate m objective formula and q resource-idle objectives formula into one single objective formula. Thus, MOTIAS (3) problem will become biobjective MOTIAS (4) problem:

$$\text{MOTIAS (4): maximize } \varnothing(x) = \sum_{i=1}^m \sum_{j=1}^n w_i f_{ij} x_j + r(x) \tag{8a}$$

$$\text{minimize } \Pi(x) = \sum_{k=1}^q \lambda_k (1 - \sum_{j=1}^n h_{kj} x_j) \tag{8b}$$

$$\text{subject to } x \in X = \{x_j \mid Hx \leq 1, x_j = 1 \text{ or } 0; j = 1, 2, \dots, n\} \tag{8c}$$

Where, $\varnothing(x)$ is the scalar derived after combining m objectives. $\Pi(x)$ is the scalar integrating q idle resources. $r(x)$ indicates the scalar of m objectives with either increased or decreased value after normalization. $H = \{h_{kj}\}$ is the matrix of the needed q resources for n investment alternatives after normalization.

3. DETERMINATION OF DEGREE OF INTERDEPENDENCE

Transportation investment alternatives have a certain degree of interdependence among themselves, and their degree of interdependence varies as every single objective changes. Under every objective, several factors influence the degree of interdependence of investment alternatives. Besides, some of these factors cannot be evaluated objectively.

Under such a situation, it was proposed in this article that a group of specialists of relevant expertise should be set up to provide professional recognition and judgment, to obtain the effects of team work and think tank, to canvas various opinions and benefits from a team group to reduce individual bias.

Based on interdependent characteristics, transportation investment alternatives are classified as independent alternatives, complementary alternatives, substitutive alternatives and common complementary substitutive alternatives in this article (as shown in Fig. 1).

3.1. Independent investment alternatives

Independent investment alternatives are those whose performance of all m objectives has been attained and will not be affected by other alternatives and vice versa. The set of independent investment alternatives is denoted in A^I . If x_j and $x_{j'}$ are two independent investment alternatives, then x_j will not affect $x_{j'}$, and $x_{j'}$ will not affect x_j either: It can be expressed either in $x_j I x_{j'}$ or $x_{j'} I x_j$ and its influences of investment results are shown in Fig. 1(a).

3.2. Complementary investment alternatives

Complementary investment alternatives, whose performance was once attained from objective i , will be influenced by other alternatives and vice versa. Thus when two investment alternatives are implemented at the same time, investment results can also be increased to the designated objective. Yet, complementary investment alternatives do not necessarily have to affect complementarity to all m objectives to be thus dubbed. As long as one or more than one objective is complementary, they are complementary investment alternatives. The set of complementary investment alternatives is denoted by A^C . If x_j and

x_j are two complementarity investment alternatives, $x_j C x_j$ is used to indicate the complementarity of x_j to x_j and $x_j C x_j$ is used to indicate the complementarity of x_j to x_j . Complementary alternatives are shown in Fig. 1(b), and the slant part shows the added performance of $x_j C x_j$ and $x_j C x_j$.

3.3 Substitutive investment alternatives

Substitutive investment alternatives are those which can partly or wholly be substituted by another after performance of i objective is achieved. In other words, another alternative can replace the original one to achieve partial or integral performance of i objective. Substitutive investment alternatives do not have to be substituted for all m objectives to be thus named. Being substitutive to only one or more than one objective, they can be categorized as substitutive investment alternatives. Substitutive investment alternatives will not increase the achieved value of performance, but they can only use one alternative to substitute for the achieved value of another. The set of substitutive investment alternatives is demonstrated with A^S . If x_j and x_j are two substitutive investment alternatives, $x_j S x_j$ indicates x_j substituting to x_j , while $x_j S x_j$ indicates x_j substituting to x_j . Substitutive investment alternatives are shown in Fig. 1(c), the slant line indicates the performance, x_j is replaced by x_j ($x_j S x_j$).

3.4. Common complementary substitutive alternatives

Transportation investment alternative x_j could be complementary to alternative x_j as well as substitutive to alternative x_j [as indicated in Fig. 1(d)]. This form of alternatives is demonstrated with A^{CS} set, which is $A^{CS} = A^C \cap A^S$.

As experts of related fields proceed to the judgment of relevant transportation investment alternatives, two stages can be marked out. At the first stage, experts will move forward to the classification judgment on transportation investment alternatives, while at the second stage experts will produce their judgment on the degree of interdependence of complementary alternatives and substitutive alternatives. If the decision group is formed by R members of related experts, every expert is allowed their subjective recognition and judgment during these two stages; as for the judgment and analysis approach made in the two stages, it is explained as follows:

Stage 1: Discrimination for classification. Among these four types of transportation investment alternatives, once complementary alternatives (A^C) and substitutive alterna-

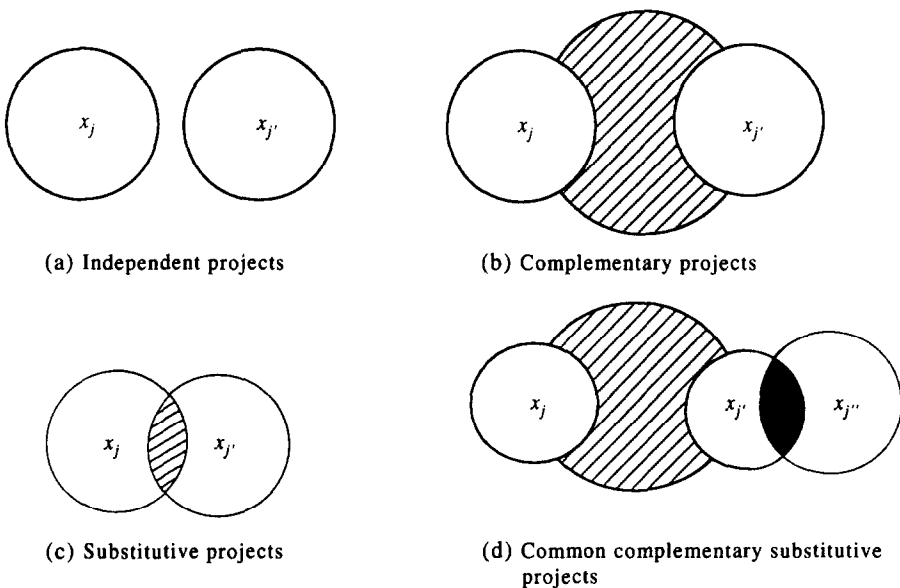


Fig. 1. Effect of different types of investment projects.

tives (A^S) are decided, independent alternatives (A^I) and common complementary substitutive alternatives (A^{CS}) can be found according to the subsequent formulas:

$$A^I = A^T - A^C - A^S - A^{CS} \tag{9}$$

$$A^{CS} = A^C \cap A^S \tag{10}$$

where, $A^T = \{x_1, x_2, \dots, x_n\}$ indicates the set constructed by transportation investment alternatives. Judging from every two investment alternatives, experts can use this pairwise comparison method to judge whether those n transportation investment alternatives listed under m objectives belong to A^C or A^S . Let $d_{jj'}^{hi}$ and $e_{jj'}^{hi}$ for instance, they denote separately that under i objectives ($i = 1, 2, \dots, m$) experts h ($h = 1, 2, \dots, R$) judge investment alternatives x_j and $x_{j'}$ ($j, j' = 1, 2, \dots, n; j \neq j'$) possess the judgment value of complementarity and substitution; when the value of $d_{jj'}^{hi}$ and $e_{jj'}^{hi}$ is 1, it says x_j and $x_{j'}$ are mutually complementary and substitutive. If the value is 0, it denotes x_j and $x_{j'}$ are non-complementary and non-substitutive, that is

$$d_{jj'}^{hi} = \begin{cases} 1, & \text{if } x_j C x_{j'} \text{ or } x_{j'} C x_j \\ 0, & \text{otherwise} \end{cases} \tag{11}$$

$$e_{jj'}^{hi} = \begin{cases} 1, & \text{if } x_j S x_{j'} \text{ or } x_{j'} S x_j \\ 0, & \text{otherwise} \end{cases} \tag{12}$$

Thus, R binary complementary judgment matrix $D^{hi} = \{d_{jj'}^{hi}\}$ and R binary substitutive judgment matrix $E^{hi} = \{e_{jj'}^{hi}\}$ can be obtained under every objective. D^{hi} and E^{hi} are not exactly symmetric matrices, mainly because x_j is complementary or substitutive to $x_{j'}$, but it does not denote $x_{j'}$ is also complementary or substitutive to x_j . Let D^{Ti} and E^{Ti} for example, indicate individually that the judgment matrix is possible complementarity and substitution and are synthetic of n transportation investment alternative under i objective by R experts, thus

$$D^{Ti} = \{d_{jj'}^{Ti} | d_{jj'}^{Ti} = \sum_{h=1}^R d_{jj'}^{hi}, j, j' = 1, 2, \dots, n; j \neq j'\} \quad \forall i \tag{13}$$

$$E^{Ti} = \{e_{jj'}^{Ti} | e_{jj'}^{Ti} = \sum_{h=1}^R e_{jj'}^{hi}, j, j' = 1, 2, \dots, n; j \neq j'\} \quad \forall i \tag{14}$$

Similarly, D^{Ti} and E^{Ti} are not necessarily symmetric matrices. D^{Ti} and E^{Ti} are the synthetic opinions of R experts, and whether the transportation investment alternatives are complementary or substitutive under a i objective can be determined by the following formulas:

$$d_{jj'}^{Ti} \geq M, 1 \leq M \leq R \tag{15}$$

$$e_{jj'}^{Ti} \geq M, 1 \leq M \leq R \tag{16}$$

where, the value of M can be resolved by R experts through discussion in this article, the value of M is taken according to majority rule as follows:

$$M = \begin{cases} (R/2) + 1, & R \text{ is even} \\ [(R-1)/2] + 1, & R \text{ is odd} \end{cases} \tag{17}$$

In other words, as long as half of the decision group experts consider x_j and $x_{j'}$ complementary or substitutive x_j and $x_{j'}$ can be regarded as complementary alternatives or substitutive alternatives.

Stage 2: Decision of degree of complementarity and degree of substitution. According to the derived set of A^S and A^C at the first stage, R experts will judge upon the degree of complementarity and substitution of the set's investment alternatives. Let $r_{jj'}^{hi}$ and $\theta_{jj'}^{hi}$ be examples; they indicate the degree of complementarity and substitution of investment

alternatives under i objectives ($i = 1, 2, \dots, m$) as experts h ($h = 1, 2, \dots, R$) judge x_j and $x_{j'}$ ($j, j' = 1, 2, \dots, n; j \neq j'$) as a result, R complementary matrix C^{hi} and substitutive matrix S^{hi} can be obtained, that is

$$C^{hi} = \{r_{jj'}^{hi} | 0 \leq r_{jj'}^{hi} \leq 1; j, j' \in A^c\}, \quad \forall i \tag{18}$$

$$S^{hi} = \{\theta_{jj'}^{hi} | 0 \leq \theta_{jj'}^{hi} \leq 1; j, j' \in A^s\}, \quad \forall i \tag{19}$$

If $r_{jj'}^{hi}$ or $\theta_{jj'}^{hi}$ is 0, it denotes that x_j and $x_{j'}$ investment alternatives are not complementary or substitutive are considered by h experts under objective i ; if $r_{jj'}^{hi}$ or $\theta_{jj'}^{hi}$ is 1, then x_j and $x_{j'}$ investment alternatives are wholly complementary or substitutive.

In the investment alternatives within A^C set, there are R notions of views toward its degree of complementarity; if these R judgment values are ranked synthetic judgment matrix C^{Ti} by R experts will be reached as follows

$$C^{Ti} = \{r_{jj'}^{hi} | j, j' \in A^C; h' = 1, 2, \dots, R'\} \quad \forall i \tag{20}$$

where

$$\hat{r}_{jj'}^{hi} = \{\hat{r}_{jj'}^{h1} \geq \hat{r}_{jj'}^{h2} \geq \dots \geq \hat{r}_{jj'}^{hR'}\} \tag{21}$$

$$\hat{r}_{jj'}^{hi} = \text{Max}_{h=1, 2, \dots, R} \{r_{jj'}^{hi}\}; j, j' \in A^C \tag{22}$$

$$\hat{r}_{jj'}^{R'i} = \text{Min}_{h=1, 2, \dots, R} \{r_{jj'}^{hi}\}; j, j' \in A^C \tag{23}$$

Similarly, synthetic judgment matrix S of the substitution degree of investment alternatives within A set is found as follows

$$S^{Ti} = \{\hat{\theta}_{jj'}^{hi} | j, j' \in A^S; h' = 1, 2, \dots, R'\} \quad \forall i \tag{24}$$

where

$$\hat{\theta}_{jj'}^{hi} = \{\hat{\theta}_{jj'}^{h1} > \hat{\theta}_{jj'}^{h2} > \dots > \hat{\theta}_{jj'}^{hR'}\} \tag{25}$$

$$\hat{\theta}_{jj'}^{hi} = \text{Max}_{h=1, 2, \dots, R} \{\theta_{jj'}^{hi}\}; j, j' \in A^S \tag{26}$$

$$\hat{\theta}_{jj'}^{R'i} = \text{Min}_{h=1, 2, \dots, R} \{\theta_{jj'}^{hi}\}; j, j' \in A^S \tag{27}$$

The degree of complementarity and degree of substitution of transportation investment alternatives $CC_{jj'}^i$ ($j, j' \in A$) and $SC_{jj'}^i$ ($j, j' \in A$) can be decided by the following formulas:

$$CC_{jj'}^i = \hat{r}_{jj'}^{Mi}, 1 \leq M \leq R \tag{28}$$

$$SC_{jj'}^i = \hat{\theta}_{jj'}^{Mi}, 1 \leq M \leq R \tag{29}$$

where, value of M can be reached by R experts working together, yet the final decision is made by majority rule here, that is value M will be reached through formula (9) and the judgment value of more than half of the group experts is greater than $\hat{r}_{jj'}^{Mi}$ and $\hat{\theta}_{jj'}^{Mi}$. In other words, $\hat{r}_{jj'}^{Mi}$ and $\hat{\theta}_{jj'}^{Mi}$ are judgment values with majority rule of the group experts. To back these judgments up with even stronger consensus, principles as “two thirds of the experts share common-views” or “three fourths of the experts share common-views” can be employed.

4. EFFECTIVE DISTANCE HEURISTIC ALGORITHM

Four types of investment alternatives A^I, A^C, A^S, A^{CS} are derived from n transportation investment alternatives within A^T after R experts integrated their judgments. Thus, n investment alternatives can all be selected for investment if q resources are fully supplied, and the total performance value $Z_i^*(x)$ of the achieved i objective is the performance value which aggregate of every investment alternative in A^I, A^C, A^S sets. However, the

duplicate computation of every investment alternative in A^{CS} set should be excluded, that is

$$Z_i^*(x) = \sum_{j \in A^I} G_{ij} + [\sum_{j \in A^C} G_{ij} + \sum_{j,j' \in A^{CS}} (CC_{jj'}^i G_{ij'} + CC_{ji}^i G_{ij})] + \{ \sum_{j \in A^S} G_{ij} + \min[\sum_{j,j' \in A^S} (SC_{jj'}^i G_{ij'} - SC_{ji}^i G_{ij}), 0] - \sum_{j \in A^{CS}} G_{ij} \}, \quad \forall i \tag{30}$$

where, the first item is the attained performance value of the investment alternatives within set A^I . The second item is the attained performance value of the investment alternatives within set A^C , and it included the increased performance value due to complementary effect. The third item is the attained performance value of the investment alternatives within set A^S , and it also included the reduced value due to substitutive effect. Since such substitutive effect could not enhance performance value, it is certain that this substitutive effect was not a positive value. As for the fourth item, it is the attained performance value of the invest value of the investment alternatives themselves within set A^{CS} and this value has to be deducted because it has already been taken into computation in the second and third items. Formula (30) can be summarized as

$$\begin{aligned} Z_i^*(x) &= \sum_{j \in A^I} G_{ij} + R_i^*(x) \\ &= \sum_{j \in A^I} G_{ij} + \{ \sum_{j,j' \in A^C} (CC_{jj'}^i G_{ij'} + CC_{ji}^i G_{ij}) \\ &\quad + \min[\sum_{j,j' \in A^S} (SC_{jj'}^i G_{ij'} - SC_{ji}^i G_{ij}), 0] \}, \quad \forall i \end{aligned} \tag{31}$$

According to the ideal value $Z_i^*(x)(i=1,2,\dots,m)$ of m objectives and the amount provided by q resources, $B_k (k=1,2,\dots,q)$, formulas (6) and (7) can be used for normalizations, and transform such transportation investment alternative selection problems into MOTIAS (4). Before further elaboration on effective distance methods to solve MOTIAS (4), definitions on symbols must be done first: t : iteration; I_t : set of accepted investment alternatives; A^T_t : set of all investment alternatives; P_j : vector of objective performance achieved by x_j , i.e.

$$P_j = (f_{1j}, \dots, f_{ij}, \dots, f_{mj}), \text{ for any } j. \tag{32}$$

G'_i : the performance value on i objective by all investment alternatives within the set I_t :

$$\begin{aligned} G'_i &= \sum_{j \in I_t} f_{ij} + \sum_{j,j' \in (U_t \cap A^{CS})} (CC_{jj'}^i f_{ij'} + CC_{ji}^i f_{ij}) \\ &\quad + \min\{ (\sum_{j,j' \in (U_t \cap A^S)} (SC_{jj'}^i f_{ij'} - SC_{ji}^i f_{ij}), 0 \}, \quad \forall i \end{aligned} \tag{33}$$

G'_t : vector of m objective performance respectively achieved by all investment alternatives within the set I_t

$$G'_t = (G'_1, \dots, G'_i, \dots, G'_m) \tag{34}$$

U_j : necessary resource requirement vector for x_j , i.e.

$$U_j = (h_{1j}, \dots, h_{kj}, \dots, h_{qj}), \quad \forall j \tag{35}$$

R'_k : k 's resource requirement by all investment alternatives within the set I_t

$$R'_k = \sum_{j \in I_t} h_{kj}, \quad \forall k \tag{36}$$

R' : vector performance of all investment alternatives using q resource respectively within the set I ,

$$R' = (R'_1, \dots, R'_k, \dots, R'_q) \tag{37}$$

F_t : set of candidate investment alternatives under the condition of fulfilling resource constraint

$$F_t = A_t^T \setminus \{x_j \in A_t^T \mid R'_k + h_{kj} > 1, \exists k\} \tag{38}$$

Next, we will explain the concept and meanings of effective distance of objective achievement and effective distance of resource utilization. During the process of t th ($t > 1$) iteration, objective achievement space can be categorized as the achieved region and unachieved region. The former is the achieved part of the selected transportation investment alternatives aimed at m objectives before t times, and that is the vector G^{t-1} coverage domain of the attained m objectives within set I_t investment alternatives. The latter is the constructed domain above its objective space after having deducted achieved value from the ideal value of every objective. Take two objectives ($m=2$) for example. If $t = 1$, objective space will then entirely be unachieved region [as shown on Fig. 2(a)]; if $t > 1$ the achieved region is the black color part as shown on Fig. 2(b) and the unachieved region will be covered by (GHZ^*E) .

In the unachieved region during t th iteration, there is $(n-t+1)$ selection range of investment alternatives from the starting point (i.e. the position of vector G^{t-1}) to the ideal solution (Z^*); each workable choice of investment alternative can be seen as a path which includes two links. The former link is the achieved m objectives part of the alternative and its length is shown by distance d_{ij}^{gn+} , while the latter link is the unachieved m objective part of the alternative and its length is shown with distance d_{ij}^{gn} . Thus, the total of these two links will be the length d_{ij}^{gn} of each path. When the relative importance m objectives and interdependency of investment alternatives are considered, the length of every path can be shown by weighting in Euclidian distance as follows

$$d_{ij}^{gn} = d_{ij}^{gn+} + d_{ij}^{gn}, \quad j \in F_t \tag{39}$$

$$d_{ij}^{gn+} = \left[\sum_{i=1}^m (w_i Q_{ij}^{gt})^2 \right]^{1/2}, \quad j \in F_t \tag{40}$$

$$d_{ij}^{gn} = \left\{ \sum_{i=1}^m W_i^2 [1 - (G_i^{t-1} + Q_{ij}^{gt})^2] \right\}^{1/2}, \quad j \in F_t \tag{41}$$

where $Q_{ij}^{gt} = f_{ij}, j \in (F_t \cap A^I)$ (42)

$$Q_{ij}^{gt} = f_{ij} + \left\{ \sum_{j' \in I_t} [CC_{ij'} f_{ij'} + CC_{j'i} f_{ij'}] \right\}, \quad j \in (F_t \cap A^C) \tag{43}$$

$$Q_{ij}^{gt} = f_{ij} - \text{Min} \left\{ \sum_{j' \in I_t} [SC_{ij'} f_{ij'}, 0] \right\}, \quad j \in (F_t \cap A^S) \tag{44}$$

$$Q_{ij}^{gt} = f_{ij} + \left\{ \sum_{j' \in I_t} [CC_{ij'} f_{ij'} + CC_{j'i} f_{ij'}] \right\} - \text{Min} \left\{ \sum_{j' \in I_t} [SC_{ij'} f_{ij'}, 0], j \in (F_t \cap A^{CS}) \right\} \tag{45}$$

To achieve the path of ideal solution Z^* through investment alternative x_j in t th iteration, their achieved and unachieved distances of objective link being d_{ij}^{gn+} and d_{ij}^{gn} will be decided upon the interdependency between x_j ($x_j \in F_t$) and the selected investment alternatives $x_{j'}$ ($j' \in I_t$). If they are complementary, d_{ij}^{gn+} will increase; if they are substitutive d_{ij}^{gn+} will decrease. If they are both complementary and substitutive, d_{ij}^{gn+} can only be

decided upon cases. Take Fig. 2 (b) for instance, its achieved objective link is from point G to Q'_j , rather than from point G to P'_j since x_j and x_j are complementary, and the unachieved objective link is from Q'_j to Z_j^* . Under substitutive situations [as eqn (43) indicated], only substitution degree of the selected investment investment alternative x_j ($j' \in I_i$) toward the unselected investment alternative is calculated; as for the substitution degree of x_j toward $x_{j'}$, since the fact that x_j has been selected cannot be changed, it is not appropriate to take this substitution degree ($SC_{jj'}$) into the calculation of objective performance value of the unselected investment alternative.

Therefore, in the t th iteration, the definition of the objective efficiency index PI_{ij}^g of investment alternative's unachieved region is

$$PI_{ij}^g = d_{ij}^{g^{w+}} / d_{ij}^{g^{w-}} \tag{46}$$

This index indicated the actual achieved effective distance x_j investment alternative to the path of ideal solution Z^* . The greater the value of PI_{ij}^g , the higher the degree of achieving m objectives in the investment alternative x_j .

In the resource utilization space, every iteration process can be divided into two parts: the utilized region and unutilized region. While the former is the region of selected investment alternative using q resource amount, the latter is the region of the amount of available resource with the amount of used resource deducted. Take two kinds of

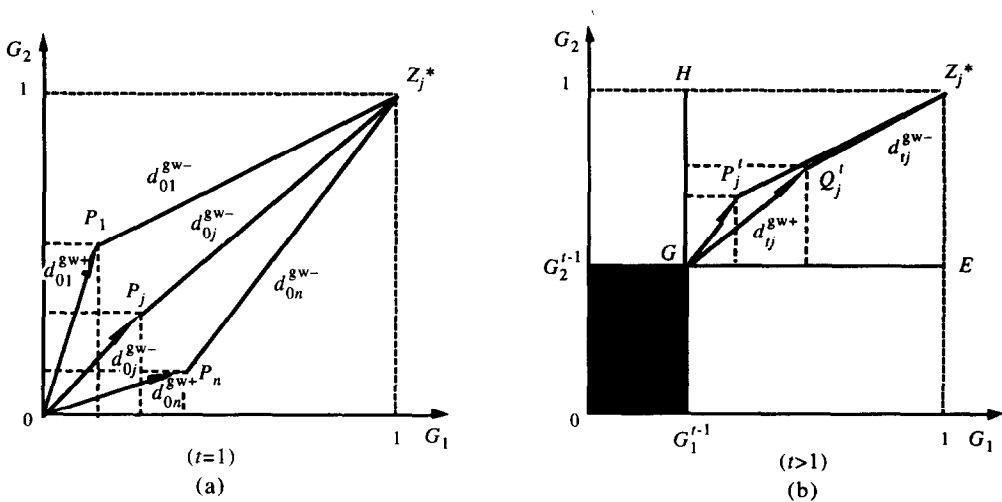


Fig. 2. The effective distance of objective achievement.

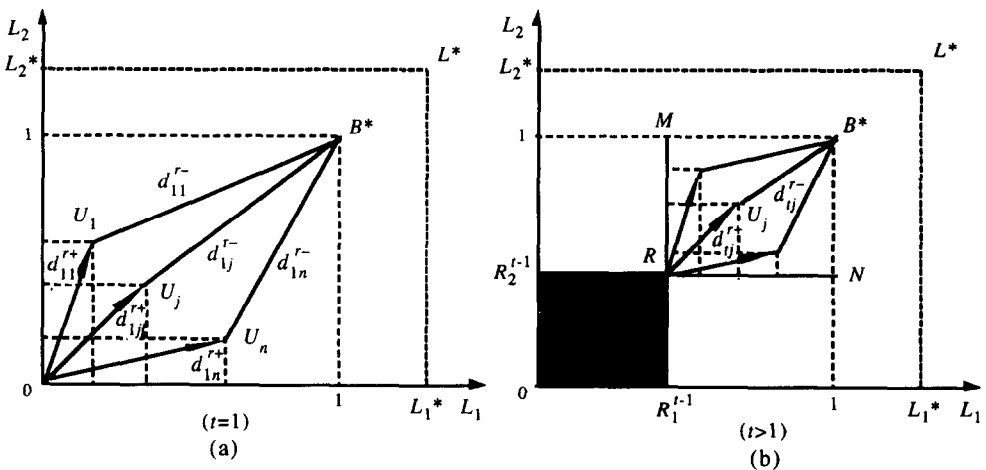


Fig. 3. The effective distance of resource utilization.

resources ($q=2$) for example; if $t=1$ resource space will be wholly a unutilized region [as shown on Fig. 3(a)]; if $t > 1$ the utilized region will be the black part [as shown on Fig. 3(b)], and the unutilized region will be the coverage by $RMB * N$.

In the unutilized region throughout t th iteration, there are good $(n-t+1)$ paths between the starting point (i.e. the position of vector R^{t-1}) to the greatest supply point B^* , and every path has its utilized resource link and unutilized resource link. The link length from the investment alternative x_j ($j \in F_t$) to its greatest resource supply point B^* will be indicated by d_{ij}^{n+} ; if the relative importance of q resource amount is considered, then d_{ij}^{n+} shows the weighting Euclidian distance of this path. d_{ij}^{n+} is the total of utilized link distance d_{ij}^{n+} and unutilized resource link distance d_{ij}^{n-} , that is

$$d_{ij}^{n+} = d_{ij}^{n+} + d_{ij}^{n-}, \quad j \in F_t \tag{47}$$

$$d_{ij}^{n+} = \left[\sum_{k=1}^q (\lambda_k h_{kj})^2 \right]^{1/2}, \quad j \in F_t \tag{48}$$

$$d_{ij}^{n-} = \left\{ \sum_{k=1}^q \lambda_k^2 \left[1 - \left(\sum_{j' \in F_t} h_{kj'} + h_{kj} \right)^2 \right] \right\}^{1/2}, \quad j \in F_t \tag{49}$$

Therefore, the resource utilization efficiency index PR_{ij} of x_j investment alternative at unutilized region in t iteration can be defined as

$$PR_{ij} = d_{ij}^{n+} / d_{ij}^{n-}, \quad j \in F_t \tag{50}$$

This index reveals the resource effective distance x_j actually utilized on the path from x_j investment alternative to the greatest resource supply point B^* . The greater the value of PR_{ij} is, that the greater the amount of q resources will be utilized by x_j investment alternative.

The achieved state and resource utilization condition of the objective should also be considered during the selection of transportation investment alternatives. With such a thought in mind, the greedy index of the profitability x_j can be thus defined according to PI_{ij} and PR_{ij} indexes in t iteration

$$GI_{ij} = PI_{ij} / PR_{ij}, \quad j \in F_t \tag{51}$$

Obviously, the greater the GI_{ij} value is the higher the profit x_j investment alternative will be derived; Thus, throughout t th iteration the greatest GI_{ij} value will be employed as the selection criterion for x_j ($j \in F_t$) investment alternative, that is

$$x_{j^*} = 1 \text{ if } GI_{ij^*} = \text{Max} \{GI_{ij}\}, \quad j \in F_t \tag{52}$$

Consequently, x_{j^*} ($j^* \in I_{t+1}$) will be the selected investment alternative in t iteration. Such iteration will continue until the greatest supply amount of a certain resource is depleted. According to the preceding elaboration, this article will put forward the solution finding steps of the heuristic algorithm for effective distance, its summary is as follows:

Step 1: Set the initial value

$$t = 1, I_t = \phi, A_t^T = \{x_1^t, \dots, x_n^t\}; x_j^t = 0, \forall j$$

Step 2: Find out respectively the achieved objective value and amount of resource use by all transportation investment alternatives within I_t set according to eqns (33) and (36).

Step 3: Decide the transportation investment alternatives within F_t according to eqn (38). If $F_t = \phi$, then go to step 9.

Step 4: Calculate the weighting Euclidian distance, d_{ij}^{n+} , according to eqns (39) – (45), and then find out the PI_{ij} value according to eqn (46).

Step 5: Calculate the weighting Euclidian distance, d_{ij}^{III} , according to eqns (47)–(49), and then find out the PR value according to eqn (50).

Step 6: Find out GI_{ij} value according to eqn (51), and then selected transportation investment alternative x_{j^*} at t iteration according to eqn (52), that is $x_{j^*} = 1$.

Step 7: $I_{t+1} = I_t \cup \{j^*\}$; $A_{t+1}^T = A_t^T \setminus \{x_{j^*}\}$.

Step 8: $t = t+1$, back to Step 2.

Step 9: Transportation investment alternatives within set I_t are approximate solutions to MOTIAS (4) problem.

Step 10: According to the nature of the independence, complementarity, substitution, common complementary substitution of transportation investment alternatives within set I_t , their respective values will be found through PR_j ($j \in F_t$) and be ranked accordingly.

5. ILLUSTRATED EXAMPLE

5.1. Problem descriptions

The local government of XYZ regions intends to invest on transportation constructions so as to improve the deteriorating traffic situation and to promote development of the regions. After careful planning and evaluation, feasible transportation investment alternatives include 10 items; Such as the construction of new roads, parking lots, and goods distribution center; the widening of existing roads and others. Local government of XYZ regions hopes that transportation investments can achieve four objectives: “the increase of local government revenue (Z_1)”, “the provision of service to local populace (Z_2)”, “the promotion of industrial development (Z_3)” and “the decrement of traveling time (Z_4)” among these objectives, the objective achievement performance of three objectives Z_1 , Z_3 and Z_4 will be considered in terms of its annual revenue increase (million), increment of production value (billion) and cutback of time (thousand hour) 5 yr after its investment project. The achievement performance of objective Z_2 will be measured by its regional serviceable populace (thousand people).

As for resources, three kinds of available resources such as capital budget, technical manpower and machinery equipment (indicated by the number of excavator) can be taken into consideration. The needed amount of the three resources for the 10 transportation investment alternatives is shown respectively: 50 billion of budget, person-month of anymore than 150 excavators. As a matter of fact, local government of XYZ regions cannot fully provide all these resources, and after prudent evaluation, only 30 billion dollars in the budget, 30,000 person-months in technical manpower and 100 excavators in machinery equipment can be proffered.

Due to the fact of limited resource, the local government of XYZ regions has to face

Table 1. The objective achievements and resource requirements

Projects	Objectives				Resources		
	Z_1 (Millions)	Z_2 (1000 person)	Z_3 (Billions)	Z_4 (1000 h)	B_1 (Billions)	B_2 (Manpower-month)	B_3 (Vehicles)
X_1	35	40	0.8	50	5.0	5	16
X_2	55	30	1.0	30	6.0	5	20
X_3	25	10	0.5	20	3.5	3	12
X_4	35	60	0.7	50	6.5	6	14
X_5	20	20	0.5	20	2.5	2	8
X_6	30	30	1.0	35	4.0	4	10
X_7	40	20	1.2	25	4.5	4	13
X_8	55	30	1.5	35	7.0	6	18
X_9	60	40	1.6	55	5.0	8	12
X_{10}	45	20	1.2	30	6.0	5	17
Total	400	300	10.0	350	50.0	48	150
The maximum resources provided					30.0	30	100

the selection problem of transportation investment alternatives, and it is hoped that under the greatest amount of the three resources provided, the selected transpiration investment alternatives can most likely achieve four objectives and have the least resource idled off. Details of the achieved degree of the four objectives and the needed amount of the three resources for the 10 transportation investment alternatives are as Table 1.

5.2. Classification and determination of interdependent degree of investment alternatives

In the 10 feasible transportation investment alternatives, a certain degree of interdependency does exist among the investment alternative under every objective, including independence, complementarity and substitution. To understand the classification of ever investment alternative, three experts are assigned to form a decision group in this article and each will judge whether the 10 investment alternatives under every objective are complementary or substitutive according to their professional knowledge and consideration upon the objective materials (to simplify the issue, it is assumed under the four objectives to have the same qualities in this article). According to judgment results of the three experts, complementary and substitutive synthetic judgment matrices D^{Ti} and E^{Ti} ($i=1,2,3,4$) be obtained as follows:

$$D^{Ti} = \begin{matrix} & \begin{matrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 & x_{10} \end{matrix} \\ \begin{matrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \end{matrix} & \left(\begin{array}{cccccccccc} - & 2 & 0 & 3 & 1 & 2 & 0 & 2 & 0 & 0 \\ & - & 1 & 3 & 0 & 2 & 0 & 2 & 1 & 1 \\ & & - & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ & & & - & 1 & 2 & 0 & 2 & 0 & 1 \\ & & & & - & 0 & 1 & 0 & 0 & 0 \\ & & & & & - & 1 & 0 & 1 & 0 \\ & & \text{Symmetric} & & & & - & 0 & 0 & 1 \\ & & & & & & & - & 0 & 0 \\ & & & & & & & & - & 0 \\ & & & & & & & & & - \end{array} \right) \end{matrix}$$

$$E^{Ti} = \begin{matrix} & \begin{matrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 & x_{10} \end{matrix} \\ \begin{matrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \end{matrix} & \left(\begin{array}{cccccccccc} - & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 \\ & - & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ & & - & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ & & & - & 1 & 1 & 0 & 1 & 0 & 0 \\ & & & & - & 3 & 1 & 3 & 3 & 0 \\ & & & & & - & 0 & 3 & 3 & 0 \\ & & \text{Symmetric} & & & & - & 1 & 0 & 1 \\ & & & & & & & - & 2 & 0 \\ & & & & & & & & - & 0 \\ & & & & & & & & & - \end{array} \right) \end{matrix}$$

Based upon the majority rule of formulas (15) and (16) as well as the membership relation of the four modes of investment alternatives (as indicated in formulas (9) and (10)), the final four modes of investment alternatives are as follows:

$$A^I = \{x_3, x_7, x_{10}\}; A^C = \{x_1, x_2, x_4, x_6, x_8\}; A^S = \{x_5, x_6, x_8, x_9\}; A^{CS} = \{x_6, x_8\}$$

Besides, three experts judge respectively on the degree of complementarity and degree of substitution of the complementary investment alternatives and substitutive investment alternatives. At the same time, judgment values are ranked from the greatest downward. Judgment matrices CC^{Ti} and SC^{Ti} ($i = 1, 2, 3, 4$) of the degree of complementarity and degree of substitution can be finally obtained. To make the problem simpler, the degree

of complementarity and degree of substitution are assumed to be the same under every objective in this example

$$C^{Ti} = (\hat{r}_{ij}^i) = \begin{matrix} & x_1 & x_2 & x_4 & x_6 & x_8 \\ \begin{matrix} x_1 \\ x_2 \\ x_4 \\ x_6 \\ x_8 \end{matrix} & \left(\begin{array}{ccccc} - & (0.4, 0.1, 0.0) & (0.2, 0.2, 0.1) & (0.4, 0.1, 0.1) & (0.1, 0.1, 0.0) \\ (0.5, 0.2, 0.1) & - & (0.7, 0.3, 0.2) & (0.4, 0.2, 0.0) & (0.2, 0.0, 0.0) \\ (0.3, 0.1, 0.1) & (0.3, 0.0, 0.0) & - & (0.2, 0.0, 0.0) & (0.4, 0.2, 0.1) \\ (0.1, 0.0, 0.0) & (0.3, 0.0, 0.0) & (0.4, 0.2, 0.0) & - & (0.1, 0.0, 0.0) \\ (0.3, 0.3, 0.1) & (0.2, 0.1, 0.0) & (0.1, 0.0, 0.0) & (0.3, 0.0, 0.0) & - \end{array} \right) \end{matrix}$$

$$S^{Ti} = (\hat{\theta}_{ij}^i) = \begin{matrix} & x_5 & x_6 & x_8 & x_9 \\ \begin{matrix} x_5 \\ x_6 \\ x_8 \\ x_9 \end{matrix} & \left(\begin{array}{cccc} - & (0.3, 0.1, 0.1) & (0.1, 0.1, 0.1) & (0.2, 0.0, 0.0) \\ (0.4, 0.2, 0.1) & - & (0.1, 0.0, 0.0) & (0.4, 0.1, 0.0) \\ (0.2, 0.0, 0.0) & (0.3, 0.2, 0.0) & - & (0.2, 0.2, 0.0) \\ (0.4, 0.3, 0.2) & (0.2, 0.0, 0.0) & (0.1, 0.0, 0.0) & - \end{array} \right) \end{matrix}$$

The degree of complementarity and degree of substitution of complementary investment alternatives and substitutive investment alternatives will thus be decided according to the consensus rule (take $M=2$ in this example) of formulas (26) and (27), and their results are shown in Table 2 and Table 3.

5.3. Selection of transportation investment alternative

As the local government of XYZ regions goes along with its transportation investment alternatives, its desirable objectives and three available resources enjoy relative importance among themselves. In this paper, the experts will use pairwise comparison to produce evaluation values on their degree of importance ranging from 1 to 9 according to every two objectives or resources with pairwise comparison. Integration of these three experts' judgment values is used by the geometric mean method (Saaty, 1989) to obtain the synthetic judgment matrix and finally the Eigenvector method of Saaty (1977b) to obtain weights. Weights of the four objectives and the three kinds of resources are achieved as follows:

$$W = (w_1, w_2, w_3, w_4) = (0.395, 0.130, 0.300, 0.175)$$

$$\lambda = (\lambda_1, \lambda_2, \lambda_3) = (0.444, 0.387, 0.169)$$

According to types of the 10 transportation investment alternatives as well as the degree of complementarity and degree of substitution of complementary investment alternatives and substitutive investment alternatives, the ideal values of the four objectives can be derived based on formula(30) as follows:

$$Z^*(x) = (Z_1^*(x), Z_2^*(x), Z_3^*(x), Z_4^*(x)) = (439.5, 356.0, 107.4, 401.5)$$

Based on the ideal values of the four objectives and the greatest supply amount of the three modes of resources, the normalization will be done with formulas (6) and (7) on the achieved values of every objective and the operational amount of the three kinds of resources, their results are shown in Table 4.

Table 2. CC_{ij} and CC_{ji}

Alternatives	x_1	x_2	x_4	x_6	x_8
x_1	0	0.1	0.2	0.1	0.1
x_2	0.2	0	0.3	0.2	0
x_4	0.1	0	0	0	0.2
x_6	0	0	0.2	0	0
x_8	0.3	0.1	0	0	0

Table 3. SC_{ij} and SC_{jj}

Alternatives	x_5	x_6	x_8	x_9
x_5	0	0.1	0.1	0
x_6	0.2	0	0	0.1
x_8	0	0.2	0	0.2
x_9	0.3	0	0	0

Effective distance heuristic algorithm can be employed to select investment alternatives according to the materials of investment alternative classification provided in Table 4, the degree of complementarity of complementary investment alternatives (indicated in Table 2) and the degree of substitution of substitutive investment alternatives (indicated in Table 3). According to the effective distance algorithm developed by this article, the approximate solution will be obtained with six iterations: $\{x_2, x_3, x_4, x_6, x_7, x_9\}$ (as shown in Table 5).

Speaking of the six selected investment alternatives, the priority of its selected investment alternatives will have to be considered upon their mutual interdependency; x_2, x_4 and x_6 are mutually complementary, x_6 and x_9 are substitutive and x_3 and x_7 are independent investment alternatives. At final ranking the priority of the six selected investment alternatives is:

$$x_6 \succ x_4 \succ x_7 \succ x_2 \succ x_9 \succ x_3$$

The sign \succ signifies preferred to. The achieved degree of ideal value of the four objectives for the final six selected investment alternatives is 60.94% (Z_1), 63.38% (Z_2), 60.43% (Z_3), 60.91% (Z_4) and the results show that every objective is capable of achieving 60% of the best attainable condition (ideal solution). As for resource utilization efficiency, the

Table 4. Normalization of objective achievement and resource use*

Alternatives	Z_1 (0.395)	Z_2 (0.130)	Z_3 (0.300)	Z_4 (0.175)	B_1 (0.444)	B_2 (0.387)	B_3 (0.169)
x_1	0.0796	0.1124	0.0745	0.1245	0.1667	0.1667	0.1600
x_2	0.1251	0.0843	0.0931	0.0747	0.2000	0.1667	0.2000
x_3	0.0569	0.0281	0.0466	0.0498	0.1167	0.1000	0.1200
x_4	0.0796	0.1685	0.0652	0.1245	0.2167	0.2000	0.1400
x_5	0.0455	0.0562	0.0466	0.0498	0.0833	0.0667	0.0800
x_6	0.0683	0.0843	0.0931	0.0872	0.1333	0.1333	0.1000
x_7	0.0910	0.0562	0.1117	0.0622	0.1500	0.1333	0.1300
x_8	0.1251	0.0843	0.1397	0.0872	0.2333	0.2000	0.1800
x_9	0.1365	0.1124	0.1490	0.1370	0.1667	0.2667	0.2200
x_{10}	0.1024	0.0562	0.1117	0.0747	0.2000	0.1667	0.1700

*The number in the parenthesis denotes the weight.

Table 5. Profitability index and final ranking

Alternatives	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$	$t=6$	Ranking
x_1	0.5169	0.4887	0.4363	0.4159	0.3900	*	*
x_2	0.5830	0.5511	0.4912	0.4880	S	S	0.5953(4)**
x_3	0.4694	0.4437	0.3957	0.3414	0.2012	0.1263	0.4425(6)
x_4	0.4320	0.4086	0.3646	0.3821	0.4278	S	0.7191(2)
x_5	0.6112	0.5579	0.3598	0.2239	0.0902	0.0630	*
x_6	0.6073	0.5525	0.5124	S	S	S	0.7621(1)
x_7	0.6588	S	S	S	S	S	0.6248(3)
x_8	0.5747	0.5432	0.4839	0.4074	0.3551	*	*
x_9	0.6488	0.6137	S	S	S	S	0.5766(5)
x_{10}	0.5439	0.5140	0.4579	0.3994	0.3086	*	*
x_j^*	x_7	x_9	x_6	x_2	x_4	x_3	—

* denotes that the iteration of the amount of resource use is more than 1.

** the number in the parenthesis denotes the priority of the selected investment alternatives profitability index. S denotes selected investment alternative at t iteration.

utilized degree of the greatest supply amount of the three modes of resources is resources 98.33% (B_1), 100% (B_2), 91.12% (B_3); in other words, condition of available resource idled off is 1.67 (B_1), 0% (B_2), 8.88% (B_3), and it shows that resources lay idle less than 10% while technical manpower (B_2) can be distributed to every investment alternative with none idled off.

6. CONCLUSION

The evaluation and selection of transportation investment alternatives are some of the major decisions of public investment, and the employment of a single objective (such as promotion of economic development) as a selection criterion profits no better under the growing complex social system and international situation. Since different objectives and available resources have to be considered, the context should see to the multiobjective investment decision making.

Past evaluation research of transportation investment alternatives reveal that most alternatives were thought to be independent rather than of any possible interdependency. As a matter of fact, some interdependency does prevail among transportation investment alternatives, such as complementarity and substitution. Therefore, this characteristic has to be borne in mind when selecting and evaluating transportation investment alternatives, and four specific types of investment alternatives among transportation investment alternatives are marked out: independent, complementary, substitutive and mutually complementary and substitutive. Once complementary and substitutive investment alternatives are decided, independent and mutually complementary and substitutive investment alternatives will be reached automatically. Furthermore, with objective materials provided and professional expertise of related-field experts this paper will achieve subjective cognition and judgment, and put forward the decisions in terms of complementary and substitutive investment alternatives as well as the degree of complementarity and degree of substitution for these investment alternatives. Consensus judgment by majority rule is available in this paper as there is more than one expert. The rule is applied to type classification and interdependency decisions to accommodate the cognition and judgment of most of the experts.

The selection problem of multiobjective transportation investment alternatives is a multiobjective 0–1 integer programming problem and will exhaust much time and human effort to locate the exact efficient solutions. In practice, strict computation for optimal solution is not required. Simple calculation to its almost approximate solution is more than enough. Efficiency notions as objective space and resource space are taken in this paper to find out the efficiency index of every investment alternative and work with it as a selection criterion. The idea of effective distance approximate solutions proposed in this paper can achieve the greatest objective with the least resource idled off. Besides, the selected investment alternatives can be ranked. When resource amount varies, sensitivity analysis can be easily made.

Facing future uncertainty and complex social systems, long-term transportation investment planning will be under a fuzzy environment and should belong to ill-structure decision problems. As a result, the future research approach will be: (1) application of fuzzy sets theory to the classification of transportation investment alternatives and decision of relative importance; (2) application of fuzzy mathematical programming to the selection of transportation investment alternatives; (3) consideration of possible interdependency among resources; (4) proceeding with multistage investment planning for investment decisions of more comprehensive robustness, and the build-up of contingency strategies for every stage.

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