

Research Article

Application of Cold Chain Logistics Safety Reliability in Fresh Food Distribution Optimization

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Abstract: In view of the nature of fresh food's continuous decrease of safety during distribution process, this study applied safety reliability of food cold chain logistics to establish fresh food distribution routing optimization model with time windows, and solved the model using MAX-MIN Ant System (MMAS) with case analysis. Studies have shown that the mentioned model and algorithm can better solve the problem of fresh food distribution routing optimization with time windows.

Keywords: Distribution and delivery, fresh food, routing optimization, safety reliability

INTRODUCTION

In the current studies of fresh food distribution system, most of them just considered physical loss or time window restraints during food distribution process on the basis of TSP problem. For example, Sexton and Choi (1986) evaluated single vehicle routing and scheduling problem with time windows by Bender's Decomposition method. Taillard *et al.* (1997) adopted the concept of Tabu Search for solving vehicle routing problem with soft windows. Koskosidis *et al.* (1992), based on general assignment mode proposed by Fisher and Jaikumar (1981), offered an optimal-solution-based heuristic method. Malandraki and Daskin (1992) explored the vehicle routing problem with time windows and location requirements. Li *et al.* (2006) optimized the distribution system considering loss of goods. However, physical loss of food and food safety is not the same concept. Even with no significant physical changes, some food such as milk, sushi, etc., may have not met the sanitary standards. Aiming at this situation, this study introduced safety reliability of food cold chain logistics to the vehicle routing optimization problem, set up a model and used MAX-MIN Ant System to solve it.

SAFETY RELIABILITY OF FOOD COLD CHAIN

The reliability is the probability of a process or a product performing its intended function for a stated period of time under specified operating conditions. So, the term of the safety reliability of food logistics unit is defined as the probability of food logistics unit retaining the safety of food within an intended scope for

a stated period of time under specified operating conditions (Zou *et al.*, 2010a). This probability is determined by the number of microorganism in foods, because bacterial hazard is the most serious factor influencing food's safety and microbial number in food varies dynamically in the course of logistics. Though food also suffers from physical hazard and chemical hazard during logistics, the probabilities of those hazards are generally considered as tiny statistical constants for a practical food logistics system. Hence, the greater the number of microorganism presented in food, the smaller the safety reliability of food is, vice versa.

According to "T. T. T" (Time-Temperature-Tolerance) theory of food logistics, the number of microorganism in specific food during logistics is mainly controlled by temperature and time. Many models can be applied for modeling the growth of microorganism in food. Zwietering *et al.* (1996) believed that the following exponential model had best prediction effect after he researched several microbial growth models:

$$N_t = N_0 e^{b^2(T-T_{\min})^2(t-\lambda)} \quad (1)$$

where,

- N_t = The concentration of microorganism at time t (CFU/g)
- N_0 = The initial concentration of microorganism (CFU/g)
- b = A parameter in experiment
- T = The temperature during logistics (°C)
- T_{\min} = The temperature at which no growth will occur (°C)

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λ = The lag time of microorganism growth

Let $\Delta T = T - T_{\min}$, the above equation can be converted as:

$$\ln(N_t) = \ln(N_0) + b^2 \Delta T^2 (t - \lambda) \quad (2)$$

To eat putrid food is liable to be sick. The illness probability is proportional to the common logarithm of microorganism number in food. Therefore, safety reliability of food can be defined as follows:

- The value of safety reliability plus illness probability is 1.
- The safety reliability of food is 1 if the concentration of microorganism is equal to or less than 1 CFU/g. The reason is: if the concentration of microorganism in food is 1 CFU/g, then $\log_{10} N = 0$, therefore the safety reliability of food is 1; if the concentration of microorganism in food is less than 1 CFU/g, food safety is better, its safety reliability is also 1.
- If the concentration of microorganism in food reaches N_D (the minimum concentration to cause food borne disease), the safety reliability of food is zero. It means that at this point the food cannot be eaten and the safety reliability of food is the least.

For a cold chain logistics system composed of m cold chain units, its safety reliability R_i after food continuously passes through the i^{th} ($i \leq m$) unit can be expressed as (Zou *et al.*, 2010b):

$$R_i = R_0 - d \sum_{j=1}^i \Delta T_j^2 t_j \quad (0 \leq R_i \leq 1) \quad (3)$$

where,

R_0 = The initial safety reliability of food cold chain system

$\Delta T_j = T_j - T_{\min}$ (T_j is the temperature in logistics unit j)

t_j = Logistics time of cold chain unit j

d = A parameter related to food variety

MODELING

As illustrated in Fig. 1, food distribution network $G(V, A)$ generally consists of distribution center, refrigerated vehicles and retail sites. The problem can be described as follows: the distribution center has m vehicles of same model and deadweights Q_0 ; these vehicles set off from distribution center (V_0), pass through all retail sites ($V_i: i = 1, 2, \dots, n$) and then return to distribution center; the food distributed are of single type and food safety continuously change; the demand quantity of retailer i is q_i and bounded with delivery time, otherwise rejected; the requirement is to arrange the dispatch sequence, dispatch time and routing of vehicles starting from fresh food distribution center in such a way as to minimize the total cost and maximize the safety of the distribution system subject

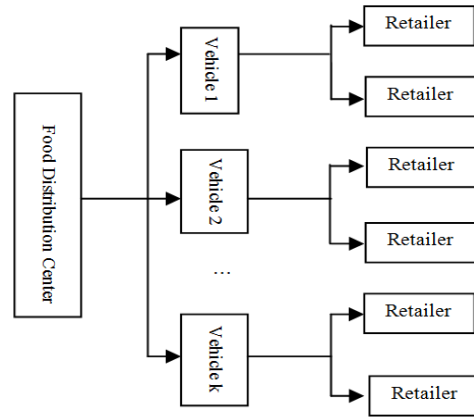


Fig. 1: Distribution system of fresh food

to delivery quantity fulfilling the need of retailers but not exceeding vehicle's load capacity.

Note that we set the lowest comprehensive distribution cost and the highest safety reliability as subjective function. The comprehensive distribution cost includes vehicle transport cost and loss cost of food safety reliability.

Here, we consider the duration of vehicle k departing from distribution site i until it leaving the next distribution site j to be a cold chain logistics unit U_{ij} , whose distribution time includes the travel time from distribution site i to j t_{ijk}^d and the process time at site j (containing loading and unloading time, receiving time and meal time) t_{ijk}^h :

$$t_{ijk} = t_{ijk}^d + t_{ijk}^h \quad (4)$$

Assume the temperature in the vehicle remains constant during the distribution process, then the loss of food safety reliability after it passes cold chain logistics unit U_{ij} is:

$$F_{U_{ij}} = d \sum_{j \in L} q_j \cdot \Delta T^2 t_{ijk} \quad (5)$$

L represents the set of sites following site i in route k . Because demand quantity of retailers are not identical, total loss of safety reliability is not only associated with delivery time but also with the sequence of retail sites in the route. Let n_k the number of retail sites committed to vehicle k , R_k the set of routes that vehicle k has passed, q_i^k the demand quantity of retail site of sequence i in route k , then total loss of food safety reliability from retail site of order $i-1$ to retail site of order i in route k is:

$$F_{U_{(i-1)i}} = d \Delta T^2 \sum_{j=i}^{n_k} q_j^k \cdot (t_{(i-1)i}^d + t_{ik}^h) \quad (6)$$

and loss of safety reliability in the entire distribution process is:

$$F = d\Delta T^2 \sum_{l=1}^K \sum_{i=1}^{n_k} \sum_{j=i}^{n_k} q_j^k \cdot (t_{(i-1)i}^d + t_{ik}^h) \quad (7)$$

Assume variable cost of the vehicle C_d is proportional to its travel time, then:

$$C_d = c \sum_{i=0}^n \sum_{j=0}^n \sum_{k=0}^m t_{ijk} x_{ijk} \quad (8)$$

where,

c = The transportation cost of vehicle per unit time
 t_{ijk} = The travel time of vehicle k in route section (V_i, V_j)
 $t_{ijk} = t_{jik}$

$$x_{ijk} = \begin{cases} 1 & \text{if vehicle } k \text{ passes section } (V_i, V_j) \\ 0 & \text{otherwise} \end{cases}$$

The sale of fresh food features high timeliness that have to limit its distribution with time windows. We apply hard time window constraints because of the characteristics of high timeliness and coordination in food cold chain logistics, consequently the constraint $m_j \leq e_j \leq n_j$ (where e_j is the arrival time of vehicle at the customer j) is appended to the optimization model.

To sum up, the fresh food distribution routing optimization model with time windows and load capacity is as follows:

$$\text{Min} Z = c \sum_{i=0}^n \sum_{j=0}^n \sum_{k=1}^m t_{ijk} x_{ijk} + c_p d \Delta T^2 \sum_{l=1}^K \sum_{i=1}^{n_k} \sum_{j=i}^{n_k} q_j^k \cdot (t_{(i-1)i}^d + t_{ik}^h)$$

$$s.t \quad \sum_{i=0}^n x_{ijk} = 1 \quad j = 0, 1, \dots, n; \quad i \neq j \quad (9)$$

$$\sum_{i=0}^n x_{ijk} = 1 \quad k = 1, 2, \dots, m; \quad i \neq j \quad (10)$$

$$\sum_{j=1}^n x_{ijk} = \sum_{j=1}^n x_{jik} \leq 1 \quad i = 0, \quad k = 0, 1, 2, \dots, m \quad (11)$$

$$\sum_{k=1}^m \sum_{j=0}^n x_{ijk} \leq m \quad i = 0 \quad (12)$$

$$m_j \leq e_j \leq n_j \quad (13)$$

$$\sum_{j=1}^{n_k} q_j^k \leq Q_0 \quad k = 0, 1, 2, \dots, m \quad (14)$$

$$\sum_{k=1}^K n_k = n \quad (15)$$

where,

Formula (9) : Each retail spot to be served once only, no duplicate service

Formula (10): Each retail spot to be served by one vehicle only

Formula (11): Each vehicle departs from the distribution center and returns to same distribution center

Formula (12): The number of vehicles departing from V_0 cannot exceed the total number of vehicles

Formula (13): The arrival time of vehicle must be within a range acceptable by retail sites

Formula (14): Vehicle load capacity

Formula (15): Services to all spots are not missed

SOLUTION

Fresh food distribution routing optimization problem with time windows is an extension of VRPTW problem, and hence a NP-hard problem without effective polynomial algorithms as of yet. Ant Colony Optimization (ACO) algorithms are heuristic methods proved effective to find approximation to large-scale TSP problem. MAX-MIN Ant System (MMAS) is the modification of ACO algorithm that can effectively prevent search stagnation by putting limits on maximum and minimum value of pheromone trails (τ_{\max} , τ_{\min}) on each path. The algorithm steps are as follows:

Step 1: Initialization of correlated variables: Set the initial time $\Delta \tau_{ij} = 0$, Pheromone trail on each path $\tau_{ij} = 1$, iteration number $nc \leftarrow 0$, $k \leftarrow 1$, vehicle driving time $T_{\text{solu}} = 0$, vehicle remaining load $Q_{\text{net}} = Q_0$, set of retail sites in outstanding demand $V_{\text{net}} = \{V_1, V_2, \dots, V_n\}$, $Z_{\text{best}} = M$, M is a relatively large positive number.

Step 2: Define the set of allowable candidate moves by ants V_{allow} via the restraints of vehicle load capacity and time windows. Judge whether V_{allow} is an empty set, if it is, set $k \leftarrow k + 1$, $T_{\text{solu}} = 0$, $Q_{\text{net}} = Q$, $V_{\text{allow}} = V_{\text{net}}$.

Step 3: Calculate the move probability of ants' candidate nodes:

$$P_{ij}^k = \frac{[\tau_{ij}]^\alpha \cdot [\eta_{ij}]^\beta}{\sum_{l \in V_{\text{allow}}} [\tau_{ij}]^\alpha \cdot [\eta_{ij}]^\beta} \quad (16)$$

If $j \in V_{\text{allow}}$, generate a random number and choose the next node V_j , ants are to be positioned according to the mentioned random number and probability, then update Q_{net} , T_{solu} and V_{net} .

Table 1: The demands and time requirements of distribution sites

Retail sites	1	2	3	4	5	6	7	8
Demand	0.6	0.5	0.4	0.75	0.5	0.4	0.8	1.0
Processing time	0.5	0.5	0.3	0.6	0.4	0.5	0.8	0.8
Time window	(1, 3)	(1, 5)	(4, 7)	(2, 4)	(1, 4)	(1, 5)	(4, 8)	(2, 5)
Retail sites	9	10	11	12	13	14	15	
Demand	1.2	0.75	0.6	1.0	0.4	0.5	0.6	
Processing time	1.0	0.5	0.8	1.0	0.2	0.4	0.6	
Time window	(2, 5)	(3, 5)	(4, 6)	(1, 2)	(2, 4)	(2, 7)	(3, 5)	

Table 2: Optimized results

Items	Path					
	0-9-2-0	0-8-6-3-0	0-12-4-0	0-13-10-11-0	0-5-15-14-0	0-1-7-0
Vehicle number	1.0	2.0	3.00	4.00	5.0	6.0
Deadweight tonnage (tons)	1.7	1.8	1.75	1.75	1.6	1.4
Travel distance (km)	225.0	325.0	175	235.00	270.0	180.0
Travel time (h)	6.0	8.1	5.10	6.20	6.8	4.9
Transportation cost (RMB Yuan)	225.0	325.0	175.00	235.00	270.0	180.0
Loss of safety (RMB Yuan)	56.1	74.8	47.00	29.30	56.6	45.0
Distribution cost (RMB Yuan)	281.1	399.8	222.00	264.30	326.6	225.0

Step 4: Judge whether V_{net} is an empty set. If not, return to step 2; if it is an empty set, means The deliveries to all sites have accomplished, then take note of number of ants $m \leftarrow k$.

Step 5: Update pheromone trails on each side (i, j) :

$$\tau_{ij}(t+1) = \rho\tau_{ij}(t) + \Delta\tau_{ij}(t) \quad (17)$$

Step 6: Define and update the higher bound and lower bound on values of pheromone trails:

$$\tau_{ij}^{max}(t) = \begin{cases} \rho^k \cdot \tau_{ij}(0) + \frac{1}{1-\rho} \frac{2}{f(S^{gb})} \\ \frac{1}{1-\rho} \frac{2}{f(S^{gb})} \end{cases}$$

Otherwise; $0 < k < 8, k > 8$

Step 7: Concerning each side (i, j) : Set $\Delta\tau_{ij} \leftarrow 0$; $nc \leftarrow nc + 1$. Calculate objective function value and judge whether the value has improved. Take note of the solution so far if the target function value is improved.

Step 8: If $nc < N_C$ (the maximum iteration number with no change of best-so-far solution), re-iterated; otherwise abort.

Case: A distribution center of certain fresh milk producer covers 15 retail sites demanding for distribution service. The load capacity of vehicle is no more than 2 tons; the demand quantity of 15 sites, the arrival time windows of conveyances and the processing time after arrival are shown in attached Table 1; Assume distribution temperature is 10°C, fresh milk's experimental constant $d = 10^{-5}$, traffic conditions among the distribution sites are same, the vehicle speed is 50 km/h, unit transportation cost is RMB Yuan 1.00/km, unit loss of fresh milk's safety is RMB Yuan 10,000/ton. The problem is how should the distribution center arrange its distribution route and priority order so

as to obtain the lowest logistics distribution costs (distribution cost and loss cost of safety) satisfying the constraints of arrival time windows.

We use MATLAB 7.0 for programming and substitute with the parameters and distance matrix, $\alpha = 1, \beta = 5, \rho = 0.5$, number-of-ants = 15, $NC = 10$. The results show that it requires 6 vehicles for the distribution service and the routing is: 0-9-2-0, 0-8-6-3-0, 0-12-4-0, 0-13-10-11-0, 0-5-15-14-0, 0-1-7-0. The load capacity and distribution costs of each vehicle are shown as Table 2. For this case, the total distribution cost is RMB Yuan 1,718.80.

CONCLUSION

It is necessary to consider loss of food safety reliability when evaluate fresh food distribution routing optimization problem, consequently it will be more difficult to solve the distribution routing optimization model. The example demonstrates that using MMAS can better solve fresh food delivery routing optimization problem with time windows.

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