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A model for facilities planning for multi-temperature joint distribution system

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ABSTRACT

New technologies, such as replaceable cold accumulation and insulation box multi-temperature joint distribution (MTJD), provide precise temperature control, thereby reducing negative effects on food quality from exposure to extreme temperatures. This study compares conventional technologies with new ones, and constructs a binary integer-programming model to determine multi-temperature logistics techniques and food handling volume required for maximization of cost-efficiency in a hierarchical hub and spoke (H/S) network. It does so by minimizing the total delivery cost, comprised of terminal, food handling, and vehicle transportation costs computed, separately, by a derived algorithm. Appropriate technique(s) and handling volume for each terminal and vehicle routing are solved by Branch & Bound method, under the "best-first search" principle. The results indicate the model is feasible for facilities planning for MTJD. The replaceable cold accumulation and insulation box MTJD technique is suitable for operation networks with densely distributed terminals and uneven temporal and/or spatial demand distribution.

1. Introduction

This study aims to construct a model to solve complicated facilities planning problems associated with multi-temperature joint distribution (MTJD). The model deals with selection of alternative configurations of equipment and facilities, and assignment of multi-temperature food in a fixed H/S network. The advantages and disadvantages of various techniques are analyzed to provide operators with a valuable reference when choosing short- or medium-term strategies.

In this study, multi-temperature logistics is defined as encompassing all processes involving the movement and storage of food, where optimal temperature control is necessary to maintain their original value and quality. Kuo (2002) classified current multi-temperature logistics techniques into two general approaches. One is the single-temperature distribution method (i.e., each vehicle distributes food in only one temperature range) which represents the traditional multi-vehicle distribution technique (Technique 1). Either regular or refrigerated vehicles are used, depending on the temperature range of the food. Although the technique requires a large initial investment, it yields cost benefits due to economies of scale. It also involves less labor, fewer facilities, and less time than the other techniques since food handling, loading, and unloading at terminals with this type of distribution method are relatively simple.

The other is the multi-temperature joint distribution (MTJD) approach, in which each vehicle can distribute food of varying temperatures, and can be further divided into two types. The first type is mechanical refrigerated compartment division multi-temperature joint distribution technique (Technique 2). This is currently the most commonly used MTJD method, and is often combined with Technique 1 above. That is, the operator uses Technique 1 to distribute food on routes between hubs, and applies Technique 2 on routes between hubs and customers. The technique involves dividing a single vehicle compartment into different zones of regular, refrigerated, and frozen temperatures. This technique also involves a low level of labor, facility-use, and time. The second type is replaceable cold accumulation and insulated box multi-temperature joint distribution technique (Technique 3). This MTJD technique was developed by the Energy and Resource Laboratory, Industrial Technology Research Institute in Taiwan. It utilizes replaceable cold accumulators (eutectic plates) of different-temperatures and sizes in standardized cold insulated boxes and cabinets to maintain precise temperatures. Cold accumulators accumulate cold through freezers installed at terminals. The boxes and cabinets with cold accumulators are then used in regular vehicles, which enhance flexibility. This technique offers good compartment utilization, flexibility, excellent temperature control, low equipment cost, and long service-life; added to which, it is environmentally friendly. However, there are also disadvantages, such as lack of economies of scale and significant food handling expenses. Table 1 compares and contrasts the technological

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Table 1
Comparison of multi-temperature logistics techniques.

Technique type	1 Traditional multi-vehicle distribution	2 Mechanical refrigerated compartment division	3 Replaceable cold accumulation & insulated box
Technique characteristics	Distributed separately using various temperature vehicles	Compartments divided into different-temperature divisions, refrigerator unit driven by engine	Replaceable cold accumulation & insulated box (without refrigerator unit)
Vehicle equipment	Frozen vehicle refrigerated vehicle regular vehicle	Refrigerated vehicle (with compartment division)	Regular vehicle (with accumulation & insulated box)
Terminal equipment	Frozen warehouse refrigerated warehouse regular warehouse	Frozen warehouse refrigerated warehouse regular warehouse	Regular warehouse & freezers
Distribution mode	Single-temperature distribution	Multi-temperature joint distribution	Multi-temperature joint distribution
Freezing system	Individual vehicle freezer	Individual vehicle freezer	Collective freezer
Fault rate	High	High	Low
Temperature consistency	Low (mechanically refrigerated)	Low (mechanically refrigerated)	High
Space flexibility	Low	Medium	High
Operating cost	High	High	Low
Fixed cost	High	High	Low
Single distribution volume	High	High	Low
Loading time	Short	Short	Long

features, vehicle types, and equipment associated with the above techniques, and summarizes their advantages and disadvantages.

There is scant literature dealing with multi-temperature logistics. Kuo and Chen (2010) developed an advanced Multi-Temperature Joint Distribution System for the food cold chain. Cho and Li (2005) conducted a study on a multi-temperature storage box vehicle routing problems, based on application of Technique 3. There are more studies related to perishable commodities and low-temperature logistics than multi-temperature logistics (Charkrabarty, Giri, & Chaudhuri, 1998; Giri & Chaudhuri, 1998; Hariga, 1996; Hsu, Hung, & Li, 2007; Jacxsens, Devlieghere, & Debevere, 2002; Zhang, Habenicht, & Spieβ, 2003), but most of them focus on discussions regarding stock models or VRP of perishable commodities.

Food distribution strategy is currently tending toward the use of shipments containing a variety of food types, in small amounts and at varying temperatures, and there are few studies to support this shift. Thus, studies in this area will make contributions not only from an academic but also from a practical perspective. Because of the obvious advantages associated with new technology, analyzing its application possibilities and its impact is important. Recent MTJD techniques offer more diversified alternatives that provide freight operators with more choices in regard to what is best for their distribution service. However, since each technique has different strengths, operators need to determine the best techniques for various routes and terminals in accordance with their distribution demands. This study takes into account the configuration of an operational network, the temporal and spatial distribution of different-temperature food demands, variations in costs, and the capacity utilization of each multi-temperature technique. The combinations of various techniques available for operation in service networks increase exponentially with the numbers of terminals and routes in use. In addition, the use of vehicles of various sizes may influence decisions as to how and which techniques should be applied at terminals.

Based on the above considerations, this study constructed a model to determine optimal multi-temperature logistic techniques for terminal and vehicle routing operations by minimizing the total delivery costs of transportation and food handling. The remainder of this paper is organized as follows. Section 2 describes the formulation of the binary integer-programming model. The algorithm for solving the vehicle transportation cost is introduced in Section 3. Section 4 presents a case study to illustrate the feasibility and results of the models and, finally, in Section 5 we draw our conclusions and offer some suggestions for future studies.

2. The binary integer-programming model

Operation networks can be classified into Line-haul Operation and Local Service networks. Logistics operators commonly divide the entire distribution region into several clusters, each consisting of several depots and one hub, which collect and distribute all food to or from depots. These depots are the mediums between the operator and customers. The distribution service between depots and the customers belongs to the local service network and is not included in this study. The study focuses mainly on discussion of Line-haul Operation Networks, which are similar to hierarchical H/S networks, as shown in Fig. 1.

Based on the work of Bryan and O'Kelly (1999), the hierarchal H/S network in this study is characterized by the assignment of a single hub (i.e., a depot can be assigned to only one hub in each cluster). The entire Operations Network is divided into several clusters. The paths inside the cluster are the secondary lines, which connect each depot to its hub. The secondary line has a unidirectional loading or unloading feature (Current, 1988; Current, ReVelle, & Cohon, 1986; Lin, 2001; Lin & Chen, 2004) and takes the hub in the cluster as the origin and destination for vehicle routing, allowing stops midway. The hubs are connected by large-sized

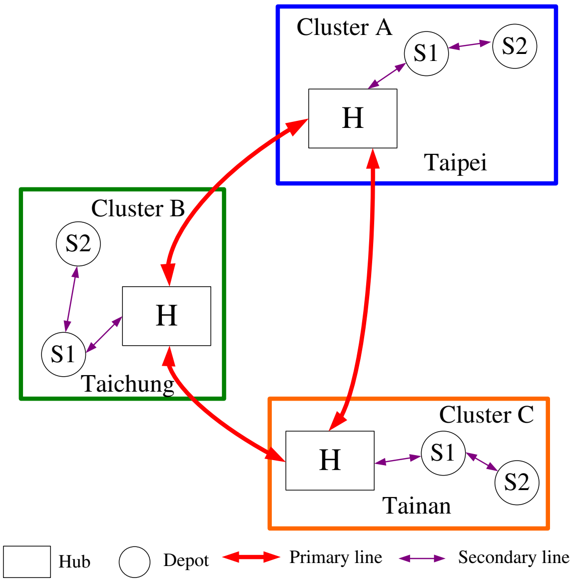

Fig. 1. Basic form of hierarchical hub and spoke network.

vehicles on a path called the primary line that can accommodate loading/unloading operations. The vehicle path in this study has features for vehicle type and capacity; therefore, the path does not conform to the features of the minimum spanning tree.

This study aimed to minimize daily delivery costs, including transportation and food handling costs. Transportation costs include the terminal cost and the vehicle cost, part of which is the fixed cost of the initial investment, which is mainly related to the vehicle's type and size. Vehicles of different types also differ in maintenance costs and service-life. The operating cost incurred from vehicle deliveries refers to the cost of fuel consumption, and is mainly related to the delivery distance (vehicle path), vehicle type, and size. In this study, these vehicle costs are generally viewed as vehicle purchase and operating costs. Terminal costs include an initial setup and operating cost and are related to the adopted technology and handling volume. For regular food free of temperature control requirements, those costs do not vary due to the adopted technology. Food handling costs arise from the process of food loading and unloading in the terminals, and are commonly outsourced.

As vehicle size increases, vehicle purchase and operating costs increase, yet the average fixed cost per unit of food decreases for the capacity load of a vehicle, thereby resulting in economies of vehicle size. The size and type of vehicles can directly influence the choice of terminal techniques. This study develops a problem-solving framework to simplify the problem and incorporate the effect into our model.

First, we focus on constructing a binary integer-programming model by minimizing the terminal transportation and food handling costs to determine the techniques and the food handling volumes for the terminals. Second, we relax the integer constraints based on the results of the first model in order to develop an algorithm to determine vehicle transportation cost and routing operations. Then we combine the results of the model and the algorithm to search for the appropriate technique(s) for each terminal and vehicle routing operations according to the Branch and Bound method using "the best-first search" approach. By applying this approach, the model is not only featured with economies of vehicle size but can also be solved in Polynomial-time. Table 2 describes the symbols and the definitions of the parameters and decision variables used in the binary integer-programming model.

Based on practical situations noted in our research, we have divided terminal procedures into outbound and inbound, each including food handling and storage processes. The configurations of equipment for inbound and outbound could be different, but the extent of imbalances on the solution of the model is limited due to the fact the model takes into account cost features, such as economies of scale, and minimizes the total food handling cost (C_{T}), terminal setup cost, and operating cost per day (C_{S}). Given this, the configurations of equipment being overly imbalanced between inbound and outbound could be avoided.

The food handling costs C_{T} per day for food delivered to/from depots and to/from hubs are calculated, respectively, based on the different types of MTJD techniques used, as shown in Eq. (1):

$$\begin{aligned} C_T = {} & \sum_t \sum_k \sum_{s^k} \left[\alpha^t \cdot \sum_p \sum_a \left(D^{t,a}_{s^k,p} + D^{t,a'}_{s^k,p} \right) \right] \\ & + \sum_t \sum_{k_1} \left\{ \alpha^t \cdot \left[\sum_{k_2} \sum_p \sum_a \left(D^{t,a}_{k_1k_2,p} + D^{t,a}_{k_2k_1,p} \right) \right. \right. \\ & \left. \left. + \sum_{s^{k_1}} \sum_p \sum_a \left(D^{t,a}_{s^{k_1},p} + D^{t,a'}_{s^k,p} \right) \right] \right\} \end{aligned} \tag{1}$$

Table 2
Definition of symbols, parameters and decision variables.

Symbol	Definition
p	path $p \in P$, where P is the set of all paths. Each path is comprised of a number of links, including inbound and outbound directions.
a	temperature range: $a = 1$ for frozen, 2 for refrigerated, $a = 1$ for regular.
t	distribution technique: $t = 1$ for traditional multi-vehicle distribution technique, $t = 2$ for mechanical refrigerated compartment division technique, $t = 3$ for replaceable cold accumulation and insulated box technique.
h	hub $h \in H$, where H is the set of all hubs.
k	cluster $k \in K$, where K is the set of all clusters. As each cluster has only one hub, $\lvert H \rvert = \lvert K \rvert$.
S	terminal $s \in S$, where S is the set of all terminals, including hubs and depots. If $s = h^k$, the hub is inside cluster k; if,$s = s^k$ the depot is inside cluster k.
Parameter	Definition
α^{t} (NTD/unit)	slope between food handling volume and food handling cost for technique t.
β (NTD/unit)	slope between food handling volume and terminal setup and operating cost for technique 3.
C_n/C'_n (NTD)	terminal setup and operating cost for techniques 1 and 2 and food handling volume level n.
q_n/q'_n	upper limit of food handling volume in the depot/hub for techniques 1 and 2 and food handling volume level n.
$V^t_a/V^{t'}_a$	maximum vehicle capacity of temperature range a on the secondary/primary path under technique 1 or 2.
$V^t/V^{t'}$	maximum vehicle capacity of the secondary/primary path under technique 3.
$d^{s_k}_a/d^{s'_k}_a$	average daily demand for food of temperature range a, delivered to/from depot s^k.
d^{k_1,k_2}_a	average daily demand for food of temperature range a, delivered from cluster k_1 to cluster k_2, where $k_1k_2 \in M$ and M is the set of all food origin-destination pairs on the primary path.
$b_{s^k,p}$	1, if secondary path p passes depot s^{k} 0, otherwise.
$b_{k_1k_2,p}$	1, if primary path p links k_1 to k_2 0, otherwise
$b^{k_1k_2}_{h_1h_2,p}$	1, if primary path p links k_1 to k_2 via link h_1h_2 (i.e., the link from hub h_1 to hub h_2), $h_1h_2 \in A$, where A is the set of all links on the primary path 0, otherwise.
Decision variable	Definition
$D^{t,a}_{s^k,p}/D^{t,a'}_{s^k,p}$	daily volume of temperature range a food, delivered to/from depot s^{k} along secondary path p, under technique t.
$D^{t,a}_{k_1k_2,p}$	daily volume of temperature range a food, delivered from cluster k_1 to cluster k_2 along primary path p under technique t.
$\delta_{s,n}$	1, if terminal s adopts techniques 1 and 2,and food handling volume level n 0, otherwise.

Since Techniques 1 and 2 can share facilities in the same terminal, they can be considered as a whole. Terminals that use these techniques, and those that use Technique 3, have quite different cost patterns. The setup costs associated with Techniques 1 and 2 are sunk costs and a great amount of setup capital is required. This cost exhibits scale economies, varies due to capacity utilization, and mainly includes hardware facilities costs and energy costs necessary for refrigerated and frozen food. As the terminal's food handling volume increases, the daily terminal setup and operating costs increase. Terminals of different levels also have their respective upper limits for daily food handling volume. The daily volume cannot exceed these upper limits; hence, an optimal level for daily food handling volume should be chosen for each terminal.

The setup cost is minor for terminals that adopt Technique 3, which, likewise, features a low threshold and minimal cost for initial investment. Using this technique, little equipment is needed, depending on the handling volume of the multi-temperature food. However, this technique does not yield economies of scale; the electricity fee attributed to the operating cost of this technique is positively correlated to the volume of the equipment. Thus, this study assumes the terminal setup and operating cost paid per day for Technique 3 has a positive linear relationship with the volume of refrigerated and frozen food processed by the terminal each day, as shown in Eq. (2). The decision variables are $D^{t,a}_{s^k,p}/D^{t,a'}_{s^k,p}, D^{t,a}_{k_1k_2,p}$, and $\delta_{s,n}$ Furthermore, the technique(s) and food handling volume of each terminal and the number of vehicles of a given size equipped with the different cooling technologies that are assigned to the different routes are derived from decision variables using a vehicle transportation cost algorithm, according to the Branch & Bound method under the principle of "the best-first search.

$$C_S = \sum_k \sum_{s^k} \sum_n C_n \cdot \delta_{s^k,n} + \sum_k \sum_n C'_n \cdot \delta_{h^k,n} + \sum_k \sum_{s^k} \left[\beta \cdot \sum_p \sum_{a=1}^{2} \left(D^{t=3,a}_{s^k,p} + D^{t=3,a'}_{s^k,p}\right)\right] + \sum_{k_1} \left\{\beta \cdot \left[\sum_{k_2} \sum_p \sum_{a=1}^{2} \left(D^{t=3,a}_{k_1k_2,p} + D^{t=3,a}_{k_2k_1,p}\right) + \sum_{s^{k_1}} \sum_p \sum_{a=1}^{2} \left(D^{t=3,a}_{s^{k_1},p} + D^{t=3,a'}_{s^k,p}\right)\right]\right\} \tag{2}$$

The constraints of the binary integer-programming model constructed in this study are shown in Eqs. (3)–(15). In the hierarchical H/S network, the bottleneck along the secondary path will appear in the flow to or from the terminal where the vehicle path has passed. Therefore, we use separate constraints for terminal handling capacity of inbound and outbound shipments. Eqs. (3) and (4) are constraints for the terminals adopting Techniques 1 and 2 where the actual distribution volume must be less than the capacity provided by vehicles for each of three-temperature ranges. Eqs. (5) and (6) are constraints ensuring the volume of food delivered is less than the daily available capacity of regular vehicles for Technique 3. This constraint indicates Technique 3 has greater flexibility in volume usage than Techniques 1 and 2 due to using regular vehicles. The bottleneck of transportation capacity along the primary path must appear in the flow on the link where the vehicle path has passed. Eqs. (7) and (8) are constraints on capacity, because actual distribution volumes using Techniques 1, 2 and 3 must be less than the capacity the vehicles can handle each day. Parameter "*V*" defines an aggregate food handling capacity in a certain temperature range for all vehicles of a given technique type on a path. The value of *V* is determined in the constraints by an upper bound, which is estimated by assuming the operator adopts only one technique on a path and excludes all other techniques. For serving a given demand volume on a path, the required total vehicle capacity for a given technique is always larger than when using mixed techniques. Eqs. (9) and (10) address the situation for depots and hubs adopting Techniques 1 and 2, where the service capacity of refrigerated food by terminal operators must be greater than the actual volumes handled in the terminals. Eq. (11) denotes that when the terminal adopts Techniques 1 and 2, it can provide, at most, one level of food service capacity due to its large sunk setup cost. Eq. (12) sets constraints such that the food volume delivered *to* depot s^k must be greater than the actual demand of depot s^k. Eq. (13) sets constraints such that the food volume delivered from depot s^k must be greater than the overall demand of depot s^k. Eq. (14) sets constraints such that the food volume delivered from cluster k_1 to cluster k_2 must be greater than the total demand of the depots in the clusters where k_1 and k_1 are the origin and destination of each origin-destination pair. Eq. (15) indicates that some of the decision variables in the model are binary integers.

$$\text{Min } C_T + C_S$$

$$\sum_{s^k} D^{t,a}_{s^k,p} \cdot b_{s^k,p} \le V^t_{\mathrm{a}} \quad \forall p \in P;\ \ t = 1,2;\ \ a = 1,2,3;\ \ k \in K \tag{3}$$

$$\sum_{s^k} D^{t,a'}_{s^k,p} \cdot b_{s^k,p} \le V^t_a \quad \forall p \in P;\ \ t = 1,2;\ \ a = 1,2,3;\ \ k \in K \tag{4}$$

$$\sum_{s^k} \sum_a D^{t,a}_{s^k,p} \cdot b_{s^k,p} \le V^t \quad \forall p \in P; \quad t = 3; \quad k \in K \tag{5}$$

$$\sum_{s^k} \sum_a D^{t,a'}_{s^k,p} \cdot b_{s^k,p} \le V^t \ \forall p \in P; \quad t = 3; \quad k \in K \tag{6}$$

$$\sum_{k_1k_2} D^{t,a}_{k_1k_2,p} \cdot b^{k_1k_2}_{h_1h_2,p} \le V^{t'}_a \quad \forall p \in P;\ h_1h_2 \in A;\ t = 1,2;\ a = 1,2,3 \tag{7}$$

$$\sum_{k_1k_2} \sum_a D^{t,a}_{k_1k_2,p} \cdot b^{k_1k_2}_{h_1h_2,p} \le V^{t'} \quad \forall p \in P; \quad h_1h_2 \in A; t = 3 \tag{8}$$

$$\sum_n q^n \cdot \delta_{s^k,n} - \sum_p \sum_{t=1}^{2} \sum_{a=1}^{2} \left[\left(D^{t,a}_{s^k,p} + D^{t,a'}_{s^k,p}\right) \cdot b_{s^k,p}\right] \ge 0 \quad \forall k \in K; \\ s^k \in S^k \tag{9}$$

$$\sum_n q_n \cdot \delta_{h^{k_1},n} - \sum_p \sum_{t=1}^{2} \sum_{a=1}^{2} \sum_{k_2} \left(D^{t,a}_{k_1k_2,p} \cdot b_{k_1k_2,p} + D^{t,a}_{k_2k_1,p} \cdot b_{k_1k_2,p}\right) - \sum_{s^{k_1}} \sum_p \sum_{t=1}^{2} \sum_{a=1}^{2} \left(D^{t,a}_{s^{k_1},p} + D^{t,a'}_{s^{k_1},p}\right) \cdot b_{s^{k_1},p} \ge 0 \ \forall k_1 \in K \tag{10}$$

$$\sum_n \delta_{s,n} \le 1 \ \forall s \in S \tag{11}$$

$$\sum_p \sum_t D^{t,a}_{s^k,p} \cdot b_{s^k,p} \ge d^{s^k}_a \ \forall k \in K; \quad s^k \in S^k; \quad a = 1,2,3 \tag{12}$$

$$\sum_p \sum_t D^{t,a'}_{s^k,p} \cdot b_{s^k,p} \ge d^{s^{k'}}_a \ \forall k \in K; \quad s^k \in S^k; \quad a = 1,2,3 \tag{13}$$

$$\sum_p \sum_{h_1h_2} \sum_t D^{t,a}_{k_1k_2,p} \cdot b^{k_1k_2}_{h_1h_2,p} \ge d^{k_1k_2}_a \ \forall k_1k_2 \in M; \ \ a = 1,2,3 \tag{14}$$

$$b_{s,n} \in \{0,\ 1\} \ \forall s \in S, n \tag{15}$$

3. Vehicle cost algorithm

Vehicle transportation costs increase, while the average transportation cost per unit of food decreases, with vehicle size. However, as long as food distribution demand and frequency can be met, operators are likely to choose small vehicles to maximize the load factor (while minimizing vehicle transportation costs). Fig. 2 illustrates the relationship between vehicle purchase and operating costs, and the maximum food volume loaded by vehicle each day. When the latter is small, the operator will choose the smallest vehicle to maximize the load factor and distribution frequency while minimizing cost as long as demand can be accommodated. However, when demand exceeds specific vehicle capacity with the most intensive usage frequency this path can provide (Points a and b), the operator will shift to a larger vehicle. Once a larger vehicle has been selected, it will serve with less frequency. Afterward, the frequency can be increased if the demand grows. Vehicle size will then be changed again until the capacity provided by the largest vehicle and the most intensive frequency (Point c) cannot meet demand. At this point, the operator must use another vehicle path to provide the service. The minimized cost as shown by the solid line in Fig. 2 is comprised of several cost-line segments of various vehicle sizes.

This study designed a vehicle cost algorithm for a hierarchal H/S network with three clusters, each of which contains two depots. Fig. 3 depicts the framework of the vehicle cost algorithm. The study first solves the binary integer-programming model constructed by relaxing the integer conditions, and then uses the vehicle cost algorithm to calculate vehicle costs, type, size and service frequency for the primary and secondary lines, sequentially. This calculation framework can be further described.

Step 1-1. Choose the primary and/or secondary line(s) to calculate

In the first round, simultaneously choose the primary and secondary lines in one cluster to calculate. In other rounds, merely choose secondary lines in another cluster to calculate.

Step 1-2. Calculate the food volumes to/from the terminal(s)

Use the solution of the binary integer-programming model to calculate the food volumes of each and all temperature range food delivered to/from the terminal(s) by all vehicles on the primary and/or secondary lines under Techniques 1 & 2 and Technique 3, respectively. Food using Techniques 1 & 2 and Technique 3 need different facilities not only in terminals but also in vehicles. Using the constructed programming model, we calculate the volume of each temperature range food based on the given cooling configuration of the terminals. We then input those volumes and apply the cost algorithm to find all feasible vehicle delivery combinations and then choose the best. The algorithm ensures the combinations of vehicles with various techniques are consistent with a given cooling configuration of the terminals.

Step 2. Calculate the maximum food volume loaded by the vehicle in one day

The types of vehicles available to an operator depend on the techniques adopted. Different techniques also influence vehicle capacity availability. Technique 1 delivers each temperature range food separately, and has the highest vehicle capacity availability, followed by Technique 2, which jointly delivers all temperature range food, and then Technique 3, which also jointly delivers all temperature range food and has the lowest available capacity due to required temperature-controlled boxes and/or cabinets in the compartment. However, in actual operation, load factors depend on the composition of different-temperature food and the flexibility of different techniques in loading the food into vehicles. The load factor is one of the key factors that practically influences vehicle transportation cost.

The secondary line has four feasible paths, including two all-service paths (passing through all depots) and two direct paths (no stop-over), and each path is comprised of both inbound and outbound directions. Therefore, the blend of vehicles with a given cooling configuration inbound to a terminal is assured to be the same as the blend of vehicles outbound. Since the maximum

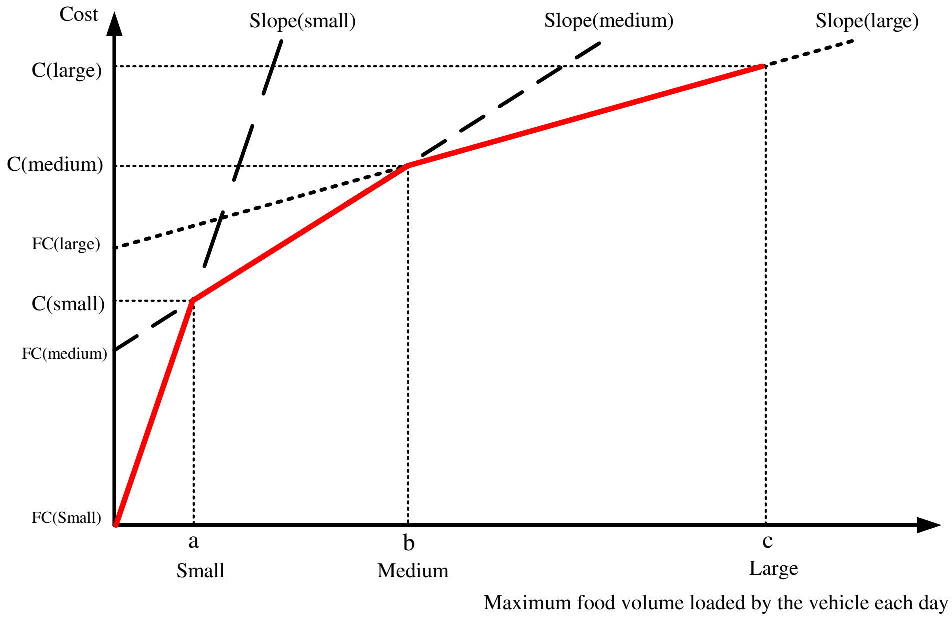

Fig. 2. Relation between vehicle purchase, operating cost, and maximum food volume loaded by vehicle each day.

volume of food loaded by vehicles on the secondary line in one day must appear in the flow to or from the terminal, when the all-service path is chosen based on the delivery volume, only the path with the lowest cost can be chosen. While the primary line has six feasible paths, three of which are all-service paths and the balance direct paths, then the maximum food volume loaded by vehicles on the all-service paths cannot be the same and should be considered separately. Finally, based on the paths on the primary line, calculate the maximum daily food volume by vehicle for each of a variety of delivery combinations. When the calculation is completed, proceed to the next step.

Step 3. Select delivery combination

Following the greed principle, select the delivery combination with the maximum food volume as calculated in the previous step, and obtain the vehicle types, paths, sizes, service frequency, and types of food delivered. Then, move to the next step.

Step 4. Recalculate the food volume to and from the terminal

Calculate food volume to/from the terminal(s) that can potentially be reduced based on the results obtained from the previous step, by following the principle that “the more the food volume in the terminal, the earlier the reduction takes place.” Then, again, obtain the new results by Step 1-2.

Step 5. Check that the calculations on the cluster and the primary line are complete

When the new results for all variables related to food volumes to/from the terminal(s) along the primary or secondary lines in the

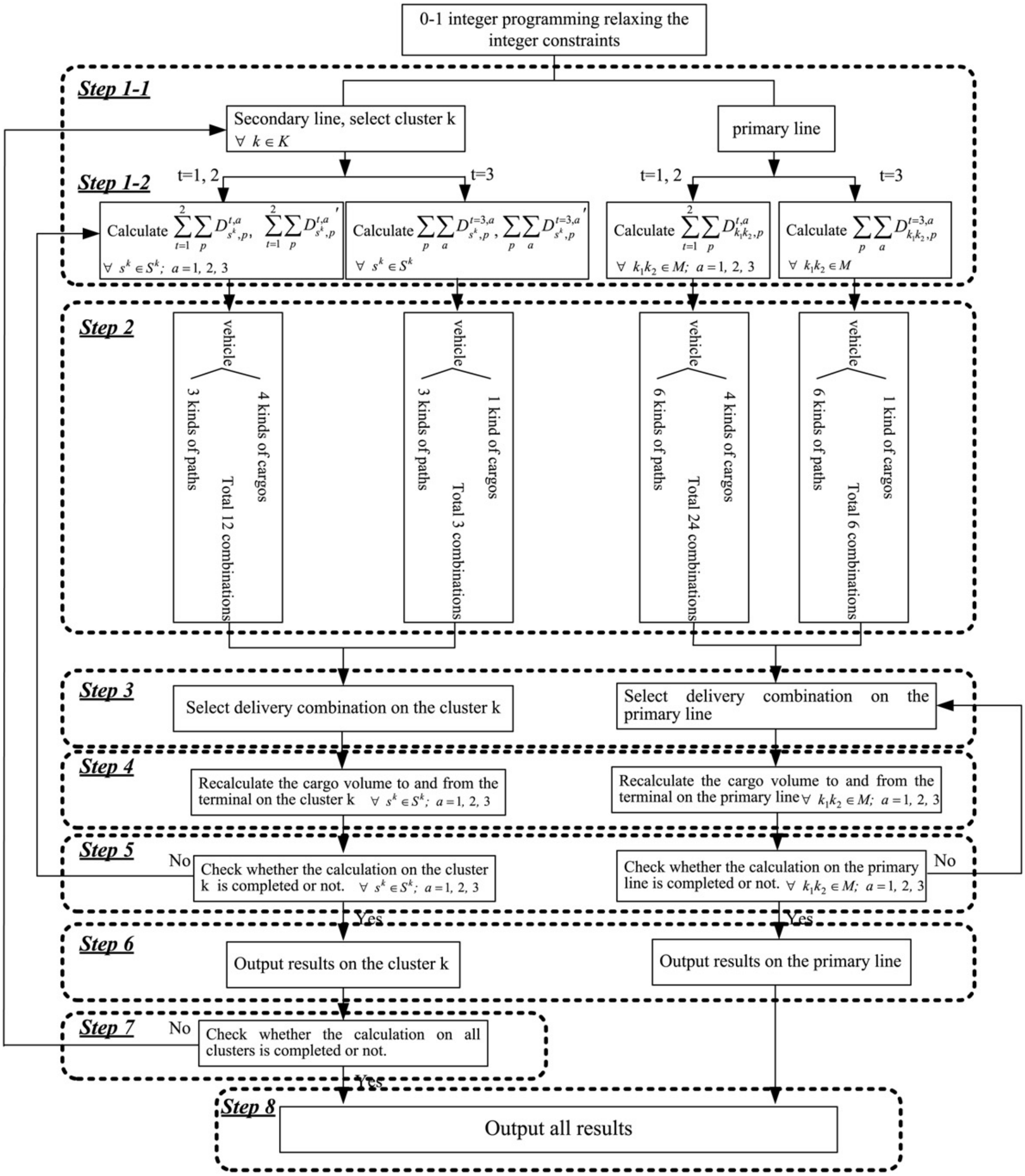

Fig. 3. Vehicle transportation cost algorithm framework.

Table 3
Terminal setup and operating costs for techniques 1 & 2.

Hub					
Handling volume (Level n)	4,000 units ($n = 1$)	8,000 units ($n = 2$)	12,000 units ($n = 3$)	16,000 units ($n = 4$)	20,000 units ($n = 5$)
Number of storage slots	1,000	2,000	3,000	4,000	5,000
Setup cost (NTD)	35,000	59,000	72,000	83,000	97,000
Maintenance & operating cost (NTD/day)	57,500	99,750	136,750	168,250	194,250
Overall cost (NTD/day)	92,500	158,750	208,750	251,250	291,250
Initial investment (NTD)	64.75 million	109.15million	133.2 million	153.55 million	179.45 million
Depot					
Handling volume (Level n)	2,000 units ($n = 1$)	4,000 units ($n = 2$)	6,000 units ($n = 3$)		
Number of storage slots	500	1,000	1,500		
Setup cost (NTD)	17,500	29,500	36,000		
Maintenance & operating cost (NTD/day)	28,750	49,875	68,375		
Overall cost (NTD/day)	46,250	79,375	104,375		
Initial investment (NTD)	32.38 million	54.58 million	66.6 million		

cluster are 0, the calculation is completed and proceeds to the next step. Otherwise, return to Step 1-2.

Step 6. Output some results

Output vehicle cost(s) along the primary and/or the secondary line(s) in the cluster and other relevant results, including the sizes, types, paths, and service frequency of the vehicle fleet.

Step 7. Check whether the calculations for all clusters are complete

When the calculations are completed for all primary and secondary lines, move to the next step. Otherwise, return to Step 1-1 and carry out calculations regarding a secondary line in another cluster.

Step 8. Output all results

Output vehicle costs on the primary line and the secondary lines in all clusters, as well as other results including the sizes, types, paths, and service frequency of the vehicle fleet.

Finally, this study focuses on eliciting a solution from the binary integer-programming model by combining the algorithm results with the Branch and Bound method under the principle of "the best-first search." Using this approach, economies of vehicle size can be reflected (i.e., when demand is large enough, the operator will choose the largest possible vehicles). The approach also reflects the feature of Technique 2, (i.e., vehicles with three-temperature compartments can deliver three-temperature food at the same time, but compartment space cannot be shared). Furthermore, the sizes and types of vehicles can directly influence the choice of terminal techniques. The vehicle cost algorithm is developed to solve the problem with the above features, which is not easily solved using the traditional integer-programming model.

4. Example

Based on the current situation of domestic logistics in Taiwan, our study area is divided into three clusters, namely: A (Taipei), B (Taichung), and C (Tainan), which are located in the northern, central, and southern parts of Taiwan, respectively. The total length of the study area from South to North is about 400 km, and is an appropriate distance for highway-truck distributions. Cluster A is more on the demand end, while Cluster C is more on the supply end of food; Cluster B has no apparent features regarding demand or supply. The overall food flows in Clusters A and C are apparently larger than in Cluster B. Regular food accounts for the majority of those distributed, followed by refrigerated food, and then frozen food. The ratio of the three is about 4:2:1.

This study sets the values of cost related parameters based on the operating condition of the example in practice. Table 3 lists the terminal setup and operating costs related to refrigeration and freezer facilities for the hub and the depot under Techniques 1 and 2, respectively. Table 4 lists the values of the parameters related to vehicle purchase and operating costs. The vehicle maintenance cost is about 7% of the purchase cost. There are large (25-ton), medium (10-ton), and small (3.5-ton) vehicles available, which can load 200, 70, and 20 units, respectively. Notably, one unit equals 180 L.

Table 5(a) shows the results of the optimal combination of vehicles used on the paths of primary and secondary lines for the example. Only those paths with assigned flows are shown and most of those are the shortest paths with all services. On primary line A→B→C, there are four vehicles of different sizes using different techniques (i.e., one medium refrigerated vehicle, one large regular vehicle, one medium regular vehicle with Technique 3, and one large refrigerated compartment division vehicle with Technique 2). The daily service frequencies for those vehicles are 6, 24, 4, and 24, respectively. All four vehicles use the shortest path for all services (i.e., line A→B→C). Use Cluster A as an example, on secondary path

Table 4
Value of parameters related to vehicle purchase and operating costs.

		Small (3.5 Tons≒20units)	Medium (10 Tons≒70 units)	Large (25 Tons≒200 units)	Lifespan
Frozen & refrigerated vehicle	Purchase cost (NTD)	0.96 million	2.8 million	4.5 million	5 years
	Operating cost (NTD/km)	5	12.5	20/Km	
Regular vehicle	Purchase cost (NTD)	0.6 million	1.6 million	3.5 million	7 years
	Operating cost (NTD/km)	4	10	16	
Three-compartment refrigerated vehicle	Purchase cost (NTD)	0.88 million	2.45 million	4.2 million	5 years
	Operating cost (NTD/km)	5/Km	12.5/Km	20/Km	

Table 5(a)
Original case study results for vehicles on paths.

Path	Vehicle type[a]	Daily frequency	Total no. of vehicles
Primary path			
A→B→C	one medium R	6	4
	one large N	24	
	one medium N[b]	4	
	one large C[b]	24	
Secondary path			
Cluster A			
H→S1→S2	one large R	5	3
	one large N	12	
	one large C[b]	12	
H→S1	one small F	2	1
Cluster B			
H→S1→S2	one large N	12	2
	one large N[b]	11	
Cluster C			
H→S1→S2	one large R	6	5
	one large N	12	
	one medium N[b]	2	
	one large C[b]	12	
	one large C[b]	5	

[a] F: frozen vehicle, R: refrigerated vehicle, N: regular vehicle, C: three-compartment refrigerated vehicle.
[b] Using MTJD technique.

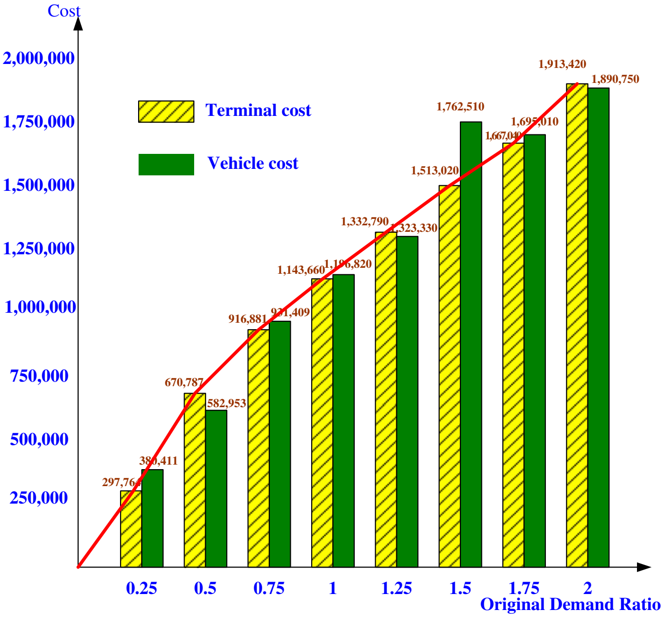

Fig. 4. Cost items changed by demand.

H→S1→S2, which is also the shortest path with all services, there is one large refrigerated compartment division vehicle with Technique 2 serving all temperature range food and one large regular vehicle serving regular food. Both vehicles serve with the same daily frequency of 12. In addition, on the same path, there is one large refrigerated vehicle serving refrigerated food with a daily frequency of 5. On the direct path H→S1 in Cluster A, there is one small frozen vehicle moving frozen food twice daily.

As shown in Table 5(a), although the frozen and refrigerated food volumes are apparently less than regular food, MTJD techniques enable the food to be served with the same high frequency as regular food. The shortest path with all services is shown to be always the optimal path and there is relatively high use of large vehicles for all techniques. The above results imply the operator not only should operate in the shortest path but also serve all terminals to realize the economies of flow consolidation, which make using large MTJD vehicles with high frequencies possible.

Table 5(b)b lists both the original results and the results of the sensitivity analysis due to demand changes for terminals. The results for the original example are shown in the column of original demand ratio equaling one and indicate Techniques 1 and 2 are suitable for the hubs and depots in Clusters A and C. The hub in Cluster B does not suggest any apparent preference among the three techniques, but all of the depots show a tendency toward the adoption of Technique 3. Hence, we can conclude that Technique 3 is suitable for those terminals with a small distribution volume. This result also conforms to the conclusion drawn from common sense and real life situations.

This results for the sensitivity analysis show that when demand is one-quarter of the original value, all hubs and depots operate with Technique 3, but as demand increases, the applicability of Technique 3 decreases. As food volumes increase, the clusters tend toward Techniques 1 and 2. However, when food volume changes irregularly, Technique 3 is used due to its flexibility. As to the proportion of techniques used, if 0.8 is regarded as the basis to judge whether the technique adopted by a terminal is primary, we find that Techniques 1 and 2 become primary for the hubs in Clusters A and C when demand is about 0.5–0.75 times that of the original case. Also, as demand increases, their advantage is maintained. Techniques 1 and 2 become primary for the hub in Cluster B when demand is about 1.25 times that of the original case.

The above results imply that Technique 3 is strategically superior for those terminals with small distributing volumes; but when

Table 5(b)
Terminal results for original case and cases due to demand changes.

			Original demand ratio							
			0.25	0.5	0.75	1	1.25	1.5	1.75	2
Cluster A	Hub	$t = 1, 2$	0[a] (0.00)[b]	3880.2 (0.85)	6827.4 (1.00)	7997.3 (0.89)	11379.0 (1.00)	13640.6 (0.99)	15382.6 (0.97)	18206.0 (1.00)
		$t = 3$	2213.0 (1.00)	671.4 (0.15)	0 (0.00)	1020.1 (0.11)	0 (0.00)	14.2 (0.01)	546.1 (0.03)	0 (0.00)
	Sum of depots	$t = 1, 2$	0 (0.00)	1183.2 (0.64)	2962.4 (1.00)	3709.2 (1.00)	4636.5 (1.00)	5549.6 (0.99)	6000.0 (0.92)	7418.4 (1.00)
		$t = 3$	927.3 (1.00)	671.4 (0.36)	0 (0.00)	0 (0.00)	0 (0.00)	14.2 (0.01)	491.1 (0.08)	0 (0.00)
Cluster B	Hub	$t = 1, 2$	0 (0.00)	1990.2 (0.59)	2985.3 (0.59)	3903.7 (0.58)	6975.5 (0.83)	7970.6 (0.79)	11681.5 (0.99)	13396.0 (1.00)
		$t = 3$	1674.6 (1.00)	1359.0 (0.41)	2038.5 (0.41)	2794.7 (0.42)	1397.5 (0.17)	2077.0 (0.21)	40.7 (0.01)	0 (0.00)
	Sum of depots	$t = 1, 2$	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	2000.0 (0.59)	2000.0 (0.49)	4756.5 (1.00)	5436.0 (1.00)
		$t = 3$	679.5 (1.00)	1359.0 (1.00)	2038.5 (1.00)	2718.0 (1.00)	1397.5 (0.41)	2077.0 (0.51)	0 (0.00)	0 (0.00)
Cluster C	Hub	$t = 1, 2$	0 (0.00)	2886.0 (0.59)	7295.4 (1.00)	8000.0 (0.83)	11045.0 (0.91)	14399.8 (0.99)	16000 (0.97)	19454.0 (1.00)
		$t = 3$	2369.4 (1.00)	1977.6 (0.41)	0 (0.00)	1641.4 (0.17)	1114.0 (0.09)	196.0 (0.01)	1020.7 (0.03)	0 (0.00)
	Sum of depots	$t = 1, 2$	0 (0.00)	0 (0.00)	2962.4 (1.00)	3410.6 (0.86)	3830.0 (0.78)	5736.8 (0.97)	5996.6 (0.87)	7910.4 (1.00)
		$t = 3$	988.8 (1.00)	1977.6 (1.00)	0 (0.00)	544.6 (0.14)	1114.0 (0.22)	196.0 (0.03)	924.9 (0.13)	0 (0.00)

[a] The numbers are handling volume of refrigerated and frozen food, unit and 1 unit = 180 L.
[b] The bracketed numbers refer to the ratio of techniques adopted by each terminal.

distribution volume and size increase, Technique 3 tends to play a supplementary role to Techniques 1 and 2. Nevertheless, it is usually difficult to substitute Techniques 1 and 2 for Technique 3, due to their tremendous sunk costs and inflexibility once employed.

When distribution demand changes, the various costs change accordingly, including those related to terminal and vehicle costs, as shown in Fig. 4. Since this study adopts the heuristic method to solve the problem, the solutions obtained are discrete points and may not be the best. It is difficult to see the relationship between demand volumes and those costs from Fig. 4. This study further assumed the terminal cost function to be $C'_S = a_1 \cdot x^{b_1}$ and the vehicle cost function to be $C'_V = a_2 \cdot x^{b_2}$, where x is the total volume of refrigerated and frozen food in all terminals, and a_1,a_2,b_1,b_2 are the parameters to be calibrated. Parameter values b_1,b_2 have economic meaning (i.e., when $b_1,b_2 < 1$, it indicates there are economies of scale in the terminal and vehicle costs). This study further calibrated those parameters using a least square method, and obtained $a_1 = 328.911$, $a_2 = 357.801$, $b_1 = 0.774574$, and $b_2 = 0.769691$, with an error margin of about 5%. The results indicate the costs related to both the terminal and the vehicles indeed exhibit economies of scale, and the vehicle costs were more significant than the terminal. This result is possibly due to the fact the terminal's handling, setup, and operating costs under Technique 3 usually lack economy of scale. Hence, the result conforms to practical expectations and to the logic of our algorithm for determining vehicle costs. This indicates an accurate and reasonable solution can be obtained from the heuristic method.

In conclusion, we know that economies of scale are critical factors affecting the results; and various costs interacts each other, causing economies of scale in terminal and vehicle costs of Techniques 1 and 2 are more significant than Technique 3. Thus, terminals and vehicles adopting Techniques 1 and 2 would provide maximum frequency services with nearly maximum capacity at different levels. Nevertheless, Technique 3 plays a supplementary role and serves non-maximum frequency service, meaning when actual demand fluctuates from assumed demand, it can be used as a buffer in response to demand uncertainty and not well-known data. It is, thus, a good idea to adjust the distribution supply using Technique 3, which has the advantage of flexibility.

5. Conclusion and recommendations

New technologies not only provide better temperature control but also reduce the effects of time and temperature on food quality and environmental impact. However, previous studies rarely dealt with the problem of analyzing and choosing between multi-temperature logistics techniques in terms of maximizing the efficiency in hub and spoke freight distribution networks. The current trend in food delivery is moving toward a variety of categories, small shipments, and multi-temperature. This study, different from the conventional flow conservation model, constructed an effective model based on practical operation to further accommodate different features of multi-temperature distribution techniques and vehicle types. It differs from previous literature in hub design and vehicle assignment in a way that is appropriately suited to solving the complicated facility-planning problem associated with MTJD. It also analyzes the advantages and disadvantages of various logistic techniques to provide operators with a valuable reference when choosing short- and medium-term strategies. By minimizing the total delivery cost (comprised of transportation costs and food handling costs), we have solved the problem of optimal application of multi-temperature logistics techniques for terminal and vehicle routing operations. This research focuses mainly on the choice of appropriate short- and medium-term operational strategies assuming the hub system is taken as given. Notably, in the long run, the optimal hub and spoke network may depend on the vehicle mix, and the interrelationships among the network design and the techniques may need to be considered. Nevertheless, it is beyond the scope of this study and could be investigated in future work for long-term strategic planning.

The results in this study indicate that Technique 3 is suitable for terminals with a small distribution volume, dense distribution of terminals, and a small size operation network. The results about vehicles also imply the operator should not only operate large vehicles in the shortest path but also serve all terminals to realize economies of flow consolidation, which makes using large MTJD vehicles with high frequencies possible. In this way, the operator not only realizes minimum costs due to economies of vehicle size and the shortest path, but also provides better service more frequently due to the flexibility of MTJD techniques.

Furthermore, when demand is uncertain and not well-known or increases over time, it is very difficult to change equipment and facilities associated with Techniques 1 and 2, thus Technique 3 evolves into an adjusting and auxiliary role. In addition, the results of our study on vehicle costs showed evidence of economy of scale, and clearly conforms adequately to practical expectations, and to the logic of the algorithm developed for determining vehicle costs. The algorithm has the following advantages: (1) it can be solved in Polynomial-time; (2) it reflects the feature of vehicle economy of scale; and (3) it shows the space flexibility of regular vehicles using Technique 3 is better than that of three-compartment refrigerated vehicles using Technique 2.

Several extensions could be made in future studies. When clusters, hubs, and depots contained in the operating network increase continuously, we suggest the problem can be solved with a common heuristic form of the Branch & Bound method, such as Column Generation. Moreover, the vehicle algorithm directly influences solution quality. Future studies should discuss the topic of vehicles in depth and further improve the vehicle cost algorithm. Environmental protection has also been a popular issue in recent years. The public imposes increasingly stricter requirements on delivery quality, and market competition has become more fierce than ever. This study provided a rigorous discussion and analysis of new technologies, so that multi-temperature logistics operators might have increased flexibility in response to the changing trends of the external environment, and of course the market, in the future.

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