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Route entropy based capacity reliability assessment and application in multi-objective satisfactory optimization of logistics network

Xin Miao^{1*}, Bao Xi², Ming Guan³ and Yan-hong Tang¹

¹School of Management, Harbin Institute of Technology, Harbin 150001, People's Republic of China.

²School of Public Administration, Dalian University of Technology, Dalian 116024, People's Republic of China.

³School of Economics and Management, Xuchang University, Xuchang 461000, People's Republic of China.

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Capacity reliability assessment and application are emerging active area in transportation science. This paper built assessment model of capacity reliability of road network from the perspective of route entropy by referring to relevant concepts and methods applied in water distribution system. Route entropy represents the uncertainty of route selection of macro traffic flow in a road network. The probability space and calculative model of route entropy were introduced as a new method with regard to the field of capacity reliability research in transportation science. This paper further demonstrated a feasible method for applying resultant capacity reliability in logistics network optimization. The decision of how to optimize a logistics network depends upon several criteria that are sometimes conflicting under a set of constraints. This paper analyzed and modeled the conflicting objectives through forming satisfactory function. The proposed approach captured essential requirements of actual logistics network and considered them synthetically into unified dimension for optimization. Improved genetic algorithm was applied to search solutions, and the applicability and validity of the method were further demonstrated by a numerical example. This paper contributed to the development of capacity reliability theory in transportation science. It may bring some inspiration to relevant scientific researchers and engineers.

Key words: Road traffic, road network, traffic flow, route choice, entropy, uncertainty, multi-objective, satisfactory optimization, logistics network

INTRODUCTION

It is well acknowledged that traffic congestion is a severe problem faced by the development of modern urban civilization (Akgungor and Dogan, 2009; Gundogdu, 2009; Tang and Xi, 2010). Emerging techniques and policies may solve this problem, but before it is solved, people have to find ways to assess capacity reliability of road traffic network so that they can distinguish where the vulnerable parts are and provide support for designing

Logistics network optimization has to meet several goals simultaneously and an appropriate logistics distribution scheme involves non-economic factors. Operation at absolute minimum cost can no longer be the only criterion for logistics distribution due to increasing concern for service level and reliability (Gursoy, 2010; Kofteci et al., 2010). However, how to measure reliability and apply it in logistics optimization is still a difficult problem to be solved. The purpose of multi-objective satisfactory optimization for logistics network is to generate efficient alternatives, which can then be presented to the decision-maker so that he/she can

*Corresponding author. E-mail: miaoxin@yahoo.cn or miaoxin@hit.edu.cn.
concrete countermeasures.

select the preferred alternative while considering conflicting and non-commensurate objectives (Malakooti, 1989).

Multi-objective satisfactory optimization is to optimize simultaneously two or more conflicting objectives under a set of constraints (Liu et al., 2000). General mathematical form of a multi-objective satisfactory optimization problem is formulated as follows:

$$\begin{aligned} &\text{Minimize} \quad \{f_1(x) = z_1, f_2(x) = z_2, \dots, f_n(x) = z_n\} \\ &\text{Subject to} \quad x \in \Omega \end{aligned} \quad (1)$$

Where, solution x is a vector of discrete decision variables, Ω is the finite set of feasible solutions. The image of a solution $x \in \Omega$ is the point $z=f(x)$ in the objective space. A point z dominates z' , if $z_j = f_j(x) \leq z'_j = f_j(x')$, $\forall j$ and $z_j < z'_j$ for at least one j . A solution x dominates x' if the image of x dominates the image of x' . A solution $x^* \in \Omega$ is a non-dominated (or efficient) solution if there is no $x \in \Omega$ such that $z=f(x)$ dominates $z^* = f(x^*)$. The solutions that are non-optimal solutions within the entire search space are named as Pareto-optimal solutions and constitute the Pareto-optimal set or Pareto-optimal frontier (Li, 2009).

Satisfactory optimization (Li and Hu, 2007) extends optimization theory through replacing optimal solution with satisfactory solutions. It can properly consider satisfactory design of system performance indexes and optimization of system parameters, and at the same time, take into account constraints and objective function integrally (Liu, 2006). This paper tries to achieve a satisfactory logistics distribution network and the basic factors considered are transportation cost, average delay and capacity reliability obtained through the route entropy method.

LITERATURE REVIEW

The concept of capacity reliability was first put forward by Chen et al. (1999) and was defined as the probability that the network can accommodate a certain traffic demand within a predefined service level. Later, Chen et al. (2002) extended the capacity reliability analysis by presenting comprehensive methodology, which related capacity reliability with uncertainty analysis. Sumalee and Kurauchi (2006) presented a Monte-Carlo simulation method to estimate capacity reliability. da Silva et al. (2010) also put forward a Monte Carlo simulation approach based on cross-entropy method to evaluate generating capacity reliability. There is no doubt it would be better to incorporate uncertainty into capacity reliability analysis as the concept in itself is unification of a fuzzy and random meaning in a dynamic environment, while

fuzziness and randomness are typical expression of uncertainty (Miao et al., 2009). Castans (1962) discovered that there are logarithmic relation between entropy and uncertainty. Later, entropy was applied in assessment of uncertainty in hydrologic systems (Amarocho and Espildor, 1973), uncertainty relations of wave mechanics (Bialynickibirula and Mycielski, 1975), uncertainty estimation of power spectrum (Schott and McClellan, 1984), uncertainty in past lifetime distributions (Di Crescenzo and Longobardi, 2002), uncertainty of resource allocation (Johansson and Sternad, 2005) and so on.

Entropy has been applied to assess reliability with uncertainty for water distribution networks and Awumah et al. (1990, 1991) were the first to suggest the use of Shannon's entropy (Shannon, 1948) for measuring the reliability of water distribution networks. Tanyimboh and Templeman (1993a) were the pioneers who put forward the entropy function for application in water distribution networks. They also designed a sequential algorithm to search the distribution of maximum-entropy flow for single-source networks (Tanyimboh and Templeman, 1993b), and in their paper, the only known conditions are the network topology, the flow directions in each pipe, and the supplies and demands at each node. Further, they demonstrated that there is intrinsic relationship between the entropy and reliability of water distribution networks (Tanyimboh and Templeman, 2000), and what they disclosed was in accordance with the maximum entropy principles (Rajagopal and Teitler, 1989), that is, a network will be more reliable if it possesses higher entropy. Ang and Jowitt (2005a) put forward a named path entropy method to calculate entropy of water distribution networks, and later they further develop this method into entropy calculation for multiple-source water distribution networks (Ang and Jowitt, 2005b).

As we know, traffic flow theory can track its origin to analogy of hydrokinetics. British scholars Lighthill and Whitham (1955) made an analogy to consider traffic flow as liquid. Through studies of traffic flow on long congested roads, they put forward the theory of traffic kinetic waves, which adopted basic theory of hydrodynamics to analyze the movement of traffic flow and obtained the continuous equation for traffic flow study (Miao et al., 2008). Therefore, we believe that entropy can be adopted to analyze the capacity reliability of road traffic network by referring to the methods used for water distribution networks.

For logistics network optimization, although network analysis and optimization are widely studied in the operations research literature (Jeet et al., 2009), traditional models that focused on minimizing fixed costs of facility location and transportation costs are no longer suitable for logistics network optimization (Eskigun et al., 2005). Recent years have seen an increasing concern on this aspect, such as Barnhart and Shen (2005), Cordeau

et al. (2006), Candas and Kutanoglu (2007), Cheong et al. (2007), Cordeau et al. (2008), Ho and Emrouznejad (2009), Jeet et al. (2009), Chiou (2009), etc. Generally speaking, the superiority of these works over the previous is that they considered multi-objective in design and optimization process, and adopted heuristic or improved search algorithms for problem solving. However, these works fall into the category of optimal optimization.

Compared with fuzzy multi-criteria optimization (Sreekumar and Mahapatra, 2009), satisfactory optimization does not involve fuzzy disposal and complicated computation that makes it easier for clear expression of manager's preference, and hence, is efficient in identifying potential solutions. If a multi-objective satisfactory optimization problem is well formulated, there should more than one solution that simultaneously leads each objective to its fullest, and a set of compromising solutions will be provided for selection. The use of satisfactory optimization allows managers to consider many worthwhile measures of performance of a system and to identify good scheme alternatives and the trade-offs between them (Badri et al., 1998). Accordingly, satisfactory optimization method is convenient for practical application. As we know, "real world optimization problems deal with competing incommensurable objectives in a complex search space. Improvement in one objective often leads to degradation in at least one of the remaining objective functions" (Ok et al., 2009). While the satisfactory optimization method "guides the multi-point searching process toward a uniformly spread-out Pareto-optimal front in multi-dimensional objective space. Thus, the distribution of the Pareto-optimal solutions well describes the relative importance between the multiple objectives or how the multiple objectives are competent with each other in the objective space" (Ok et al., 2009).

ROUTE ENTROPY BASED CAPACITY RELIABILITY ASSESSMENT

Referring to and distinguishing from path entropy, we call the entropy, which is applied to assess capacity reliability of road traffic network and analyze uncertainty of route choice of macro traffic flow, as route entropy.

Firstly, we need to express Shannon entropy as formula (2):

$$S = -K \sum_{i=1}^N p_i \ln p_i \quad (2)$$

Where, K denotes a positive constant, and p_i ($i=1, \dots, N$) denote a finite probability space, which include a series probabilistic event of finitude incompatible

probabilistic events.

The maximum-entropy formalism (Jaynes, 1957) is used to discover the probability distribution that leads to the highest value of uncertainty, thereby assuring that no information is inadvertently assumed. It is a property of the above entropy formula that it has its maximum value when all probabilities are equal.

The entropy to measure the uncertainty of route choice of macroscopic traffic flow is called route entropy. Traffic flow usually chooses the route with the minimum traffic impedance, and the uncertainty of route selection of macroscopic traffic flow reflects the dynamic changes of traffic impedances in different parts of the road network. Based on the principle of maximum entropy, the state corresponding to the maximum entropy has the highest reliability, and each route has the same chance to be selected and traffic flow distributed soundly in the whole road network in this state.

The ratio of the traffic volume in each route to the total traffic volume is called Route Flow Ratio (RFR) of each route. The RFR reflects the dynamicity of route choice of macroscopic traffic flow. It associates impedance characteristics with flow characteristics, and constitutes the theoretical basis for state estimation of road network.

Denote the traffic volume from trip generation spot to node j as (f_j^i) , $i=1, \dots, N$. Where, the N denotes the number of routes from trip generation spot to node j . Let the sum of traffic volume in each route connected to node j as q_{j0} , that is:

$$\sum_{i=1}^N f_j^i = q_{j0} \quad (3)$$

Define probability space according to RFR:

$$p_j^i = \frac{f_j^i}{q_{j0}} \quad (4)$$

According to formula (2), the route entropy of node j can be denoted as:

$$S_j = - \sum_{i=1}^N \frac{f_j^i}{q_{j0}} \ln \frac{f_j^i}{q_{j0}} \quad (5)$$

Rearrange formula (5) and obtain another form:

$$S_j = - \frac{1}{q_{j0}} \left(\sum_{i=1}^N f_j^i \ln f_j^i - q_{j0} \ln q_{j0} \right) \quad (6)$$

Let j denote a random node and it has three directly

connected upper nodes a_1 , a_2 and a_3 . There are n routes from trip generation spot O to node j , and among the n routes, there are k coincident routes from a_1 to j , m coincident routes from a_2 to j and $n-m-k$ coincident routes from a_3 to j .

Further, let $R_1 = \sum_{i=1}^k f_j^i$, $R_2 = \sum_{i=k+1}^{k+m} f_j^i$ and $R_3 = \sum_{i=k+m+1}^n f_j^i$,

then;

$$R_1 + R_2 + R_3 = q_{j0} \quad (7)$$

Let $q_{a_1,0}$, $q_{a_2,0}$, $q_{a_3,0}$ denote the traffic volume on node a_1 , a_2 and a_3 respectively, then

$$f_{a_1}^i / q_{a_1,0} = f_j^i / R_1, \quad i \in (1, k) \quad (8)$$

$$f_{a_2}^i / q_{a_2,0} = f_j^i / R_2, \quad i \in (k+1, k+m) \quad (9)$$

$$f_{a_3}^i / q_{a_3,0} = f_j^i / R_3, \quad i \in (k+m+1, n) \quad (10)$$

According to formula (5), get the following:

$$S_{a_1} = - \sum_{i=1}^k \frac{f_j^i}{R_1} \ln \frac{f_j^i}{R_1} = - \frac{1}{R_1} \left[\sum_{i=1}^k f_j^i \ln f_j^i - R_1 \ln R_1 \right] \quad (11)$$

$$S_{a_2} = - \sum_{i=k+1}^{k+m} \frac{f_j^i}{R_2} \ln \frac{f_j^i}{R_2} = - \frac{1}{R_2} \left[\sum_{i=k+1}^{k+m} f_j^i \ln f_j^i - R_2 \ln R_2 \right] \quad (12)$$

$$S_{a_3} = - \sum_{i=k+m+1}^n \frac{f_j^i}{R_3} \ln \frac{f_j^i}{R_3} = - \frac{1}{R_3} \left[\sum_{i=k+m+1}^n f_j^i \ln f_j^i - R_3 \ln R_3 \right] \quad (13)$$

Let q_{a_1j} , q_{a_2j} and q_{a_3j} denote the traffic volume on road section a_{1j} , a_{2j} and a_{3j} respectively, and let Q_j denote the total traffic volume coming to node j , then

$$R_1 / q_{j0} = q_{a_1j} / Q_j, R_2 / q_{j0} = q_{a_2j} / Q_j, R_3 / q_{j0} = q_{a_3j} / Q_j \quad (14)$$

The entropy of node j can be calculated as:

$$S_j = - \frac{1}{q_{j0}} \left[\sum_{i=1}^k f_j^i \ln f_j^i + \sum_{i=k+1}^{k+m} f_j^i \ln f_j^i + \sum_{i=k+m+1}^n f_j^i \ln f_j^i - q_{j0} \ln q_{j0} \right]$$

$$\begin{aligned} &= \frac{R_1}{q_{j0}} \left[- \sum_{i=1}^k \frac{f_j^i}{R_1} \ln \frac{f_j^i}{R_1} \right] - \frac{R_2}{q_{j0}} \ln R_2 + \frac{R_2}{q_{j0}} \left[- \sum_{i=k+1}^{k+m} \frac{f_j^i}{R_2} \ln \frac{f_j^i}{R_2} \right] - \frac{R_3}{q_{j0}} \ln R_3 + \frac{R_3}{q_{j0}} \left[- \sum_{i=k+m+1}^n \frac{f_j^i}{R_3} \ln \frac{f_j^i}{R_3} \right] - \frac{R_3}{q_{j0}} \ln R_3 + \ln q_{j0} \\ &= \frac{q_{a_1j}}{Q_j} S_{a_1} + \frac{q_{a_2j}}{Q_j} S_{a_2} + \frac{q_{a_3j}}{Q_j} S_{a_3} - \frac{R_1}{q_{j0}} \ln \frac{R_1}{q_{j0}} - \frac{R_2}{q_{j0}} \ln \frac{R_2}{q_{j0}} - \frac{R_3}{q_{j0}} \ln \frac{R_3}{q_{j0}} \end{aligned} \quad (15)$$

If j has n upper nodes and let $p_{nj} = q_{nj} / Q_j = R_n / q_{j0}$, then the route entropy of node j can be denoted as:

$$S_j = \sum_{n \in U(j)} (-p_{nj} \ln p_{nj} + p_{nj} S_n) \quad (16)$$

Where, $U(j)$ is the set of the nodes which directly connected to node j . For a road network with multiple trip generation spots, the upper node of the trip generation spots can be seen as a virtual source and S_n denotes the route entropy of the upper node n .

The above model can be solved by sequential algorithm (Wu and Tian, 2003). The source or virtual source of trip generation can be regarded as the initial node of a network and there is no conflux in such a node, therefore, there is zero entropy in the initial node. The initial node is the starting point of sequential algorithm, which will search all the routes of the network and easy to be adapted into computer program. The entropy of a node denotes the uncertainty of the whole process that the traffic flow start from the source and flow into this node. From formula (16), we know that the entropy at any node include not only the uncertainty of the upper nodes but also the uncertainty of conflux in current node. In a word, route entropy can reflect the uncertainty of route choice of macro traffic flow, that is, the capacity reliability of a road network.

THE MULTI-OBJECTIVE SATISFACTORY OPTIMIZATION MODEL

A logistics network can be expressed as a weighting nondirectional graph $G=(V, E)$, where, V is the node set of the network, E is the link set of the distribution paths. Let $|V|$ denote the node number of G and $|E|$ denote the link number. Link $\varepsilon_{ij} = (v_i, v_j)$ denotes path between node v_i and v_j . If $\varepsilon_{ij}=0$, it means there is no path between the two nodes, where, $i, j=1, 2, \dots, n$ and $v_i, v_j \in V$.

To express state of each distribution path by the above graph, let R_+ denote positive real number set and R^+ denote non-negative real number set, then we have distribution delay $delay(e_{ij}): E \rightarrow R_+$, transportation cost

$cost(e_{ij}): E \rightarrow R_+$ and capacity reliability
 $rel(e_{ij}): E \rightarrow R^+$.

Known conditions:

- 1) Matrix of freight vehicles between two nodes
- 2) Road capacity values
- 3) Function of transportation cost
- 4) Reliability probability of road section and nodes

According to the above network, multi-objective satisfactory optimization model for logistics network design can be expressed as:

$$\begin{cases}
 \text{Minimize } C(G), D(G), 1-R(G) \\
 \text{Maximize } Overall_sat(G) = F(Sat_c(G), Sat_d(G), Sat_r(G)) \\
 Sat_c(G) = g(C(G)) \\
 Sat_d(G) = h(D(G)) \\
 Sat_r(G) = s(R(G))
 \end{cases} \quad (17)$$

Constraints:

- (1) Reliability and practical existence of road network
- (2) Capacity range of road network

Where, $C(G)$ denotes transportation cost in the network, $D(G)$ denotes average distribution delay and $R(G)$ denotes reliability of the network. $Sat_c(G)$, $Sat_d(G)$ and $Sat_r(G)$ denote satisfaction functions of corresponding performance indexes, that is, cost, delay and reliability, respectively. $Overall_sat(G)$ denotes overall satisfaction function. Minimization of $C(G)$, $D(G)$ and $1-R(G)$ denote minimization of transportation cost, average distribution delay and unreliability of distribution network, respectively. Maximization of $Overall_sat(G)$ denotes maximization of overall satisfaction degree of the logistics network G .

Satisfaction function is used for quality evaluation of satisfactory solutions (Huang et al., 2008). In practice, different satisfaction functions of performance indexes should be designed according to different backgrounds of optimization problems.

Overall satisfaction function is to transform multi-objective optimization model into single objective optimization model by synthesizing two or more performance indexes together. Here, a frequently used overall satisfaction function, which has simple structure, is adopted in this paper.

$$Sw = f(s) = \sum_{i=1}^m \omega_i s_i, \sum_{i=1}^m \omega_i = 1 \quad (18)$$

Where, w_i is the weight of s_i , $i=1, 2, \dots, m$. By formula Miao et al. 3339

(18), overall satisfaction function Sw can be obtained from linear weighting computation of s_i . Weight w_i reflects manager's preference for performance index s_i . Analytical hierarchy process can be applied to determine w_i .

METHOD TO SOLVE THE MODEL

Logistics network consists of large number nodes, complicated connections and different logistics volumes. Therefore, as for optimization of logistics network, transportation cost, logistics volumes, distribution routes, node location, node capacity, distribution delay and other factors should be taken into integrated consideration to achieve low-cost, high-performance network. A feasible approach for network optimization is to divide a whole network into several subnetworks and optimize these subnetworks in advance, and then, consider each subnetwork as a node to design the overall network structure. Accordingly, optimization of logistics network may follow the following steps:

- 1) Divide Logistics network into subnetworks;
- 2) Optimize the connections of nodes and links in each subnetwork;
- 3) Optimize the connections among subnetworks.

Here, improved genetic algorithm is applied to search the satisfactory solution of logistics network optimization problem, and the objective is to find a network that has merits of high reliability, low cost and less delay. Since these indexes have different dimensions, overall satisfaction function is applied to integrate the three indexes into one dimension.

Subnetwork division

The principle to be followed in subnetwork division process is that the logistics volume between any two subnetworks should be kept as small as possible and the logistics volume in each subnetwork should be kept as large as possible. In other words, two nodes with less logistics volume between them should be assigned to different subnetworks and two nodes with large logistics volume between them should be assigned to one subnetwork to enhance efficiency and cohesion of a subnetwork, and at the same time, this approach can cut down transportation cost and distribution delay between any two subnetworks.

Simplification of the network

Assume there are n distribution centers and m subcenters in logistics network. Figure 1 shows a simplified logistics network with 4 distribution centers and 8 subcenters.

Freight volume between subcenters can be denoted by a $m \times m$ -matrix U , thereinto, u_{ij} denotes freight volume from subcenter i to subcenter j . Let a $n \times n$ -matrix X_1 denote the connection relationship among distribution centers. Thereinto,

$$X_{1ij} = \begin{cases} 1 & \text{if } i \text{ connect with } j \\ 0 & \text{else} \end{cases} \quad (19)$$

Let a $n \times m$ -matrix X_2 denote the affiliation of subcenters to 3340 Sci. Res. Essays

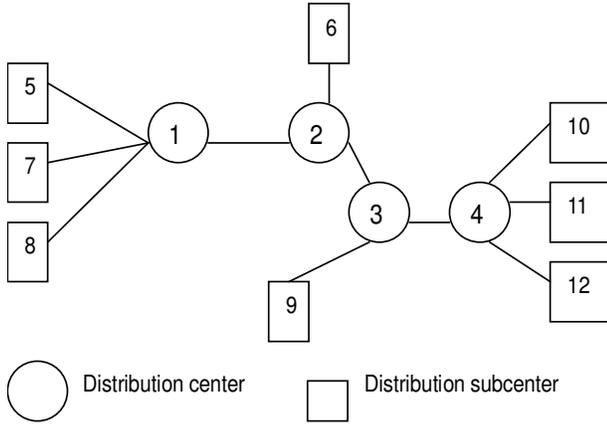


Figure 1. Simplified logistics network.

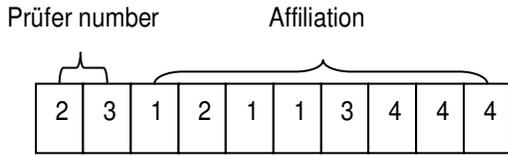


Figure 2. Code of distribution centers and subcenters.

distribution centers. Thereinto,

$$x_{2ij} = \begin{cases} 1 & \text{if subcenter } j \text{ affiliates to center } i \\ 0 & \text{else} \end{cases} \quad (20)$$

Then, $\sum_{i=1}^n x_{2ij} = 1 \quad \forall j = 1, 2, \dots, m$. Let a $n \times n$ -matrix T denote freight volume among distribution centers, thereinto, t_{ij} denotes freight volume from a subcenter, which affiliates to center i , to center j . Then, $T = X_2 U X_2^T$, where, X_2^T is the transposed matrix of X_2 .

Satisfactory optimization algorithm

For real-world multi-objective problems, the evaluation of objective functions usually requires a large amount of computation. Moreover, solving multiobjective problems often requires much longer computing time than solving single-objective problems as a result of multi-dimension to be considered for optimization. Therefore, it is essential to design efficient algorithm for solving multi-objective problems. This paper uses improved GA to speed up search process.

Code scheme

Use Prüfer code for distribution centers and clustering code for

subcenters.

Prüfer code:

Setp 1: assume node i as the minimal labelled node in tree T ;
 Setp 2: if node j is the adjacent node of i , let the label of j as the i^{th} item of the Prüfer sequence;
 Setp 3: delete node i and link (i, j) , and let $n=n-1$;
 Setp 4: repeat the above steps until only two nodes remained, then a sequence with $n-2$ number can be obtained.

Reductive algorithm:

Prüfer sequence can be reverted to a tree. Assume a Prüfer sequence consists of $n-2$ numbers, and the reductive algorithm is shown as follows:

Setp 1: Assume W as a universal set of nodes, $W = \{1, 2, \dots, n\}$. P is a Prüfer sequence, \bar{P} is the complementary set of P ;

Setp 2: Assume i is the minimal labelled legal node in \bar{P} and j is the leftmost number in P , then add link (i, j) into tree T , and delete i and j from P and \bar{P} respectively; judge whether j exist in P , if it does not exist, add j into \bar{P} , and repeat step 2 until P is empty;

Setp 3: If there is no number in P , \bar{P} must have two nodes r and s , then add link (r, s) into tree T , end.

Prüfer sequence is applicable to code a tree. Distribution centers can be denoted by Prüfer sequence with $n-2$ numbers. In order to express the relation of distribution centers and subcenters, subcenters can be denoted by clustering code. For n distribution subcenters and m distribution centers, the chromosome consists of $n+m-2$ numbers. For example, the code for Figure 1 is shown in Figure 2, thereinto, the first two numbers are Prüfer numbers, and the rest eight numbers respectively denote the i^{th} subcenter affiliated to one of the distribution center 1, 2, 3, or 4.

Evaluation function

Three performance indexes, that is, transportation cost, average delay and capacity reliability are the main consideration and their satisfaction functions need to be determined. Then determine weights for each performance index to constitute overall satisfaction function.

Satisfaction function of performance indexes:

Satisfaction functions of the three performance indexes can be expressed as Figures 3 to 5 (Wen et al., 2006):

Overall satisfaction function:

Overall satisfaction function corresponding to the above satisfaction functions of performance indexes is constituted as formula (21):

$$Overall(x) = \frac{w_c sat_c(x) + w_d sat_d(x) + w_r sat_r(x)}{w_c + w_d + w_r} \quad (21)$$

Where, w_c , w_d and w_r are the weights of satisfaction degree of performance indexes.

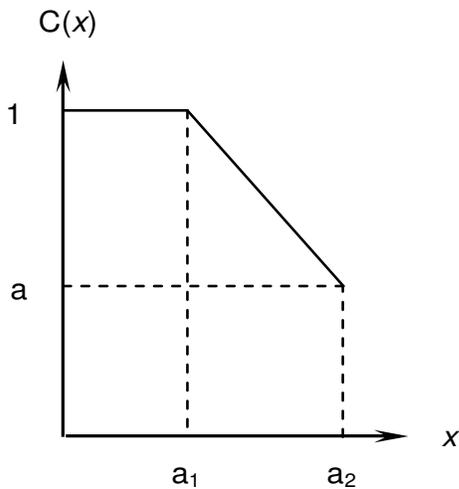


Figure 3. Satisfaction function of transportation cost.

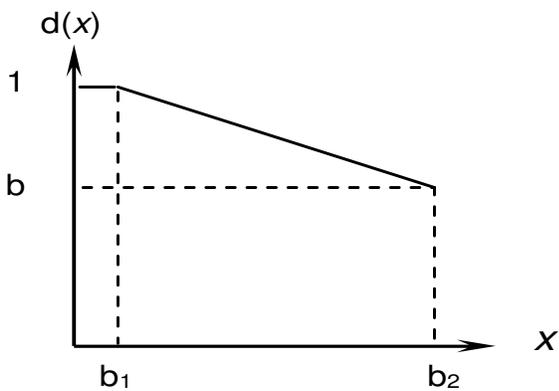


Figure 4. Satisfaction function of average delay.

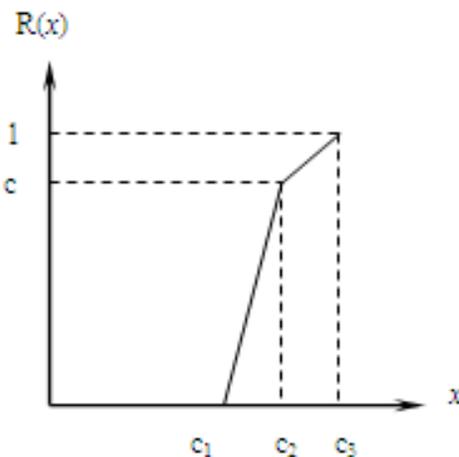


Figure 5. Satisfaction function of capacity reliability.

Genetic manipulation

Selection, crossover and mutation are implemented as previously mentioned. Roulette rules can be applied in selection process of logistics network. In order to ensure convergence of GA, the optimum individual of each generation is reserved to the next generation. Breakpoint crossover and exchange mutation can be applied in crossover and mutation process.

Chromosome rehabilitation

Considering capacity constraint of distribution centers, the number of subcenters linked to each center can not exceed g , therefore, there may be population that can not satisfy this constraint in crossover and mutation process. If we attempt to regenerate a new population of this kind, it will waste time and resources. Therefore, rehabilitation needs to be implemented on links between distribution center and subcenters. Let G denote a set of distribution centers that satisfy the above constraints. If the number of subcenters linked to center i exceeds g , substitute i with a random selection from G .

Terminal conditions

Terminate search when any one of the following conditions is satisfied:

- 1) Predefine a maximum number of generation times and terminate until iterative times reach the maximum number;
- 2) Overall satisfaction degree will not change any more or change little during the span of a number of generation times.

NUMERICAL EXPERIMENT RESULTS

Define parameters of GA as follows: population size = 80, maximum iterative times = 100, crossover rate = 0.6, mutation rate = 0.2. For satisfaction function of transportation cost, let $a_1 = 400$, $a_2 = 900$; for satisfaction function of average delay, let $b_1 = 5$, $b_2 = 50$; for satisfaction function of capacity reliability, let $c_1 = 0.6$, $c_2 = 0.80$, $c_3 = 1.00$. In addition, let $a = 0.5$, $b = 0.6$, $c = 0.8$.

Considering transportation cost, average delay and capacity reliability as equally important, let $w_c = w_r = w_d = 1/3$ in calculation of overall satisfaction function. Then, the optimization results are shown as Table 1 and the corresponding logistics network structure is shown as Figure 6, and the curve of overall satisfaction degree in the GA search process is shown as Figure 7.

Figure 7 showed that overall satisfaction degree enhances with generation number of GA search, and finally, kept unchanged. The convergence speed was fast that demonstrates the validity of the multi-objective satisfactory optimization method for logistics network.

DISCUSSION

The optimization result of the numerical example showed its effectiveness and efficiency. The proposed approach

Table 1. Performance indexes and optimization results.

Weight	Transportation cost	Average delay	Capacity reliability	Satisfaction degree of transportation cost	Satisfaction degree of average delay	Satisfaction degree of capacity reliability	Overall satisfaction degree
$w_c=w_d=w_r=1/3$	582	27	0.92	0.82	0.80	0.92	0.85

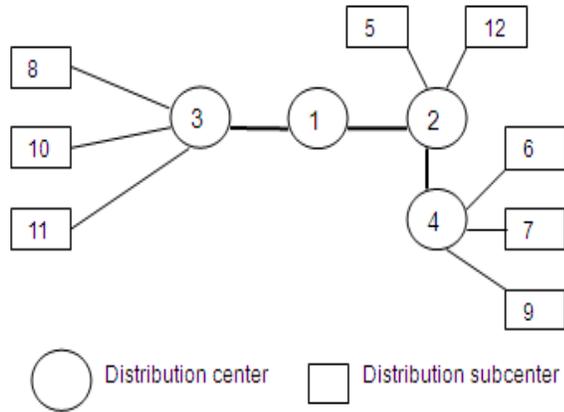


Figure 6. Optimal logistics network structure.

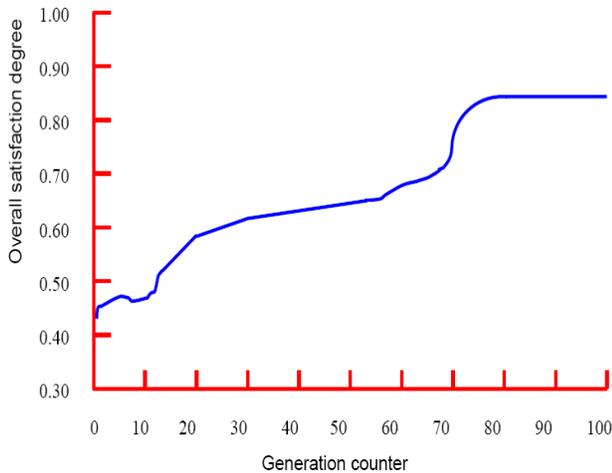


Figure 7. Curve of overall satisfaction degree.

exhibited the potential applicability and significance of multi-objective satisfactory optimization techniques on the design of logistics network. The presented methodology is of great significance, especially when the objective function incorporates conflicting variables, for practical applications in the field of logistics network design. The feature of multi-objective satisfactory optimization is of high significance equally to both decision makers as well as the analysts because the analysts are concerned with

fulfilling multiple objectives simultaneously while decision makers are concerned with the quality of their decisions (Singh and Chakrabarty, 2010). The intentions of both parties can be accomplished by adopting the presented methodology. The proposed model could be useful in solving a wide variety of similar problems, and help in making better decisions in transportation and logistics systems with multiple objectives. The application of multi-objective satisfactory optimization method is not limited in system design, and this paper only adopted network structure as an example to demonstrate the applicability of this method. Some detailed multi-level considerations can also be tackled in similar ways.

CONCLUSIONS

This research provides a new insight for assessment of capacity reliability of road network and offers a new perspective for logistics network optimization with reliability consideration. The intrinsic similarity between traffic flow and liquid flow may help researcher in transportation science to discover some law for further development of the theory and practice of transportation engineering and management. Large-scale logistics network optimization is a complicated and difficult task, and essentially, a multi-objective satisfactory optimization problem. This practical approach presented in this paper can solve some similar problems in logistics system and contributed to management method and operation practice. It allows a broader view of the problem and weights the alternatives in accordance with managers' inclination.

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