A Study on the Mixed Fleet Multi-temperature Common Distribution: Heuristics and Computational Analysis

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Abstract: - This paper considers two special methods of operation for the multi-temperature common distribution in the ‘cold-chain’ logistics. The first is that carriers utilize the engine-driven frozen truck divided into three parts to hold goods of different temperatures. The second is that carriers utilize the multi-temperature storage box, found in a general truck, to hold those goods. We transferred the previous operations into two Heterogeneous Multi-temperature Fleet Vehicle Routing Problems, HMFVRP1 and HMFVRP2. A set of 168 instances, created by modifying VRP and VRPTW benchmark instances, is used to compare the performance of HMFVRP1 and HMFVRP2. In addition, real costs and the capacities of different sized trucks are set for these test instances. Then, we also develop a simple heuristic algorithm to solve these HMFVRPs. Computational results present that, in average, HMFVRP2 performs superior to HMFVRP1 in both of vehicle usage cost and travel distance. Such a finding could offer an alternative toward improving the performance and efficiency of the practical multi-temperature common distribution.

Key-Words: - Multi-temperature Common Distribution, Heterogeneous Fleet, Vehicle Routing Problem.

1 Introduction

In recent years, the demand for ‘cold-chain’ logistics and multi-temperature common distribution has risen rapidly. Reports indicated that the world's demand for perishable goods, such as refrigerated foods, fresh fruits and flowers, rose from 42 million tons in 1987 to 44 million tons in 1990 and was likely to reach 53 million tons by 2000 [6]. Furthermore, according to the statistics from the Industrial Economics and Knowledge Center (IEK) under Industrial Technology Research Institute (ITRI), Taiwan's market share of refrigerated foods varies in retail channels, with the total market scale of the refrigerated foods already exceeded 200 billion NT dollars in 2000 [13]. The fast ascending demand for refrigerated foods means profits for the participants of the cold chains.

At a CVS distribution center in Taiwan, logistics carrier must deliver goods of different temperatures, such as hot foods (over 60), normal temperature goods (18~25), refrigerated foods (-2~7) and frozen foods (under -18), to its clientele. In order to maintain the high quality of those goods, carrier has to adopt an optimum temperature control on multi-temperature commodities in the processes of supplying, storing and delivering. Moreover, most of the freezer trucks currently in use are equipped to carry only low-temperature foods with an equal basic product temperature, so that different types of low-temperature foods must be distributed via different deliveries, causing reduced efficiency in vehicle use. Or two or more freezer trucks must be purchased for the transfer of goods with different product temperatures, which increases investment and operating costs. Therefore, how to distribute multi-temperature goods at the same time and at lower cost raises an important issue.

Tarantitlis and Kiranoudis [18] discussed on how to deliver perishable foods efficiently. They proposed a Heterogeneous Fixed Fleet Vehicle Routing Problem (HFFVRP) model to improve the transportation cost of the case firm. Then, Tarantitlis and Kiranoudis [19] studied the case of fresh meat distribution and transferred it to the Open Mulit-Depot Vehicle Routing Problem (OMDVRP). Using the List Base Threshold Accepting (LBTA) to solve the OMDVRP, they reduce 17% of the routing cost of the case firm. In addition, Tarantitlis et al. [20, 21] respectively presented two meta-heuristics, LBTA and Back-tracking Adaptive Threshold Accepting (BATA), to solve the previously mentioned HFFVRP.

Recently, the Energy and Resources Laboratories (ERL) of the ITRI has developed an innovational technology, i.e. the multi-temperature refrigerated transport system with no-drive refrigeration (MRTS), which is enabled to meet the needs of Taiwan's geography, climate, and societal conditions [12]. Cho and Li [2] developed an extended vehicle routing model based on the usage of the above multi-temperature refrigerated transport system. They named this model the Multi-temperature Refrigerated Container Vehicle Routing Problem (MRCVRP). During that research, a heuristic method was also proposed for solving the MRCVRP and sixty instances of four different scenarios were generated to identify the performance of their heuristic method.

Although the previous literatures have considered the heterogeneous fleet or multi-temperature refrigerated container to deliver perishable goods, further study on the common distribution that combines heterogeneous fleet with multi-temperature refrigerated container still does not emerge satisfactory.

Therefore, in this research, we considered two special methods of operation for the multi-temperature common distribution as follows: The first - carriers utilize the engine-driven frozen truck divided into three parts to hold goods of different temperatures. The second - carriers utilize the multi-temperature refrigerated containers to hold goods of different temperature in a general truck. We also transferred the previous operations into two special Vehicle Routing Problems, named HMFVRP1 and HMFVRP2, and developed a simple heuristic algorithm to solve them. In addition, a set of instances was generated to evaluate the performance of the proposed problems and heuristic methods.

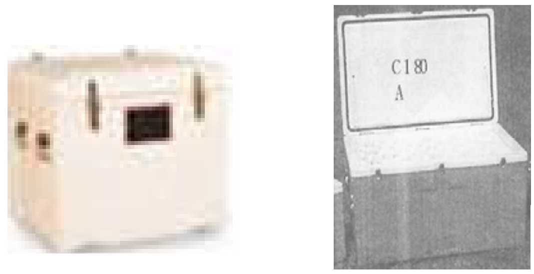
This paper is organized as follows. Section 2 firstly surveys the technology of the multi-temperature refrigerated transport system. In Section 3, we present the mathematical programming formulation of the HMFVRPs. Section 4 describes a simple heuristic method for solving the HMFVRPs. Test instances, experimental designs and analysis of results are reported in Section 5. Finally, Section 6 concludes our findings and suggests several directions of further research.

2 The Technologies of Multi-temperature Refrigerated Transport Systems

In Taiwan, traditional logistics carriers use different types of vehicles, such as general trucks and refrigerated vans, to transport multi-temperature goods respectively. One example of the transport equipment usually used in Taiwan is the mechanical engine-driven compressor freezer truck. Carriers divide the loading area of this freezer truck into three parts: normal temperature, refrigerant, and frozen. In this way, carriers are capable of carrying multi-temperature goods in the same truck. Nevertheless, this kind of freezer truck is frequently forced to idle their engines due to traffic congestion and loading/unloading operations. As a consequence, the truck has to consume more fuel to keep the appropriate temperature during the process of delivery.

On the other hand, the MRTS developed by the ERL is an innovative product [12]. The MRTS possesses an automatic cold augmentation design, a cold energy conversion design, a shipping container accommodation design, a high-efficiency eutectic plate (see Fig. 1(a)), and a multi-temperature refrigerated container structure (see Fig. 1(b)).

(a) Eutectic plate



(b) Multi-temperature refrigerated container

Fig. 1 Major Components of the MRTS

The eutectic plate is to make use of freezing apparatus for pre-cooling, and the multi-temperature refrigerated container is to offer proper cubage for the placement of articles and eutectic plates. Placed in the top part of container, the eutectic plate releases a constant cooling capacity previously accumulated in the cold room during the freezing process. Eutectic refrigeration allows the required temperature to be maintained at least 24 hours for chilled and frozen products. These MRTS technologies ensure that the new-type refrigerated transport system can be used with standardized refrigerated shipping containers. The ability to carry products with different temperatures not only reduces the number of delivery trips needed, but also keeps delivery costs lower than using ordinary chilled trucks.

In Taiwan, the MRTS has been, actually, used to make deliveries to coffee shop chains like Starbucks and IS coffee shops, as well as low-temperature shipments and home deliveries by Ta Jung Transportation Inc [14]. The only disadvantage is that the investment in the MRTS is still costly, and the container is heavy and space-consuming.

3 Problem Definitions

As mentioned above, this research considered two kinds of multi-temperature common distribution systems, freezer truck and MRTS. In practice, logistics carriers usually own trucks of different sizes, such as 1.5 tons, 3.5 tons, and 10 tons. Therefore, we combined the use of heterogeneous fleet with multi-temperature common distribution systems to propose an extended model of vehicle routing, as named Heterogeneous Multi-temperature Fleet Vehicle Routing Problem (HMFVRP). In addition, the model that considers the use of the tri-temperature-spaced freezer truck is named HMFVRP1. The model that considers the use of MRTS, i.e. combination of multi-temperature refrigerated containers and general trucks, is named HMFVRP2.

The classical VRP considers the capacity constraint of trucks and the demand of a single commodity. The proposed HMFVRPs need to simultaneously satisfy the capacity constraints of different sized trucks and temperatured spaces for loading multiple commodities classified by their storing temperature.

The HMFVRP can be described in detail as follows. Given a set of customers with demands for different temperature goods, the heterogeneous fleet of trucks must depart from the central depot, sequentially deliver (pick up) goods to (from) all customers, and finally return to depot. Every truck serves customers under the restrictions not only on its overall capacity but also on the loading spaces or refrigerated containers with different temperatures. The objective of HMFVRPs is to minimize total cost concerning trucks usage cost and route travel cost. Other assumptions and restrictions are stated as follows:

1. Goods are classified as three kinds of temperatures, i.e. normal temperature (18~25), refrigeration (-2~7) and frozen (under -18).
2. Goods are held and carried by the normal plastic vessels for freezer trucks (HMFVRP1) or the refrigerated containers for general trucks (HMFVRP2).
3. For HMFVRP1, the temperature of goods per plastic vessel must be the same. Similarly, those vessels whose temperatures of goods are identical must be loaded on the space with the same temperature.
4. For HMFVRP2, the temperature of goods per refrigerated container must be the same, that is, each refrigerated container is able to assign a specific temperature according to the goods in it.
5. The capacity (volume) of the plastic vessels is equal to that of the refrigerated containers.
6. The unit of goods is calculated by vessel or container, so that the demand for goods of some temperature from a single customer is integral in vessel or container. The goods for different customers or for different temperatures can not be put on the same vessel or container.
7. Demands for goods of different temperatures from a single customer have to be served by the same truck, that is, partial delivery (pick-up) is not permitted.
8. The capacity of trucks with the same size, for example, 1.5 tons, is identical, no matter if it's a freezer truck or general truck. The capacities of different sized trucks can be dissimilar. The capacity is also calculated by vessel or container.
9. The ratio of space for some temperatures in every kind of freezer truck is fixed. For example, in the case that a freezer truck can accommodate a load of 100 vessels; the ratios of normal, refrigerant and frozen spaces are 2: 3: 5. The numbers of vessels of three temperatures that could be loaded on this truck are 20, 30 and 50 respectively. Similarly, for a 150-capacited truck, the numbers of vessels of three temperatures are 30, 45 and 75 respectively.
10. Supposing that the numbers of available trucks and vessels or containers are unlimited.

Fig. 2 and Fig. 3 illustrate the differences of loading operation between HMFVRP1 and HMFVRP2.

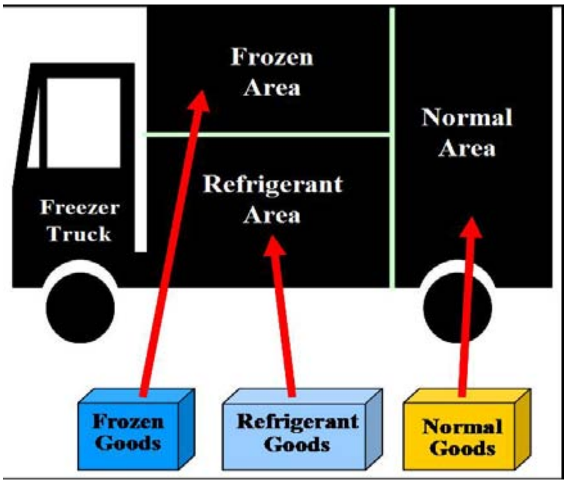


Fig. 2 Loading operation of HMFVRP1.

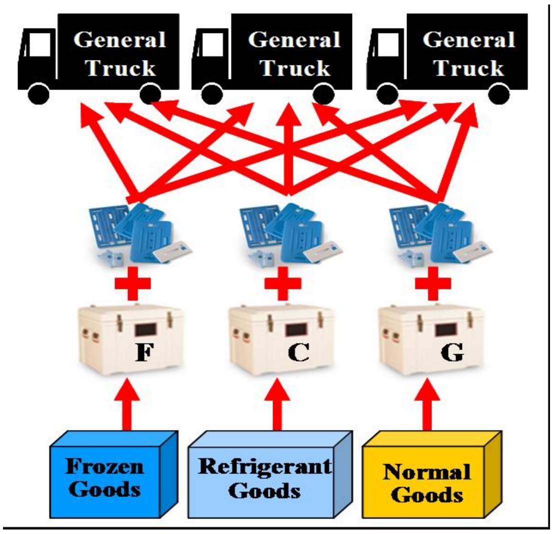


Fig. 3 Loading operation of HMFVRP2.

We precisely defined the HMFVRP1 and HMFVRP2 by presenting their mathematical programming formulations, which were revised from the VRP formulation due to Golden et al. [10]. Firstly, related sets, parameters and decision variables are stated as follows:

- M = {1, 2, …, m}, the set of the commodities' sorts. Each kind of commodity is in a specific temperature level.
- N = {0, 1, 2, …, n}, the set of customer nodes. Where 0 refers to the depot, and 1 ~ n refer to customers.
- T = {1, 2, …, t}, the set of vehicles' types.
- V = {1, 2, …, v}, the set of numbers of available vehicles. As early mentioned, the number of vehicles is unlimited, but it is reasonable that the v is set to be less than the value of n.
- c_{ij} = travel cost (distance or time) of arc (i, j).
- d_{hi} = demand for kind h commodity of customer i.
- f_l = fixed usage cost of type l freezer truck.
- g_l = fixed usage cost of type l general truck.
- q_l = capacity of type l freezer or general truck.
- r_h = ratio of space that kind h commodity can occupies on the freezer truck. As above, these ratios are the same among all types of truck.
- x_{ijk} = 1, if arc (i, j) is traversed by vehicle k; x_{ijk} = 0, otherwise.
- y_{kl} = 1, if vehicle k is assigned as type l; y_{kl} = 0, otherwise.
- X = (x_{ij}), arc selection matrix, so that exactly one arc (i, j) emanates from each node i and exactly one arc (i, j) is directed into each node j.
- S = any restrictions that avoid sub-tour solutions.

(HMFVRP1)

$$\text{Minimize: } \sum_{k=1}^{v}\sum_{l=1}^{t} f_l \cdot y_{kl} + \sum_{i=0}^{n}\sum_{j=0}^{n}\sum_{k=1}^{v} c_{ij}\cdot x_{ijk} \qquad (1)$$

Subject to

$$\sum_{j=0}^{n}\sum_{k=1}^{v} x_{ijk} = 1 \qquad \forall i \in N \setminus \{0\} \qquad (2)$$

$$\sum_{j=0}^{n} x_{ijk} - \sum_{j=0}^{n} x_{jik} = 0 \qquad \forall i \in N, k \in V \qquad (3)$$

$$\sum_{j=1}^{n} x_{0jk} \le 1 \qquad \forall k \in V \qquad (4)$$

$$\sum_{l=1}^{t} y_{kl} - \sum_{j=1}^{n} x_{0jk} = 0 \qquad \forall k \in V \qquad (5)$$

$$\sum_{i=1}^{n}\sum_{j=0}^{n} d_{hi}\cdot x_{ijk} - r_h \cdot \sum_{l=1}^{t} q_l \cdot y_{kl} \le 0 \qquad \forall h \in M, k \in V \qquad (6)$$

$$X \in S \qquad (7)$$

$$x_{ijk} = 0 \; or \; 1 \qquad \forall i \,\&\, j \in N, k \in V \qquad (8)$$

$$y_{kl} = 0 \; or \; 1 \qquad \forall k \in V, l \in T \qquad (9)$$

The objective function (1) states that total cost should be minimized. Constraint set (2) states that each customer i must be served by exactly one vehicle. Constraint set (3) is the flow conservation equation requiring that each vehicle k leaves node i if and only if it enters that node. Constraint set (4) states that each vehicle k can be only used once at the most. Constraint set (5) is a logic constraint that states if a vehicle k is used, it must be assigned to some type l. Constraint set (6) indicts that the aggregated demand for kind h commodity loaded on vehicle k can not exceed the space capacity of temperature h. Constraint set (7) is the sub-tour breaking constraint. Constraint sets (8) and (9) define the domain of decision variables respectively.

(HMFVRP2)

Minimize: $\sum_{k=1}^{v}\sum_{l=1}^{t} g_l \cdot y_{kl} + \sum_{i=0}^{n}\sum_{j=0}^{n}\sum_{k=1}^{v} c_{ij} \cdot x_{ijk}$ (10)

Subject to

$$\sum_{j=0}^{n}\sum_{k=1}^{v} x_{ijk} = 1 \qquad \forall i \in N \setminus \{0\} \qquad (2)$$

$$\sum_{j=0}^{n} x_{ijk} - \sum_{j=0}^{n} x_{jik} = 0 \qquad \forall i \in N, k \in V \qquad (3)$$

$$\sum_{j=1}^{n} x_{0jk} \le 1 \qquad \forall k \in V \qquad (4)$$

$$\sum_{l=1}^{t} y_{kl} - \sum_{j=1}^{n} x_{0jk} = 0 \qquad \forall k \in V \qquad (5)$$

$$\sum_{h=1}^{m}\sum_{i=1}^{n}\sum_{j=0}^{n} d_{hi} \cdot x_{ijk} - \sum_{l=1}^{t} q_l \cdot y_{kl} \le 0 \qquad \forall k \in V \qquad (11)$$

$$X \in S \qquad (7)$$

$$x_{ijk} = 0 \, or \, 1 \qquad \forall i \,\&\, j \in N, k \in V \qquad (8)$$

$$y_{kl} = 0 \, or \, 1 \qquad \forall k \in V, l \in T \qquad (9)$$

The formulation of HMFVRP2 is very similar to that of HMFVRP1. Instead of the objective function (1) and capacity constraint (6) stated in HMFVRP1, the HMFVRP2 adopts a new objective function (10) and a new capacity constraint (11). Other constraints are the same as in HMFVRP1. That is, the major difference between HMFVRP1 and HMFVRP2 is the capacity constraint. Constraint set (11) states that the total demand for all kinds of commodities loaded on vehicle *k* can not exceed the capacity of vehicle *k*. To be more precise, the HMFVRP2 can be simplified into the classical VRP if we set the total demands for all kinds of commodities of a customer to be equal to the demand of customer in VRP formulation.

4 Solution Methods

Due to the NP-hard complexity of related VRP, most of the solution methods to solve the real-world-sized related VRP instances are heuristics or meta-heuristics. For the traditional VRP heuristics, the special issue due to Bodin et al. [1] provides a very comprehensive survey. For the solution methods of Heterogeneous Fleet VRPs, readers can refer to the following literature: Golden et al. [11], Ghetsens et al. [9], Salhi and Rand [15], Gendreau et al. [8], Han and Cho [7], and Tarantilis et al. [20, 21].

The proposed heuristic algorithm is compounded from three modules. The first, the initial solution construction (ISC) module, applies a modified Farthest-start Nearest Neighbor (FNN) method to construct an initial solution. The second, the neighborhood search (NS) module, attempts to improve the initial solution by sequentially executing intra-route 2_opt and Or_opt arcs exchanges as well as inter-route 1_0 and 1_1 nodes interchanges. The third, the vehicle replacement (VR) module, changes the vehicle type assigned to current routes. Fig. 4 depicts the flow chart of our proposed heuristic method.

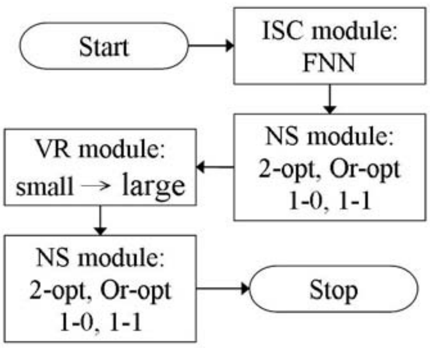


Fig. 4 Flow chart of the proposed heuristic

As shown in Fig. 4, the process of this heuristic is sequential. Note that the NS module is executed twice, before and after the VR module. The details of these three modules are illustrated as follows.

4.1 Initial Solution Construction (ISC) Module

We utilized a modified Nearest Neighbor method, named as the Farthest-start Nearest Neighbor (FNN) method. The FNN selects the customer node *i** whose distance (or travel cost) is the largest from depot 0 to form the initial partly route, 0 – *i**. Then, FNN begins to extend its route according the original rule of nearest-neighbor until the capacity constraints (6) or (11) can not be satisfied any more.

Fig, 5 explains the concept of FNN method. Among the eight customer nodes, node 1 has the largest distance to reach the depot, so that FNN chooses node 1 as the first node of route 1 being served. In addition, FNN extends route 1 to node 2 that is the nearest neighbor from node 1. Then, FNN repeats the nearest-neighbor search until the capacity constraint is violated, and FNN close the route 1. Because not all of customers are served, FNN restarts the farthest-start and nearest-neighbor procedure to form the next route, named as route 2.

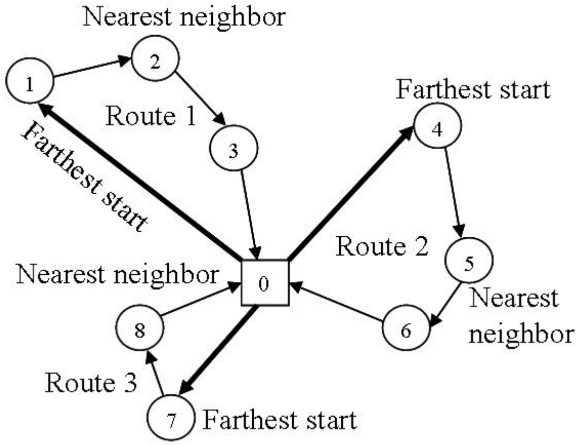


Fig. 5 Concept of the FNN method

4.2 Neighborhood Search (NS) Module

In the NS module, we adopted four traditional neighborhood search methods [4] to sequentially improve the initial solution obtained by ISC module:

- 2-opt intra-route arcs exchange, see Fig. 6(a);
- Or-opt intra-route arcs exchange where the parameter p = 1 and 2, see Fig. 6(b);
- 1-0 inter-route node interchange, see Fig. 6(c); and
- 1-1 inter-route node interchange, see Fig. 6(d).

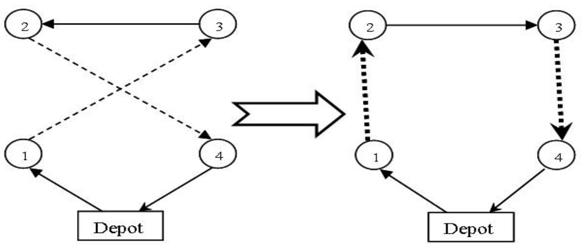
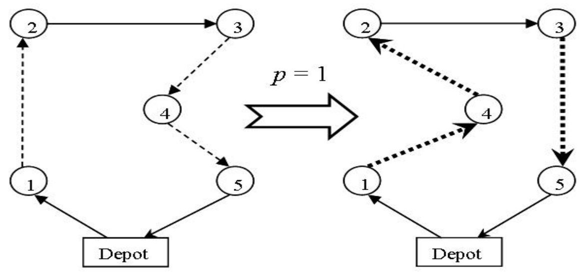


Fig. 6(a) Concept of the 2-opt exchange method



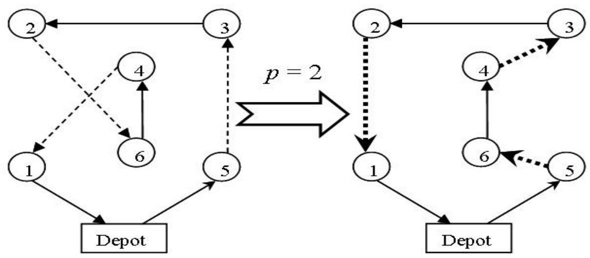


Fig. 6(b) Concept of the Or-opt exchange method

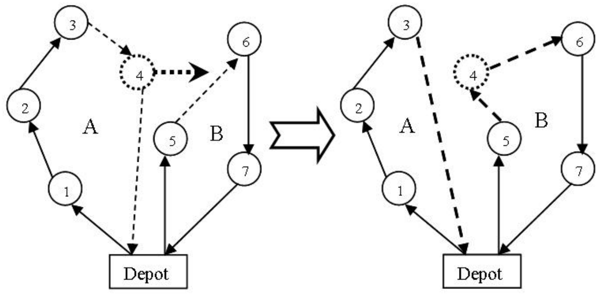


Fig. 6(c) Concept of the 1-0 interchange method

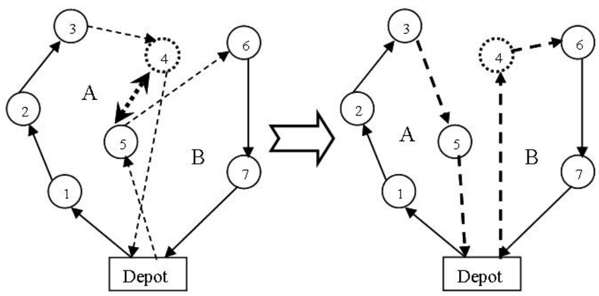


Fig. 6(d) Concept of the 1-1 interchange method

As mentioned above, the NS module has to execute twice. Hence, we adopted best-improvement rule to execute the four NS heuristics.

4.3 Vehicle Replacement (VR) Module

When the initial solution was improved by NS module, we used the VR module to change the type of vehicle. The VR module relaxes the capacity of every vehicle to the largest size, and combines two or more small routes into a large route according to the modified savings formula (12). Where s^*_{ij} is the total savings by merging node i and node j that belong to two different routes respectively; s_{ij} is the savings of travel distance calculated by equation (13) [5]; us_{ij} is the savings of vehicle usage cost calculated by equation (14). In equation (14), f_{li} and g_{li} mean the freezer truck's or general truck's usage cost of type l where this vehicle originally serves node i. The same definition is for f_{lj} and g_{lj}. And, $f_{l(i+j)}$ and $g_{l(i+j)}$ mean the freezer truck's or general truck's usage cost of type l where this vehicle merges routes originally serve node i and node j respectively.

$$s_{ij}^{*} = s_{ij} + us_{ij} \quad (12)$$

$$s_{ij} = c_{i0} + c_{0j} - c_{ij} \quad (13)$$

$$us_{ij} = f_{l_i} + f_{l_j} - f_{l_{(i+j)}} \quad or$$
$$us_{ij} = g_{l_i} + g_{l_j} - g_{l_{(i+j)}} \quad (14)$$

Then, we utilized the NS module to improve routes again. Finally, we adjusted the vehicle type of every route to the most suitable size.

5 Computational Experiments

The proposed HMFVRP models intend to deal with the vehicle routing of multi-temperature common distribution using heterogeneous fleet. In order to identify the potentiality of HMFVRP models in the improvement of the cold-chain logistics, computational experiments on testing the performance of HMFVRPs are reported. First, a set of HMFVRP instances created from VRP and VRPTW benchmarks are illustrated in Section 5.1; then, two stages of experiments are designed in Section 5.2 for computational tests; and finally, the results of the testing are summarized and analyzed in Section 5.3.

5.1 Bank of Testing Instances

We created a bank of 168 HMFVRP instances by modifying from Solomon's VRPTW benchmark instances [16], Taillard's VRP benchmark instances [17] and Homberger's VRP benchmark instances [22]. This bank is used to compare the performance of heuristics to solve HMFVRP1 and HMFVRP2. The sizes of these instances are 100, 200, 385, 400, 600, 800 and 1000 customers.

Furthermore, real costs and capacities of different sizes of trucks are set for these test instances. In accordance with Cho et al. [3], we set four sizes of trucks, 3.5 tons, 7 tons, 15 tons and 20 tons. The capital cost of freezer truck is about 1.5 times than that of general truck with the same size.

Let the level of commodities' temperature be three (normal temperature, refrigerant, frozen). We assumed four scenarios for the demands of goods as follows:

- Scenario 1: Demands of goods on all temperature levels for all customers are identical. We established three types of demands for every customer and every temperature level, 10, 20 and 30. There are total of 42 instances in Scenario 1.
- Scenario 2: Demands of goods for customers are not identical; demands on all temperature levels for some customer are identical. The demands of goods on every temperature level for customers refer to that in Solomon's instances, C101, R101 and RC101 [16], respectively. There are total of 42 instances in Scenario 2.
- Scenario 3: Demands of goods for customers are not identical; demands on all temperature levels for some customer are also different. In Scenario 3, we assumed the demand of normal temperature goods is less than that of refrigerant and frozen goods. Moreover, the percentages of normal temperature, refrigerant and frozen goods are set as 20%: 40%: 40%, 30%: 35%: 35%, 40%: 30%: 30%. There are total of 42 instances in Scenario 3.
- Scenario 4: Demands of goods for customers are not identical; demands on all temperature levels for some customer are also different. In Scenario 4, we assumed the demand of normal temperature goods is more than that of refrigerant and frozen goods. Moreover, the percentages of normal temperature, refrigerant and frozen goods are set as 80%: 10%: 10%, 70%: 15%: 15%, 60%: 20%: 20%. There are total of 42 instances in Scenario 4.

In all Scenarios, the ratios of spaces for loading various temperatures goods on a freezer truck are equal to the percentages of goods demands.

5.2 Designs of Experiments

This research designed a two-staged experiment to analyze the performance and potential of the proposed HMFVRP models and heuristics. The first stage of experiment aims to decide on an efficient sequence to execute the four neighborhood search methods. The second stage of experiment compares HMFVRP1 with HMFVRP2 according to their performances on solving instances. The details of experimental designs are explained as follows.

- Experiment I: Based on the 168 instances, we firstly adopted ISC module to generate the initial solutions for HMFVRP1 and HMFVRP2. Then, used 24 combinations of 2-opt, Or-opt, 1-0 and 1-1 methods to improve initial solutions. The criterion to evaluate the effectiveness of various combinations is the rate of improvement, *RI*. As shown in Equation (15), $C(\cdot)$ is the objective value of some solution; X_{ISC} is the initial solution by ISC module; X_{NS} is the improved solution by NS module.

$$RI = \frac{C(X_{ISC}) - C(X_{NS})}{C(X_{ISC})} \times 100\% \qquad (15)$$

● Experiment II: Based on the 168 instances, we applied the complete heuristic procedure, stated in Section 4, to solve HMFVRP1 and HMFVRP2 instances. The performance of HMFVRP1 and HMFVRP2 are respectively evaluated according to four scenarios, and conducted a series of hypothesis tests.

5.3 Results of Experiments

Because the units and scales of vehicle usage cost and of travel distance are different, we compare these two objective values respectively.

● Results of Experiment I:

As shown in Fig. 7, the average *RI* values of vehicle usage cost among the 168 instances are significant. That is, the average *RI* values are 52% for HMFVRP1 and 48% for HMFVRP2. Similarly, as shown in Fig. 8, the average *RI* values of traveling distance are 73% for HMFVRP1 and 71% for HMFVRP2. Although the average *RI* values of HMFVRP2 are slightly less than that of HMFVRP1, the absolute average objective values of HMFVRP2 are better than that of HMFVRP1.

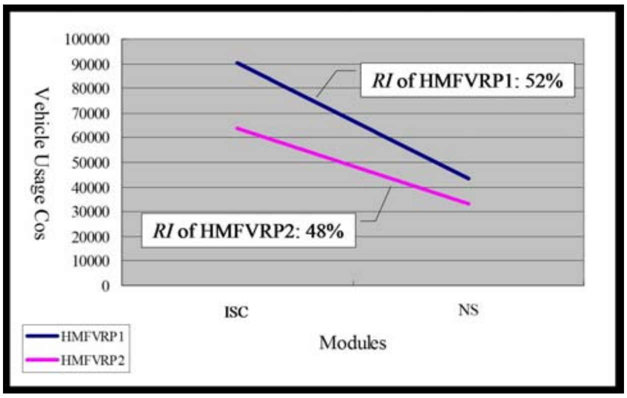


Fig. 7 Comparison of *RI* value of vehicle usage cost.

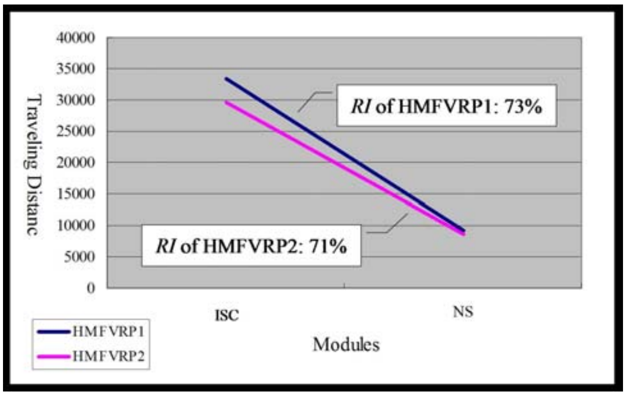


Fig. 8 Comparison of *RI* value of traveling distance.

There are twenty-four combinations of the four interchange are tested on the 168 instances. As shown in Fig. 9, the combination N3-1, i.e. in the sequence of 1-0, 1-1, Or-opt and 2-opt, obtains the best performance on improving the HMFVRP1 initial solution among the 24 combinations. Similarly, as shown in Fig. 10, the combination N3-5, i.e. in the sequence of 1-0, 2-opt, 1-1 and Or-opt, has the best performance on improving the HMFVRP2 initial solution among the 24 combinations.

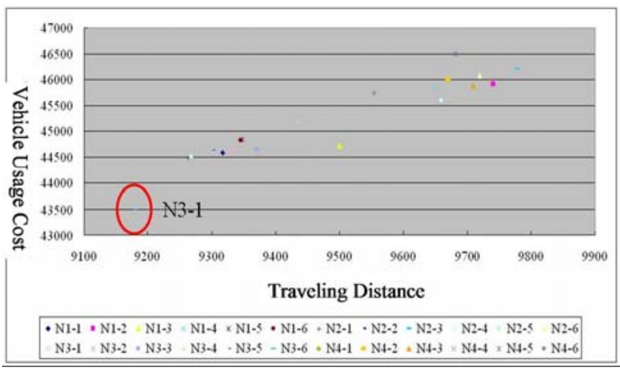


Fig. 9 Comparison of combinations for HMFVRP1.

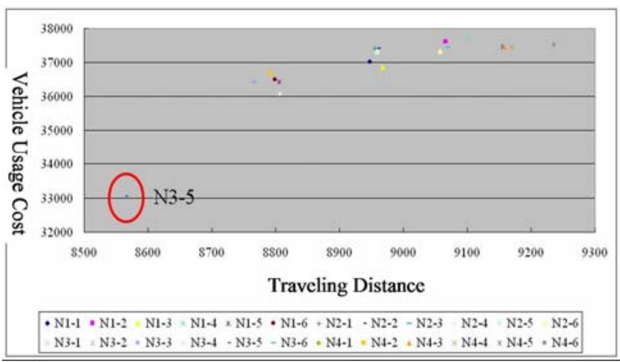


Fig. 10 Comparison of combinations for HMFVRP2.

Therefore, in Experiment II, we decided to adopt combination N3-1 in executing NS module for HMFVRP1 and to adopt combination N3-5 in executing NS module for HMFVRP2.

● Results of Experiment II:

Due to that 42 instances in every Scenario each can be considered a large sample, we applied Z-test to conduct the hypothesis test of pairing sample. The hypothesis is illustrated as Equation (16), where μ_d is the average value of the difference between HMFVRP1 and HMFVRP2 in solving the same instance.

$$\begin{cases} \mathrm{H}_0 : \mu_d \leq 0 \\ \mathrm{H}_1 : \mu_\mathrm{d} > 0 \end{cases} \tag{16}$$

Table 1 ~ Table 4 summarize the results of hypothesis tests for the four scenarios. Assuming that the significant level α is equal to 0.05, we rejected the null hypothesis in all scenarios and objectives. That is, the HMFVRP2 apparently performed much better than HMFVRP1.

Table 1 Result of hypothesis test in Scenario 1.

Objectives	Vehicle usage cost	Traveling distance
μ_d	18166.19	1909.77
σ_d	20775.30	3340.37
p-value	0.000000	0.000163

Table 2 Result of hypothesis test in Scenario 2.

Objectives	Vehicle usage cost	Traveling distance
μ_d	15862.86	1646.44
σ_d	15833.08	2679.41
p-value	0.000000	0.000057

Table 3 Result of hypothesis test in Scenario 3.

Objectives	Vehicle usage cost	Traveling distance
μ_d	38758.57	5108.98
σ_d	38920.57	7474.05
p-value	0.000000	0.000007

Table 4 Result of hypothesis test in Scenario 4.

Objectives	Vehicle usage cost	Traveling distance
μ_d	11308.10	1295.21
σ_d	10787.93	2929.93
p-value	0.000000	0.002937

6 Conclusions and Suggestions

Multi-temperature common distribution service is becoming gradually popularized within the convenience stores, supermarkets and cold food markets. With the invention of multi-temperature refrigerated container and transport system, it offers a brand-new technology and business solution in practice. This article proposes two HMFVRP (Heterogeneous Multi-temperature Fleet Vehicle Routing Problem) models which enable application in multi-temperature common distribution.

The main contributions of this study are twofold. The first is to put forward the mathematical programming formulation of HMFVRP and to design a simple heuristic method to solve HMFVRP. The second is to generate a set of 168 HMFVRP instances to verify the effectiveness of the proposed heuristic method and the feasibility of HMFVRP models.

According to the computational results, we found that: (1) the NS module can effectively improve the initial solution obtained by the ISC module; (2) proper combination of four interchange heuristics is effective in lowering down the vehicle usage cost and travel distance; and (3) among 168 instances classified into four Scenarios, the HMFVRP2 apparently performed superior to HMFVRP1. Such a result implies that the use of MRTS has high potential in multi-temperature common distribution.

This study does not only propose a basic mathematical formulation and a heuristic algorithm for HMFVRP, but also proves their benefits by means of experimental tests. Still, many subjects need be discussed. The following issues shall be considered in future research on HMFVRP:

1. This study did not consider the cost of refrigerated containers. As we known, this cost is apparently higher than that of the plastic vessels. Hence, carriers may simultaneously use freezer truck and MRTS to deliver goods. In the future, a mixed HMFVRP model could be considered.
2. This study designed a simple heuristic method applicable to solve the HMFVRP, yet something could be improved. For example, introduction of some meta-heuristics, like the tabu search, ant system, or threshold accepting, possibly promoting the performance of problem-solving.
3. This study assumed that the capacity of vehicle and refrigerated container are fixed. Hence, vehicles or refrigerated containers of different sizes can be simultaneously considered in the future.
4. Further consideration of the time-window constraint on serving customers should be emphasized.
5. It is important to collect the actual demands and operating data from some cold-chain logistics companies. Using the practical data, we can identify the real performance of HMFVRP.

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