

A Model for Vehicle Routing Problem for Multi-Temperature Joint Distribution System with Carbon Emission Constraints

Hao Sun

School of Management, Shanghai University
Shanghai, China
E-mail: sunhao576@163.com

Abstract—This paper aims to study the optimal location and vehicle routing problem in Multi-Temperature Joint Distribution System. We have constructed a food cold chain model that takes into account the carbon emissions into its objective function. The proposed model simultaneously minimizes logistic costs and environmental impacts of carbon emissions by providing a bi-objective binary integer-programming model. What's more, a numerical example are presented to verified the validity of the model. The result indicate that this model is feasible for the optimal location and vehicle routing problem. This model contributes to decision makers to find the best Pareto Optimal solutions in Multi-Temperature Joint Distribution System according to their preference.

Keywords- *Multi-temperature joint distribution system; Carbon emission; Vehicle routing problem*

I. INTRODUCTION

Nowadays, customers, governments, companies, non-profit and profit organizations, all of them are very concerned about the problem of climate change and environmental protection. Sustainable and green development is an inevitable trend for the economic in the future. Environmental issues can also impact on numerous logistical decisions throughout the supply chain such as location, sourcing of raw material, modal selection, and transport planning, among others [1]. In this case, sustainable and green supply chain management is a high topic in supply chain management area. Therefore, it is necessary for designing and operating of supply chain with the targets in decreasing carbon emissions and other environmental metrics.

The food cold chain involves to the safety levels and quality of food. Through the control and monitor of temperature, the cold chain can reduce the rate of degradation of food, maintain the freshness of food. Multi-Temperature Joint Distribution System (MTJD) was presented by Kuo [2]. It was developed by the Energy and Resource Laboratory, Industrial Technology Research Institute in Taiwan [3]. This method is a technique to transport and storage of food in multi-products and multi-temperature cold logistics, which could realize the optimal temperature control for all kinds of perishable foods with different temperature requirements. MTJD through using a replaceable cold accumulation and insulated box (cold box), dividing a vehicle compartment into several zones to

storage different foods whose optimal preserving temperature is different. Due to the demand for various kinds of food in retailer, MTJD will have a great application value on routes between hubs and retailers in logistics. This paper aims to study the optimal location and vehicle routing problem in MTJD. We have constructed a food cold chain model that takes into account the carbon emissions into its objective function. The proposed model simultaneously minimizes logistic costs and environmental impacts of carbon emissions by providing a bi-objective binary integer-programming model. We hope that through this model to help decision makers to find the best Pareto Optimal solutions in MTJD.

The rest of the paper is structured as follows: Section 2 we review some of relevant current studies in food cold chain and in multi-temperature joint distribution. Section 3 describes the problem modeling and the formulation of the binary integer programming model. Section 4 introduces the solution method. Section 5 presents a numerical example to illustrate the application and results of the proposed model. Finally, Section 6 concludes our main findings and offer some suggestions for future studies.

II. LITERATURE REVIEW

A. Carbon emission constraints for food cold chain

Due to the importance of food supply chain management, many researchers have studied the food cold chain with emission constraints. Validi have studied the design of a capacitated distribution network involved in the distribution of milk with the carbon emission constraints, and present a green multi-objective optimization model minimizes CO₂ emissions from transportation and total costs in the distribution chain [4]. Soysal have researched the logistical network problems of perishable food products under emissions consideration, they considered road structure, vehicle and fuel types, loads, distances and return hauls while integrating emissions into a MOLP model [5]. Govindan introduced a two-echelon location-routing problem with time-windows for sustainable supply chain network design and optimizing economic and environmental objectives in a perishable food supply chain network [6]. Soysal presented a new multi-period inventory routing problem model that includes truck load dependent distribution costs for a comprehensive evaluation of CO₂ emission and fuel

consumption, which is more useful for the decision makers in food logistics management [7]. The above literatures have made a great research achievement in the design and optimization of food cold chain logistics network. But it is regrettable that these studies mainly considered the food cold chain logistics with only a single product. It is more realistic and meaningful to research the distribution of multi products in the supply chain.

B. Multi-temperature joint distribution System

Multi-temperature joint distribution system is a relatively new topic in supply chain research field. The research in this field is still not enough. Kuo first proposed the Multi-Temperature Joint Distribution System for the food cold chain. This technology could facilitated innovation in logistics services and gave the logistics sector a competitive advantage in the area of thermal protection for perishable shipments and temperature sensitive products [2]. Hsu and Liu have modeled facilities planning for multi-temperature joint distribution for food, they compared and incorporated the features of different techniques into the model, then found an optimal strategies for the terminals and routing in hub and spoke operation [3]. In addition, Hsu considered dynamic demands and various temperature control techniques in modelling the operation planning for joint multi-temperature food distribution. Through this model to determine the optimal delivery cycles for different temperature range foods [8]. Tao Rong proposed a multi-temperature joint distribution technology and presented the general path for its implementation, then they built the multi-temperature cold chain joint distribution optimization model that comprehensively considered the cost of distribution, cargo loss and penalty [9].

Through the review of the literatures we can find that there are many scholars have studied respectively on the food cold chain with emission constraints and multi-temperature joint distribution system. But few scholars present a discussion on the multi-temperature joint distribution system with emission constraints. This is the reason we study the vehicle routing problem of multi-temperature joint distribution system with carbon emission constraints for food cold chain..

III. PROBLEM DESCRIPTION

In this model, we study a food cold chain network which including suppliers, distribution centers and retailers (Fig. 1). Every supplier supplies different kinds of food, which the best storage conditions (mainly the temperature) is different. In order to keep the food is fresh and safety, all the food must be stored in the best storage conditions through the whole food cold chain network. All kinds of food are distribute from suppliers to distribution centers to retailers. At the stage of distribution from suppliers to distribution centers, all the food is distributed with the traditional frozen vehicle and refrigerated vehicle. But at the stage of distribution from distribution centers to retailers, all the food is distributed in the multi-temperature joint distribution. What's more, the environmental impact in this network, such as the carbon emissions is taken into account. In addition, we assume that the carbon emission is related to open distribution centers, delivery and the use of

replaceable cold accumulation and institute boxes. As a result, firstly, we should decide which point is the best location to build distribution center; secondly, we should optimize the vehicle routing. So we propose a bi-objective binary integer-programming mathematics model. The objectives include the minimization of total cost of food cold chain and the minimization of total emission of carbon in the network. We aim to study two problem in the multi-temperature joint distribution: (a) the best number and location of distribution centers, (b) the most optimal vehicle routes.

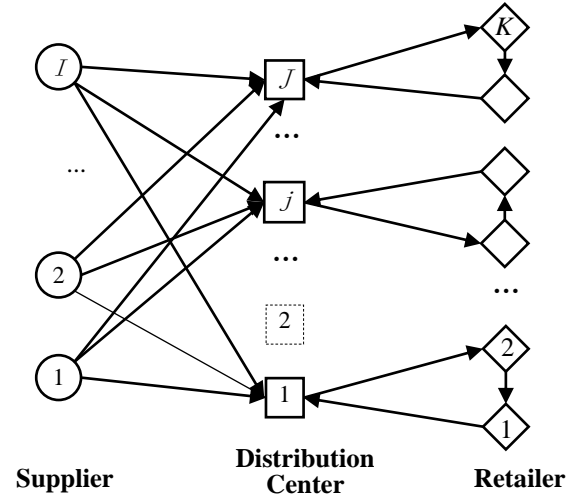


Figure 1. A schematic example of a vehicle routing problem in the food cold chain network

A. Assumptions

Some main assumptions involved in this problem are as follows:

- There is no spoilage takes place during the transportation of every food.
- This model does not consider the recycling reverse logistics of food.
- The demand of retailers is certain and known. All of the demand must be satisfy by distribution centers.
- Each retailer's demand of all kinds of foods' can only be satisfied by only one distribution center, and be delivered by only one vehicle. Suppliers cannot directly to distribute food to retailers.
- Each vehicle can only service a distribution center, and every vehicle must return to its distribution center of origin.
- There are plenty of vehicles and cold boxes can be used in this model.
- Distribution centers have limited capacity.
- The total cost of supply chain includes opening costs of distribution centers, transportation costs and the fixed cost of using cold boxes.
- The quantity of carbon emissions of the food cold chain is classified into three categories: (a) the quantity of carbon produced by the opening of distribution centers; (b) the quantity of carbon produced by the vehicles during the transportation; (c) the quantity of carbon produced by the using of the cold boxes.

B. Notations

The following notations are used in the proposed model:

1) Sets of indices:

- I The set of indices $\{i = 1, 2, \dots, I\}$ used for suppliers
- J The set of potential distribution centers $\{j = 1, 2, \dots, J\}$
- K The set of indices $\{k = 1, 2, \dots, K\}$ used for retailers
- C The set of indices $\{c = 1, 2, \dots, C\}$ used for cars

2) Parameters:

- l_{ij} Distance between suppliers i and distribution center j .
 - l_{jk} Distance between distribution center j and retailer k .
 - $l_{kk'}$ Distance between retailer k and retailer k' .
 - C_j^i Handling capacity of distribution center j for the food of supplier i .
 - C_b^i Handling capacity of box for the food of supplier i .
 - p Maximum number of boxes loads in a vehicle.
 - D_{\max} Maximum desired number of distribution centers.
 - d_k^i Demand required by retailer k to the supplier i .
 - F_j Opening cost of distribution center j .
 - F_b^i Average cost unit time when the replaceable cold accumulation and institute boxes distribute food i with optimal temperature control.
 - F_i Average cost unit distance when traditional frozen vehicle distribute food i with optimal temperature control.
 - F_0 Average cost unit distance of regular vehicle in the multi-temperature joint distribution.
 - E_j The quantity of carbon emissions of opening distribution center j .
 - E_i Average quantity of carbon emissions of unit distance when traditional frozen vehicle distribute food i with optimal temperature control.
 - E_0 Average quantity of carbon emissions of unit distance when regular vehicle distribute food.
 - E_b^i Average quantity of carbon emissions of unit time when the replaceable cold accumulation and institute boxes distribute food i with optimal temperature control.
 - ρ Weight coefficient, which is used to weigh the influences of the construction of distribution centers in this model.
- ### 3) Decision variables:
- $\mu_j = \begin{cases} 1 & \text{if distribution center } j \in J \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$
 - $Z_{jk}^c = \begin{cases} 1 & \text{if distribution center } j \in J \text{ service retailer } k \in K \text{ with vehicle } c \\ 0 & \text{otherwise} \end{cases}$
 - $\omega_{jk}^c = \begin{cases} 1 & \text{if vehicle } c \text{ traverses arc } (j, k) \\ 0 & \text{otherwise} \end{cases}$
 - $\omega_{kk'}^c = \begin{cases} 1 & \text{if vehicle } c \text{ traverses arc } (k, k') \\ 0 & \text{otherwise} \end{cases}$
 - y_c^i The amount of the cold boxes which is used to ship food of supplier i in the vehicle c .

C. The binary integer-programming model

$$\text{Min OBJ1} = \rho \cdot \sum_{j \in J} F_j \cdot \mu_j +$$

$$\sum_{i \in I} \sum_{j \in J} F_i \cdot l_{ij} \cdot \mu_j + \sum_{c \in C} \sum_{j \in J} \sum_{k \in K} F_0 \cdot l_{jk} \cdot (\omega_{jk}^c + \omega_{kj}^c) + \sum_{c \in C} \sum_{k \in K} \sum_{k' \in K} F_0 \cdot l_{kk'} \cdot \omega_{kk'}^c + \sum_{i \in I} \sum_{c \in C} F_b^i \cdot y_i^c \quad (1)$$

$$\text{Min OBJ2} = \rho \cdot \sum_{j \in J} E_j \cdot \mu_j +$$

$$\sum_{i \in I} \sum_{j \in J} E_i \cdot l_{ij} \cdot \mu_j + \sum_{c \in C} \sum_{k \in K} \sum_{k' \in K} E_0 \cdot \omega_{kk'}^c \cdot l_{kk'} + \sum_{c \in C} \sum_{j \in J} \sum_{k \in K} E_0 \cdot l_{jk} \cdot (\omega_{jk}^c + \omega_{kj}^c) + \sum_{i \in I} \sum_{c \in C} E_b^i \cdot y_i^c \quad (2)$$

$$\sum_{j \in J} \mu_j \leq D_{\max} \quad (3)$$

$$\sum_{c \in C} \sum_{j \in J} Z_{jk}^c \leq 1 \quad \forall k \in K \quad (4)$$

$$\sum_{c \in C} \left(\sum_{j \in J} \omega_{jk}^c + \sum_{k' \in K} \omega_{kk'}^c \right) = 1 \quad \forall k \in K \quad (5)$$

$$\sum_{c \in C} \left(\sum_{j \in J} \omega_{jk}^c + \sum_{k' \in K} \omega_{kk'}^c \right) = 1 \quad \forall k \in K \quad (6)$$

$$\sum_{k \in K} \omega_{jk}^c - \sum_{k' \in K} \omega_{k'j}^c = 0 \quad \forall c \in C, \forall j \in J \quad (7)$$

$$\omega_{jk}^c \leq Z_{jk}^c \quad \forall c \in C, \forall j \in J, \forall k \in K \quad (8)$$

$$\sum_{j \in J} \sum_{k \in K} \omega_{jk}^c \leq 1 \quad \forall c \in C \quad (9)$$

$$\sum_{j \in J} \sum_{k \in K} \omega_{kj}^c \leq 1 \quad \forall c \in C \quad (10)$$

$$\sum_{k \in K'} \sum_{k' \in K'} \omega_{kk'}^c \leq |K'| - 1 \quad \forall c \in C, K' \subseteq K, |K'| \geq 2 \quad (11)$$

$$\sum_{c \in C} \sum_{k \in K} d_k^i \cdot Z_{jk}^c \leq C_j^i \cdot \mu_j \quad \forall j \in J, i \in I \quad (12)$$

$$\sum_{j \in J} \sum_{c \in C} \sum_{k \in K} d_k^i \cdot Z_{jk}^c \leq \sum_j C_j^i \cdot \mu_j \quad \forall i \in I \quad (13)$$

$$\sum_{j \in J} \sum_{k \in K} d_k^i \cdot Z_{jk}^c \leq y_i^c \cdot C_b^i \quad \forall c \in C, i \in I \quad (14)$$

$$\sum_{i \in I} y_i^c \leq p \quad \forall c \in C \quad (15)$$

$$\mu_j \in \{0, 1\} \quad \forall j \in J \quad (16)$$

$$Z_{jk}^c \in \{0, 1\} \quad \forall j \in J, k \in K, c \in C \quad (17)$$

$$\omega_{jk}^c \in \{0, 1\} \quad \forall j \in J, k \in K, c \in C \quad (18)$$

$$\omega_{kk'}^c \in \{0, 1\} \quad \forall k \in K, k' \in K, c \in C \quad (19)$$

Equation (1) is the objective function of the total cost of food cold chain, which includes opening costs of distribution centers, transportation costs and the fixed cost of using cold boxes. What's more, from a long-term perspective, because this model just consider a single cycle to optimal the design of food cold chain network, the role of ρ is to weigh the influence of distribution centers in this model. Equation (2) is the objective function minimize the total carbon emissions, which includes the carbon produced by the opening of distribution centers, transportation and cold boxes. Constrains (3) guarantee

that the amount of opened distribution centers should not exceed D_{max} . Constrains (4) ensures that each retailer is serviced by a single distribution center and a single vehicle. Constrains (5-6) illustrate that if retailer k was serviced by vehicle c , there should be a single path for c to enter k and a single path to leave. Constrains (7-10) guarantee that each vehicle should utmost service to a distribution center, leave and finally return to its distribution center of origin. Constrains (11) to avoid sub tours. Constrains (12) ensures that the storage capacity of distribution center j in food i should be respected, and if distribution center j was opened, the total quantity of i food of retailers, which was serviced by j , should not exceed the capacity of distribution center j . Constrains (13) ensures that the total storage capacity of opened distribution centers should satisfy the total demand of retailers. Constrains (14) guarantee that the total quantity of food i of retailers which is serviced by vehicle c should not exceed the total capacity of cold boxes which is used to ship food i in the vehicle c . Constrains (15) limits the amount of cold boxes in every vehicle should not exceed ceiling p . Constrains (16-19) indicates that some of the decision variables in this model are binary integers

IV. SOLUTION METHODS

It is clear that this model is a multi-objective mathematical programming problem. It is different to find a solution to make each objective to achieve the optimal value at the same time. Instead, a Pareto Optimal solution is a feasible point in the solution space, which as a consequent of a trade-off between objective functions is inevitable. Normally, maxi-min method, ϵ -constraint method, goal programming, utility function method are applied for solving multi-objective mathematical programming problem. Mavrotas^[10] proposed an augmented ϵ -constraint method to solve multi-objective problem. The augmented ϵ -constraint method taken out some defects of the conventional method, such as, uncertainty about efficiency of the obtained solutions, increasing in solution time when there are more than two objective functions [11]. Therefore, we decide to solve this model with the augmented ϵ -constraint method. General algebraic modeling system (GAMS) was used to realize this method. And the CPLEX solver is employed to solve the proposed model.

V. NUMERICAL EXAMPLE

Now we will present an application of the proposed model using a numerical example. We assume that there was a food cold chain logistics network in a city. The network includes 3 suppliers ($I=3$), 5 potential points ($J=5$) to build distribution centers, and 12 retailers ($K=12$) random division in the corners of the city. All the retailers have a random extraction of characteristics, such as location, amount of every food demand. Three suppliers supply three kinds of perishable foods, whose optimal preserving temperature is different, such as frozen, refrigerated and regular temperatures. In this example, we assume that $\rho=0.4$, $p=4$, $D_{max}=3$, $f_0=3RMB/km$. The values of carbon emissions related parameters based on the literature[12], we can get the value of parameters: $E_0=0.438kg/km$. Through the information we can get that per 1 kwh electricity emit CO_2 785g, then we can calculate that

$$E_b^{i1} = 15.7kg/time, E_b^{i2} = 11.7kg/time, E_b^{i3} = 7.86kg/time.$$

Other data are shown in Table I-V.

TABLE I. DISTANCE FROM DISTRIBUTION CENTER TO RETAILERS (KM)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12
J1	30	50	35	40	40	110	65	30	35	105	100	80
J2	60	25	50	80	35	70	80	90	30	120	40	35
J3	70	55	25	35	80	40	30	35	65	40	60	90
J4	55	25	20	50	50	15	30	50	20	35	35	40
J5	110	40	50	90	90	25	30	100	75	30	35	55

TABLE II. DISTANCE BETWEEN THE RETAILERS (KM)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12
K1	0	40	40	40	100	90	90	25	35	105	120	110
K2	-	0	50	90	30	30	50	70	25	55	30	30
K3	-	-	0	35	55	30	30	40	35	50	60	75
K4	-	-	-	0	70	65	40	25	55	60	90	90
K5	-	-	-	-	0	60	70	50	25	100	45	30
K6	-	-	-	-	-	0	30	60	40	25	30	50
K7	-	-	-	-	-	-	0	50	45	25	40	75
K8	-	-	-	-	-	-	-	0	40	80	85	80
K9	-	-	-	-	-	-	-	-	0	50	40	35
K10	-	-	-	-	-	-	-	-	-	0	40	90
K11	-	-	-	-	-	-	-	-	-	-	0	40
K12	-	-	-	-	-	-	-	-	-	-	-	0

TABLE III. DEMAND OF RETAILERS (T)

	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12
I1	0.4	0.9	1.1	0.5	0.8	1	0.6	0.6	1	0.6	0.6	0.7
I2	0.5	0.8	0.6	0.8	0.4	1.2	0.7	0.4	1.1	0.9	0.9	0.5
I3	0.7	1.2	0.7	1	1	1.5	0.9	1	0.8	0.5	1	0.5

TABLE IV. OPENING COSTS AND CARBON EMISSIONS OF DISTRIBUTION CENTERS

	J1	J2	J3	J4	J5
Opening costs (RMB)	165000	180000	170000	200000	165000
Carbon emissions (kg)	800	700	760	650	800

Table VI show us the detail of some solutions. These results show us that when the total cost of food cold chain are optimal, $J1$ and $J5$ are selected to open distribution centers, and there are four paths to realize the distribution of all the retailers' demand. But when the total carbon emissions get its optimal value, $J1$ and $J4$ are selected to open distribution, and the paths are different with the results of above.

According to the results shown in Fig 2. We can find that there is no solution could optimize both objective functions simultaneously. But all the solutions are effective for this model. From the trend line we can also find that carbon emissions are gradually increasing with the decrease of total cost. When total costs get the best

target, the value of carbon emissions will be very big. As a result, the decision makers can choose the Pareto Optimal solution according to their preference.

TABLE V. CAPACITY OF DISTRIBUTION CENTER (T)

	J1	J2	J3	J4	J5
I1	8	8	8	6	9
I2	8	8	8	6	9
I3	10	9	10	8	10

TABLE VI. SOME RESULTS OF PARETO OPTIMAL SOLUTIONS

Pareto optimal solutions		path
1	Total cost (RMB)	138160
	Total carbon emissions (kg)	1879.4
		J5-K10-K7-K3-J5 J5-K11-K6-J5 J1-K1-K8-K4-J1 J1-K9-K2-K12-K5-J1
2	Total cost (RMB)	143270
	Total carbon emissions (kg)	1703.75
		J2-K5-K1-K9-J2 J2-K12-K2-K11-J2 J3-K3-K9-K5-J3 J3-K4-K8-K1-J3
3	Total cost (RMB)	151830
	Total carbon emissions (kg)	1629.95
		J1-K3-K8-K4-J1 J1-K9-K5-K12-K1-J1 J4-K7-K10-K11-J4 J4-K6-K2-J4

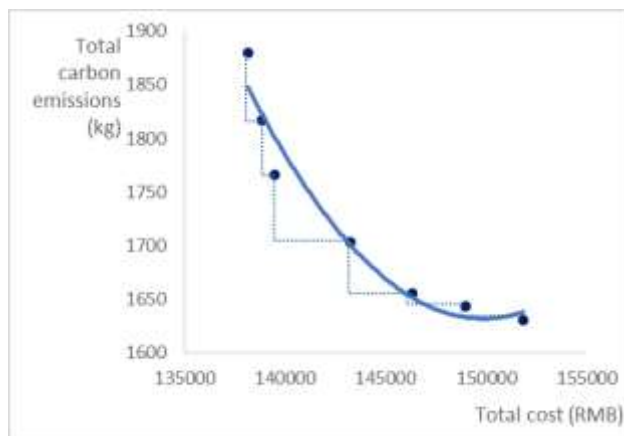


Figure 2. Pareto optimal fronts of this example

VI. CONCLUSIONS

The Compared to multi-temperature joint distribution system (MTJD) with traditional multi-vehicle distribution, MTJD has obvious advantages in joint distribution of multi-products. MTJD is more flexible and convenient. In the terminal distribution of multi-products cold chain logistics, MTJD will have a great promotion value in the future. This study mainly research the design of network of MTJD in multi-products cold chain logistics with carbon emissions. We innovatively construct a binary

integer-programming model which simultaneously minimizes logistic costs and environmental impacts of carbon emissions. From this model we can get the optimal location and routing planning with the consideration of logistics cost and environmental metrics. This model's Pareto Optimal solutions will give decision makers more conducive suggest on the sustainable development.

Several extensions could be made in future studies. Future studies could take account stochastic demand and time-windows into modeling. What's more, researchers can pay more attention to the different aspects of sustainability of food cold chain. Last but not list, future studies could consider some reality elements in the design of food cold chain, such as emergencies, the timeliness of perishable food.

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