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A HEURISTIC ALGORITHM FOR THE MULTI-DEPOT VEHICLE ROUTING PROBLEM WITH OUTSIDER CARRIER SELECTION

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Key words: multi-depot vehicle routing problem with pickup and delivery, carrier selection, heuristics, 0-1 integer programming, logistics.

ABSTRACT

The delivery and pickup of goods from a depot to local customers is an important and practical problem of a logistics manager. In practice, professional logistics company owns more than one depot and the fleet is composed of different types of trucks. This situation is a multi-depot vehicle routing problem with delivery and pickup.

When the everyday demand is known, the logistics manger is facing a deterministic multi-depot vehicle routing problem with simultaneously pickup and delivery. In reality, the demands fluctuate over time within a year. When the total demand is greater than the whole capacity of owned trucks, the logistics manager may consider using an outsider carrier to transport a shipment because it may bring significant cost savings to the company.

The purpose of this paper is developing a heuristic algorithm not only to route a limited number of trucks from different depots to customers with simultaneously pickup and delivery, but also to make a selection of outsider carriers by minimizing a total cost function. Both the mathematical model and the heuristic algorithm are developed. A variety of test problem were examined. The average percentage deviation from the optimum for the twenty test problems is 1.74% and the execution time for all test problems is less than a second. The results are encouraging as our algorithm obtains the optimal or near-optimal solutions in an efficient way in terms of time and accuracy.

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I. INTRODUCTION

The Vehicle routing with pickup and delivery is an important and practical problem for logistics managers. In many sectors of the economy, transportation costs amount for a fifth or even a quarter (lumber, wood, petroleum, stone, clay, and glass products) of the average sales amount, (Schneider, 1985). Thus appropriately identifying and modeling the problems and developing algorithms to solve them have been the continuing research effort in the last several decades.

Professional distribution company owns more than one depot and the fleet is composed of different types of trucks. This situation is a multi-depot vehicle routing problem with pickup and delivery. Our motivation for this study stems from observations on a local logistics company. This company operates from several depots and owns different types of trucks. Its main business is delivering food and beverages to wholesalers. The wholesalers often need to return some food, recyclable glass bottles for beverages, and baskets for food at the time when the logistics firm deliveries food and beverages. Since the business hours of the wholesalers are fixed, the delivery time window constraint is not a major concern. However, the company is facing fluctuations of demand from its customers. When the demands are greater than the total capacity of the company during the peak season, the company has two strategies to use: using overtime strategy or outsider carriers. Since the overtime cost is much higher than that of using an outsider carrier, sometimes using an outsider carrier is a more attractive option.

Regarding carrier selection, a logistics manager can make a choice between a truckload (a private truck) and a less-than-truckload carrier (an outsider carrier). A private truck allows a company to consolidate several shipments, going to different destinations, and in a single truck. A less-than-truckload carrier usually assumes the responsibility for routing each shipment from the origin to the destination. The freight charged by a less-than-truckload carrier is typically much higher than the cost of a private truck. Choosing the right customers to be served by outsider carriers may yield significant cost savings to the company.

In this paper, we address the problem of routing a fixed number of trucks with limited capacity from several warehouses to customers with known demand and supply by taking less-than-truckload carriers selection into consideration. The objective of this paper is to develop a heuristic algorithm to route the private trucks with simultaneous pickups and deliveries in each depot and to make a selection between truckload and less-than-truckload carriers by minimizing a total cost function. The contribution of this research is providing a useful heuristic algorithm that can help a logistics manager increases productivity and reduces the transportation cost.

The rest of the paper is organized as follows. The next section provides the literature review. Section 3 formulates the mathematical model for our problem. Section 4 presents the heuristic algorithm. Computational results are reported in Section 5. Finally concluding remarks and suggestions for future research are provided in Section 6.

II. LITERATURE REVIEW

The literature on the vehicle routing problem with pickup and delivery (VRPPD) is scarce compared to that on the traditional vehicle routing problem. In general, the VRPPD literature can be classified into three main categories:

(1) delivery-first and pickup-second VRP,
(2) mixed pickup and delivery VRP, and
(3) simultaneous pickup and delivery VRP.

Over the past decades, this problem has been studied by Anily (1996), Toth and Vigo (1996; 1997; 1999), Salhi and Nagy (1999), Gendreau et al. (1999), and Osman and Wassan (2002). A more detailed review of this type of VRPPD can be found in Nagy and Salhi (2005).

Min (1989) was the first to explore the simultaneous pickup and delivery VRP. A cluster-first/route-second approach was proposed to solve a public library routing problem with one depot, two vehicles and twenty-two customers. Within the routing phase traveling salesman problems were solved to optimality as subproblems. Halse (1992) considered different version of vehicle routing problems, including the one with backhaul. A cluster-first/route-second approach was proposed for solving VRPPD with the first stage focused on assigning customers into vehicles and the second stage using a 3-opt procedure during the routing phase. Solutions to problems with up to 100 customers were reported. Gendreau et al. (1999) developed heuristics for traveling salesman problem with pickups and deliveries. First, the traveling salesman problem was solved. Then, the route was determined based on the results of first stage by taking pickups and deliveries into consideration. Dethloff (2001) studied the simultaneous VRPPD from a reverse logistics point of view. Both the mathematical formulation and insertion-based heuristic algorithm were provided. The proposed algorithm was successfully applied to a real-life problem. Recently, Nagy and Salhi (2005) proposed a heuristic algorithm to solve simultaneous VRPPD. The concepts of weak and strong feasibility were found helpful in tackling the VRPPD. Their algorithm is also capable of solving multi-depot problems. Tang and Galvão (2006) developed a tabu search algorithm to solve the vehicle routing problem with simultaneous pickup and delivery. Computational results for a set of 87 test problems were reported. Recently, Polat et al. (2015) proposed a mixed-integer mathematical optimization model and a perturbation based neighborhood search algorithm combined with the classic savings heuristic, variable neighborhood search and a perturbation mechanism. The numerical results show that the proposed method produces superior solutions for a number of well-known benchmark problems compared to those reported in the literature and reasonably good solutions for the remaining test problems.

The multi-depot vehicle routing problem has attracted less attention from the OR/MS community. Tillman (1972) used the Clarke and Wright savings criterion to solve a single and multiple terminal delivery problem. Wren and Holiday (1972) proposed a sweep procedure by sorting all customers of their polar angle. Customers are then iteratively assigned to an existing or new route based on the least additional distance. Test problems include two depots and up to 176 customers. Gillette and Johnson (1976) solved a multi-terminal vehicle dispatching problem by a clustering procedure and sweep heuristic in each depot. The authors presented results with 249 customers and up to 5 depots. Golden et al. (1977) described two approaches for MDVRP. The first one is based on the use of borderline customers and a modified savings. The second one is a two phase approach. First, customers are assigned to depots, and then a separate VRP is solved for each depot. Chao et al. (1993) presented a composite heuristic that uses infeasibility and refinements. The heuristic allows deteriorations of the current solution. Two reinitialization procedures are used to diversify the search. Test problems contain 360 cities and 9 depots. A Tabu-search heuristic algorithm for the multi-depot vehicle routing problem was proposed by Renaud, Laporte and Boctor (1996). All heuristics mentioned above considered vehicle of the same capacity.

To our knowledge, only two research attempted to treat the simultaneous pickup and delivery problem for a multi-depot system. The first one (Salhi and Nagy (1999)) suggested an insertion-based heuristic. It can insert more than one backhaul at a time. The second one (Nagy and Salhi (2005)) proposed a method that firstly found a solution and then modified the solution to make it feasible. Both research adopted the idea of borderline customers. Customers were assigned into two groups, non-borderline and borderline customers. The non-borderline customers were assigned to their nearest depots, and then the borderline customers were inserted into the single depot vehicle routing one at a time.

Little research has examined the problem of choosing between a less-than-truckload and truckload carrier. Ball et al. (1985) considered a fleet planning problem for long-haul deliveries with fixed delivery locations and an option to use an outside carrier. Agarwal (1985) studied the static problem with a fixed fleet size and an option to use an outside carrier. Klincewicz et al. (1990) developed a methodology to address the fleet size planning and to route limited trucks from a central warehouse to customers with random daily demands. Chu (2005) introduced a heuristic to simultaneously select customers to be served by external transportation providers and to route a limited number of owned heterogeneous trucks without taking the pickup into consideration. Recently, Wu et al. (2017) developed a heuristic algorithm for routing the private trucks with time windows and for selecting of less-than-truckload carriers by minimizing the total cost function.

In general, our research described here differs from previous one on fleet planning or vehicle routing in that it modifies the Clarke and Wright method by shifting the performance measure from distance to cost and also incorporates the fixed cost of different types of trucks into the model. In addition, we simultaneously consider the routing of a heterogeneous fleet of vehicles with simultaneous delivery and pickup and the selection of less-than-truckload carriers. A mathematical model is also proposed to solve the problem. To the best of our knowledge, this scenario has not been considered in the literature.

III. MATHEMATICAL MODEL

The multi-depot vehicle routing problem can be defined as follows. Let $G = (V, A)$ be a directed graph, where V is the vertex and A is the arc set. Vertex set $D = \{1, 2, \ldots, v\}$ represents the set of depots, whereas vertex set $N = \{1, \ldots, n\}$ denotes the number of customers to be served. A travelling cost, *cijkl*, is defined for the kth truck of depot l traveling from vertex i to vertex j whereas vertices (i, j), $i, j \in V$, $i \neq j$. Without loss of generality, the travelling cost can represent, according to the application environment, the distance, time, fuel consumption, etc. between each pair of vertices. Moreover, each depot $l \in D$ has a limited fleet of vehicles with the different capacity, denoted as Q_{kl}. Each customer $i \in N$ has a certain demand of goods, denoted as q_i, where $0 < q_i \leq Q_{kl}$. When the total demand of the customers is greater than the whole capacity of owned trucks, outsider carriers are available to transport the goods. Our multi-depot vehicle routing problem pursues to determine the routes of minimum travelling cost satisfying the following conditions:

(1) A multi-depot system is considered; all trucks start at the depot and return back to the starting depot.
(2) Goods may be simultaneously delivered and picked.
(3) The requirements of all the customers are known and each customer's requirement cannot exceed the truck capacity.
(4) Each customer is served by one truck (either by the private truck or the less-than-truckload carrier) and all customers' requirements must be met.
(5) The cost of operating the truck fleet consists of a fixed cost and a variable cost. The principal items in the fixed cost include personnel, insurance, and truck depreciation. The main component for the variable cost is fuel, which is usually proportional to the distance trucks traveled.

The integer programming model and the relevant notations are given below:

$$\min z = \sum_{k=1}^{ml}\sum_{l=1}^{v} FC_{kl} + \sum_{i=0}^{n}\sum_{j=0}^{n}\sum_{k=1}^{m_l}\sum_{l=1}^{v} C_{ijkl}X_{ijkl} + \sum_{i=1}^{n_l} CL_i L_i$$

s.t.

$$\sum_{k=1}^{m_l} \mathrm{Y}_{0kl} \leq m_l \quad (l = 1, \ldots, v) \tag{1}$$

$$\sum_{k=1}^{m_l}\sum_{l=1}^{v} Y_{ikl} + L_i = 1 \quad (i = 1, \ldots, n) \tag{2}$$

$$\sum_{j=0}^{n} X_{ijkl} = \mathrm{Y}_{ikl} \quad (i = 1, \ldots, n; k = 1, \ldots, m_l; l = 1, \ldots, v) \tag{3}$$

$$\sum_{j=0}^{n} X_{jikl} = Y_{ikl} \quad (i = 1, \ldots, n; k = 1, \ldots, m_l; l = 1, \ldots, v) \tag{4}$$

$$Y_{ikl} = U_{ikl} \quad (i = 1, \ldots, n; k = 1, \ldots, m_l; l = 1, \ldots, v) \tag{5}$$

$$Y_{ikl} = V_{ikl} \quad (i = 1, \ldots, n; k = 1, \ldots, m_l; l = 1, \ldots, v) \tag{6}$$

$$U_{ikl} - V_{ikl} = 0 \quad (i = 1, \ldots, n; k = 1, \ldots, m_l; l = 1, \ldots, v) \tag{7}$$

$$\sum_{i=1}^{n} q_i U_{ikl} \leq Q_{kl} \quad (k = 1, \ldots, m_l; l = 1, \ldots, v) \tag{8}$$

$$\sum_{i=1}^{n} p_i V_{ikl} \leq Q_{kl} \quad (k = 1, \ldots, m_l; l = 1, \ldots, v) \tag{9}$$

$$\begin{gathered} Z_{ikl} - q_j U_{jkl} + p_j V_{jkl} \leq Z_{jkl} + M(1 - X_{ijkl}) \\ (i = 0, \ldots, n;\ j = 1, \ldots, n;\ k = 1, \ldots, m_l;\ l = 1, \ldots, v) \end{gathered} \tag{10}$$

$$Z_{ikl} \leq Q_{kl} \quad (i = 0, \ldots, n; k = 1, \ldots, m_l; l = 1, \ldots, v) \tag{11}$$

$$Z_{ikl} \leq M\sum_{j=0}^{n} X_{ijkl} \quad (i = 0, \ldots, n; k = 1, \ldots, m_l; l = 1, \ldots, v) \tag{12}$$

$$Z_{0kl} = \sum_{i=1}^{n} q_i U_{ikl} \quad (k = 1, \ldots, m_l; l = 1, \ldots, v) \tag{13}$$

$$\forall X_{ijkl},\ L_i,\ U_{ikl},\ V_{ikl} \in \{0,1\}$$

$$Z_{ikl} \geq 0, \text{ integer}$$

i: $\{i = 0, \ldots, n\}$, the index set of customers (let the index 0 denote the depot);
j: $\{j = 0, \ldots, n\}$, the index set of customers;

k: $\{k = 1, \ldots, ml\}$, the index set of trucks;
l: $\{l = 1, \ldots, v\}$, the index set of depots;
n: the number of customers;
m_l: the number of trucks of depot l;
v: the number of depots;
FC_{kl}: fixed cost of the kth truck of depot l;
C_{ijkl}: the cost of the kth truck of depot l traveling from customer i to customer j;
CL_i: the cost charged by the less-than-truckload carrier for serving customer i;
q_i: the delivery of customer i;
p_i: the pickup of customer i;
Q_{kl}: the capacity of the kth truck of depot l;
Z_{ikl}: the load on the kth truck of depot l while it departs from customer i;

$$X_{ijkl} = \begin{cases} 1, & \text{if the } k\text{th truck of depot l travels from customer } i \text{ to } j, \\ 0, & \text{otherwise} \end{cases}$$

$$U_{ikl} = \begin{cases} 1, & \text{if the demand of customer } i \text{ is deliveried by the } k\text{th truck of depot l}, \\ 0, & \text{otherwise} \end{cases}$$

$$V_{ikl} = \begin{cases} 1, & \text{if the supply of customer } i \text{ is pickuped by the } k\text{th truck of depot l}, \\ 0, & \text{otherwise} \end{cases}$$

$$L_i = \begin{cases} 1, & \text{if the customer } i \text{ is serviced by the less} - \text{than} - \text{truckload carrier}, \\ 0, & \text{otherwise} \end{cases}$$

$$Y_{ikl} = \begin{cases} 1, & \text{if the service of customer } i \text{ is satisfied by the } k\text{th truck of depot l}, \\ 0, & \text{otherwise} \end{cases}$$

The objective of this model is to route the private trucks and to make a selection of less-than-truckload carriers by minimizing a total cost function.

Constraint (1) ensures that at most ml trucks can be used at depot l.

Constraint (2) defines that each customer is served either by a private truck or a less-than-truckload carrier.

Constraints (3) and (4) guarantee that a truck arrives at a customer and also leaves that location.

Constraints (5), (6) and (7) ensure that the delivery and pickup of a customer is served by the same truck.

Constraints (8) and (9) ensure that the total delivery and total pickup by a truck cannot exceed the truck capacity, respectively.

Constraints (10), (11), and (12) calculate the load of vehicle after having serviced a customer and impose an upper bound on the total load transported by the truck in any given section of the route.

Constraint (13) ensures that the initial vehicle load is equal to the total load transported by the truck.

IV. THE HEURISTIC ALGORITHM

In this section we describe our algorithm, called MDVRPSPD-LTL, for solving the multi-depot vehicle routing problem with simultaneous pickup and delivery, and the selection of less-than-truckload carriers. Our problem can be viewed as being solved in three stages: first, select customers who will be served by the less-than-truckload carriers; then, the remaining customers must be assigned to depots; Last, routes must be constructed that link customers assigned to the same depot. The heuristic algorithm can be decomposed into three main steps. In the following, we describe this algorithm by examining its main steps separately.main program will end when all of the data frames are processed.

1. Selection Step

The first step requires the selection of a group of customers, who will be served by the less-than-truckload carriers. In this step, we check if the demand is greater than the total capacity of owned trucks. If it is not, we skip this step and implement the next step directly.

In order to minimize the total cost, we have to design a procedure that can achieve this goal. In reality, the freight charged by the less-than-truckload carrier is usually much higher than the cost handled by a private truck. It is obvious that we should arrange the customers in ascending order based on the freight charged by the less-than-truckload carrier and choose the customers with the lowest cost.

The detail for selecting the customers is described as follows.

(1) Calculate the total demand from all customers.
(2) Calculate the whole capacity of owned trucks.
(3) If the total demand from all customers is greater than the capacity of owned trucks, go to step (4), otherwise skip this procedure.
(4) Subtract the capacity of own trucks from the total demand, which is the unsatisfied truck capacity.
(5) Arrange the customers in ascending order based on the freight charged by the less-than-truckload carrier. Starting at the top of the list, do the following.
(6) Choose one of the customers whose demand is greater than the unsatisfied truck capacity. The corresponding customer will be the first candidate served by the-less-than-truckload carrier.
(7) Calculate the total cost charged by the less-than-truckload carrier based on the first candidate in step (6).
(8) Using the data in step (5), sort the customers in descending order based on the demand. Sum up the demand of customers until the total demand is greater than the unsatisfied truck capacity. The corresponding customers will be the second group of candidates served by the-less-than-truckload carrier.
(9) Calculate the total cost charged by the less-than-truckload carrier based on the second group of customers in step (8).
(10) Make a selection between the first candidate and the second group of customers with a lower total cost based on steps (7) and (9). The selected customer or customers will be served by the-less-than-truckload carrier, and the remaining customers in the list will be served by private trucks.

2. Assignment Step

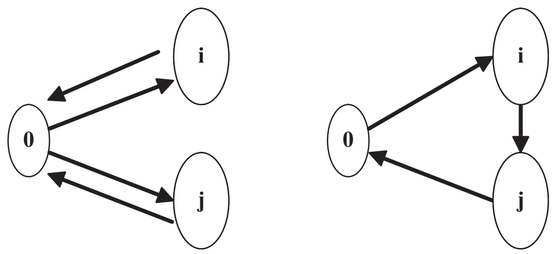
In selection step, the customers are split into two subsets; one for the less-than-truckload customers and the other for the remaining customers who will be served by the private trucks.

The main idea of assignment step consists of assigning in a cyclic way, one customer at a time. The assignment heuristic assigns the closest customer to the last assigned one, to the same depot as this last one. The assignment heuristic can be described briefly as follows.

(1) The heuristic start at the current depot and assigns to the current depot the closest customer.
(2) The heuristic assigns to this depot the closest customer to the last assigned customer to the same depot.
(3) Repeat step (2) until the total delivery/or pickup of assigned customers is greater than the total truck capacity of this depot.
(4) Set a new depot as the current depot
(5) Repeat steps (1) to (4) until all customers assigned to a depot except for the last depot.
(6) Assign all unassigned customers to the last depot without considering the truck capacity of the last depot.
(7) Check the feasibility of truck capacity of the last depot. If the total demand for all customers of the depot is greater than the truck capacity of the last depot, go to step (8), otherwise skip the following steps and go to 3 Route construction step.
(8) Subtract the truck capacity of each depot from the total demand for all customers of the same depot which is the unused truck capacity.
(9) Subtract the truck capacity of the last depot from the total demand for all customers of the last depot, which is the unsatisfied truck capacity.
(10) If the unused truck capacity in step (8) is greater than or equal to the unsatisfied truck capacity in step (9) and the truck capacity in step (8) is greater than or equal to the total demand for all customer of the depot, in step (10), exchange all customers between the last depot and the depot in step (8). Otherwise repeat steps (8) to (10) until all depots have been considered.
(11) Check the feasibility of the truck capacity of the last depot. If the total demand for all customers of the last depot is less than or equal to the truck capacity of the last depot, stop this assignment step and go to 3 Route construction step.
(12) Choose one customer in last depot and then inset the customer to first depot (i.e., an (1, 0) procedure is adopted).
(13) Repeat step (11).
(14) Choose one customer in last depot and one customer in the first depot, respectively, and then exchange two customers (i.e., an (1, 1) procedure is adopted).
(15) Repeat step (11).
(16) Choose a group of customers in last depot and a group of customers in the first depot, respectively, and then exchange two groups' customers.

Carrier mix serving customer i and j: Truckload and Truckload

Independent Shipments Consolidated Shipments



Independent Cost: Consolidated Colst:

$TL_{i0} + TL_{j0}$ $TL_i + TL_{ij}$

Revised Savings

$$S_{ij} = TL_{i0} + TL_{j0} - TL_{ij}$$
$$= FC(Z_i) + FC(Z_j) - FC(Z_i + Z_j) + (d_{i0} - d_{ij} + d_{0j})$$

Fig. 1. Savings calculation from consolidating two customers.

3. Route Construction Step

The last step constructs routes for each depot and it can be further divided into two steps, initial solution construction and refining procedure.

1) Initial Solution Construction

The initial solution construction step is composed of four procedures: construct, remove, check, and rearrange.

The construct procedure is designed to generate the initial routes. The Clarke and Wright's savings algorithm is used to solve this problem by making two modifications. The first modification is a shift in criterion from distance to cost. The second modification is a change in the savings calculation.

Before explaining the revised savings calculation, we list the relevant notations as follows:

S_{ij} = savings from consolidating shipments to customer i and j into the same truck.
TL_{i0} = the total cost of a private truck that travels from warehouse to customer i, then returns back to warehouse.
TL_{ij} = the total cost of a private truck that travels from warehouse to customer i, then from customer i to customer j and finally returns back to warehouse.
$FC(Z)$ = the fixed cost of the smallest truck that can serve a demand of Z.
d_{ij} = the distance from customer i to customer j.
v = the cost of traveling a mile for private truck($/per mile).

Fig. 1 illustrates the revised savings calculation from linking two customers.

The detail for the construct procedure is described as follows:

(1) Calculate the savings for all pairs customers based on revised savings scenario in Fig. 1.
(2) Arrange the savings in descending order. Starting at the top of the list, do the following.

(3) Find the feasible link in the list which can be used to extend one of the two ends of the currently constructed route.
(4) If the route cannot be expanded further, terminate the route. Otherwise, choose the first feasible link in the list to start a new route.
(5) Repeat Steps (3) and (4) until no more links can be chosen.
(6) Output all the routes.

The check procedure examines the feasibility of routes generated from the construct or the remove procedure. Let arrival(x) and leave(x) denote the total load of a truck arriving at customer x and the total load of a truck leaving from customer x, respectively. Arrival(x) and leave(x) can be easily calculated as follows: leave(x) = arrival(x) – q(x) + p(x), where q(x) is the delivery of customer x and p(x) is the pickup of customer x; arrival(x) is simply equal to

leave(x-1), where x-1 denotes the precedent customer in the route. Within this check procedure, for any x, arrival(x) ≤ truck capacity and leave(x) ≤ truck capacity are examined. If there is a violation, then the rearrange procedure will be executed. If there are no violations on the truck capacity, then the program will skip the rearrange procedure and go to the refining procedure directly.

The rearrange procedure is designed to achieve the feasibility of routes. Since both the total delivery and total pickup in a route do not exceed the truck capacity, rearranging the ordering of customers in a route can generate a feasible route easily. Define reduce_load(x) = q(x) – p(x), where reduce_load(x) is the decease (reduce_load(x) > 0) or increase load (reduce_load(x) < 0) of a truck while the truck makes a delivery to customer x. This procedure arranges the customers in descending order based on reduced_load(x) in infeasible route, which will produce a feasible route.

2) Refining Procedure

A refining procedure is applied to the solution obtained through the initial solution step. This procedure is composed of a succession of intra-route and inter-route arc exchanges which are well known in the literature.

(a) Intra-route improvement
Each route is improved by applying a refining procedure which considers all the feasible exchanges of two arcs belong to the route (the so called intra-route two-exchanges, Toth and Vigo (1997). Given a route, a two-exchange is obtained by replacing arcs (m, n) and (p, q) with arcs (m, p) and (n, q), as illustrated in Fig. 2.
(b) Inter-route improvement
In this step, a set of routes is obtained by using further local search procedures. These procedures are based on the so called inter-route one-exchange, two-exchanges and two consecutive vertices exchanges, illustrated in Figs. 3-5, respectively.
For each node m (belonging to route a), the one-exchange corresponding to its insertion after node p (belonging to route b), is obtained by removing arcs (l, m), (m, n) and (p, q), and replacing them with arcs (l, n), (p, m) and (m, q), as illustrated in Fig. 3.
For each node m (on route a), the two-exchanges corresponding to its exchange with node q (on route b), are obtained by removing arcs (l, m), (m, n), (p, q) and (q, r), and replacing them with arcs (l, q), (q, n), (p, m) and (m, r), as illustrated in Fig. 4.
For two consecutive nodes m and n (on route a), the two consecutive vertices exchanges corresponding to its exchange with two consecutive nodes q and r (on route b),

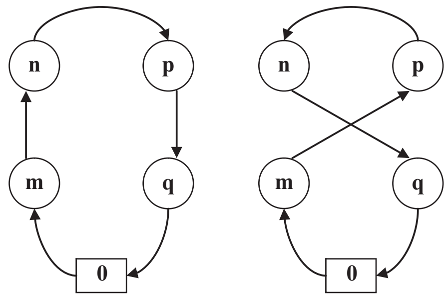


Fig. 2. Example of intra-route two-exchanges.

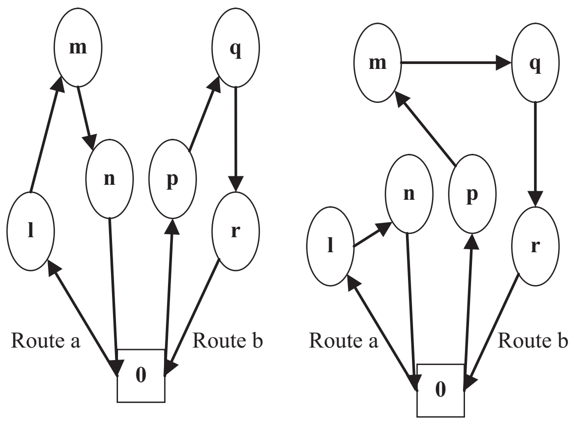


Fig. 3. Example of inter-route one-exchange.

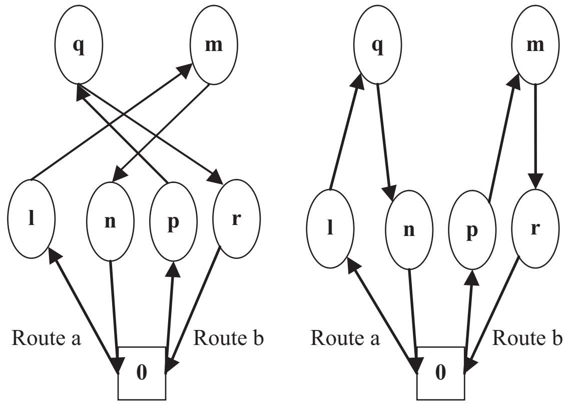


Fig. 4. Example of inter-route two-exchanges.

Table 1. Vehicle capacities and relevant costs for ten test problems with five customers.

Problem	Vehicle Capacities (cwt)	Fixed Cost ($)	Variable Costs ($)
1-1-1	40, 40	400, 400	TL $1.5/per mile, LTL $9/per mile
1-1-2	30, 30	300, 300	TL $1.5/per mile LTL $9/per mile
1-1-3	50, 50	500, 500	TL $1.5/per mile LTL $9/per mile
1-1-4	40, 40	400, 400	TL $1.5/per mile LTL $9/per mile
1-1-5	30, 30	300, 300	TL $1.5/per mile LTL $9/per mile
1-2-1	50, 30	500, 300	TL $1.5/per mile LTL $9/per mile
1-2-2	40, 20	400, 200	TL $1.5/per mile LTL $9/per mile
1-2-3	60, 40	600, 400	TL $1.5/per mile LTL $9/per mile
1-2-4	50, 30	500, 300	TL $1.5/per mile LTL $9/per mile
1-2-5	40, 20	400, 200	TL $1.5/per mile LTL $9/per mile

Table 2. Vehicle capacities and relevant costs for ten test problems with ten customers.

Problem	Vehicle Capacities (cwt)	Fixed Cost ($)	Variable Costs ($)
2-1-1	100, 100	1000, 1000	TL $1.5/per mile LTL $9/per mile
2-1-2	70, 70	700, 700	TL $1.5/per mile LTL $9/per mile
2-1-3	60, 60	600, 600	TL $1.5/per mile LTL $9/per mile
2-1-4	90, 90	900, 900	TL $1.5/per mile LTL $9/per mile
2-1-5	70, 70	700, 700	TL $1.5/per mile LTL $9/per mile
2-2-1	110, 90	1100, 900	TL $1.5/per mile LTL $9/per mile
2-2-2	80, 60	800, 600	TL $1.5/per mile LTL $9/per mile
2-2-3	70, 50	700, 500	TL $1.5/per mile LTL $9/per mile
2-2-4	100, 80	1000, 800	TL $1.5/per mile LTL $9/per mile
2-2-5	80, 60	800, 600	TL $1.5/per mile LTL $9/per mile

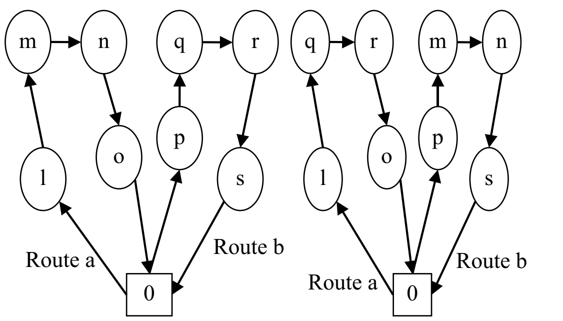


Fig. 5. Example of inter-route 2 consecutive vertices exchanges.

are obtained by removing arcs (l, m), (m, n), (n, o), (p, q) (q, r) and (r, s), and replacing them with arcs (l, q), (q, r), (r, o), (p, m), (m, n) and (n, s), as illustrated in Fig. 5.

(c) Search Procedure

A search procedure is designed to search for a better solution. From the results of extensive experiments which are not shown here, we are aware that the implementation sequence of intra-route and inter-route improvement procedure might have impacts on the quality of solution.

The improvement procedures mentioned above include intra-route two-exchanges, inter-route one-exchanges, two exchanges and two consecutive vertices exchanges. The possible permutations of four different improvement procedures are only twenty-four. Therefore, a loop procedure consisting of arranging the possible sequences of intra-route and inter-route improvement is applied on the solution obtained in the initial solution construction phase and the check procedure mentioned before is also applied during the search process to avoid the route infeasibility.

Table 3. Summary results.

Problem	Optimal Solution		Heuristics		% Deviation
	Total Costs	CPU Time	Total Costs	CPU Time	
1-1-1	1094.1	1	1094.1	0.0468	0.00%
1-1-2	1025.9	1	1032.17	0.03125	0.61%
1-1-3	1252.8	1	1252.7	0.0468	0.00%
1-1-4	1161.7	1	1161.7	0.03125	0.00%
1-1-5	1037.9	1	1039.55	0.0625	0.16%
1-2-1	1087.8	1	1095.43	0.03125	0.70%
1-2-2	965.2	1	965.2	0.03125	0.00%
1-2-3	1237.9	1	1252.7	0.03125	1.20%
1-2-4	1161.7	1	1232.1	0.03125	6.06%
1-2-5	1020.7	1	1020.7	0.0468	0.00%

Table 4. Summary results.

Problem	Optimal Solution		Heuristics		% Deviation
	Total Costs	CPU Time	Total Costs	CPU Time	
2-1-1	2305.5	22	2421.26	0.04688	5.02%
2-1-2	1747.8	28	1811.18	0.04688	3.63%
2-1-3	1835.5	38	1920.21	0.03125	4.62%
2-1-4	2116.6	27	2140.76	0.03125	1.14%
2-1-5	1822.1	40	1854.92	0.04688	1.80%
2-2-1	2323.1	46	2386.32	0.04688	2.72%
2-2-2	1796.9	43	1823.9	0.04688	1.50%
2-2-3	1855	63	1855	0.03125	0.00%
2-2-4	2084.1	24	2199.25	0.04688	5.53%
2-2-5	1829.8	38	1832.78	0.0625	0.16%

The purpose of this loop procedure is in a sense similar to that of the tabu search method to escape from a local minimum. Once a better solution is found after completing the improvement phase, the best solution record is updated. We repeat the above improvement process until all possible permutations of four different improvement procedures have been implemented.

V. COMPUTATIONAL RESULTS

Since there are no standard instances available for our problem, we generate twenty test problems to evaluate the efficiency and accuracy of our algorithm. The coordinates and demands (deliveries) of all test problems are adopted from vehicle routing test banks with the supplies (pickups) of all test problems randomly generated based on the range of half of the demand or twice of the demand. The vehicle capacities and relevant costs for twenty test problems are shown in Tables 1 and 2 and the detailed coordinates, pickups and deliveries of customers are given in the Appendix.

The solutions produced by the heuristic algorithm are compared to the optimal results from the mathematical model mentioned in section 2. The heuristic algorithm was written in FORTRAN language and the mathematical model was solved using the software LINGO version 10.0. Both of them were implemented on a PC with a 2800 MHz processor. A summary of computational results on twenty test problems are reported in Tables 3 and 4, respectively.

For problems 1-1-1, 1-1-3, 1-1-4, 1-2-2, 1-2-5 and problem 2-2-3, our heuristic algorithm obtains the optimal solution. As shown in Tables 3 and 4, both the mathematical model and the heuristic algorithm yield the same total cost. The two different approaches also obtain the same results in routing customers except for problem 1-2-5 (see Table 6). The detailed routing results of our heuristic algorithm are shown in Tables 5-8.

Table 4 shows that the solution time for the mathematical model increased dramatically with the size of the problem. Notice that the execution time reported here doesn't include the time for sub-tour breaking. Computationally, exact algorithms for the VRP are restricted to solving problems of only up to about 25 customers. Even though the Lagrangian relaxation is used for solving the problem, it is still difficult to find the optimal solution in a reasonable computing time. On the other side, our heuristic algorithm requires little time to solve the problem. Every problem takes only less than a second.

Table 5. Detailed results for test problems with five customers.

1-1-1	Optimal Solution	Depot 1: 0-3-5-0 Depot 2: 0-1-2-0 customer 4 is served by LTL
	Heuristic solution	Depot 1: 0-3-5-0 Depot 2: 0-1-2-0 customer 4 is served by LTL
1-1-2	Optimal Solution	Depot 1: 0-3-5-0 Depot 2: 0-2-4-0 customer 1 is served by LTL
	Heuristic solution	Depot 1: 0-2-4- 0 Depot 2: 0-3-5-0 customer 1 is served by LTL
1-1-3	Optimal Solution	Depot 1: 0-3-4-0 Depot 2: 0-1-5-0 customer 2 is served by LTL
	Heuristic solution	Depot 1: 0-3-4-0 Depot 2: 0-1-5-0 customer 2 is served by LTL
1-1-4	Optimal Solution	Depot 1: 0-1-2-4-0 Depot 2: 0-5-0 customer 3 is served by LTL
	Heuristic solution	Depot 1: 0-1-2-4-0 Depot 2: 0-5-0 customer 3 is served by LTL
1-1-5	Optimal Solution	Depot 1: 0-3-4-0 Depot 2: 0-1-2-0 customer 5 is served by LTL
	Heuristic solution	Depot 1: 0-5-0 Depot 2: 0-1-2-4-0 customer 3 is served by LTL

Table 6. Detailed results for test problems with five customers.

1-2-1	Optimal Solution	Depot 1: 0-5-3-1-0 Depot 2: 0-2-0 customer 4 is served by LTL
	Heuristic solution	Depot 1: 0-2-3-0 Depot 2: 0-1-5-0 customer 4 is served by LTL
1-2-2	Optimal Solution	Depot 1: 0-3-4-5-0 Depot 2: 0-2-0 customer 1 is served by LTL
	Heuristic solution	Depot 1: 0-3-4-5-0 Depot 2: 0-2-0 customer 1 is served by LTL
1-2-3	Optimal Solution	Depot 1: 0-3-4-5-0 Depot 2: 0-1-0 customer 2 is served by LTL
	Heuristic solution	Depot 1: 0-3-4-0 Depot 2: 0-1-5- customer 2 is served by LTL
1-2-4	Optimal Solution	Depot 1: 0-4-2-1-0 Depot 2: 0-5-0 customer 3 is served by LTL
	Heuristic solution	Depot 1: 0-5-0 Depot 2: 0-1-2-4-0 customer 3 is served by LTL
1-2-5	Optimal Solution	Depot 1: 0-5-4-0 Depot 2: 0-1-2-0 customer 3 is served by LTL
	Heuristic solution	Depot 1: 0-4-5-0 Depot 2: 0-1-2-0 customer 3 is served by LTL

Table 7. Detailed results for test problems with ten customers.

2-1-1	Optimal Solution	Depot 1: 0-3-9-10-7-8-0 Depot 2: 0-6-4-5-2-0 customer 1 is served by LTL
	Heuristic solution	Depot 1: 0-2-5-4-8-0 Depot 2: 0-9-10-6-3-7-0 customer 1 is served by LTL
2-1-2	Optimal Solution	Depot 1: 0-1-2-4-5-0 Depot 2: 0-9-10-8-3-6-0 customer 7 is served by LTL
	Heuristic solution	Depot 1: 0-2-4-5-9-10-0 Depot 2: 0-1-6-3-8-0 customer 7 is served by LTL
2-1-3	Optimal Solution	Depot 1: 0-5-7-6-4-0 Depot 2: 0-10-1-9-8-2-0 customer 3 is served by LTL
	Heuristic solution	Depot 1: 0-5-3-8-0 Depot 2: 0-10-6-1-2-9-4-0 customer 7 is served by LTL
2-1-4	Optimal Solution	Depot 1: 0-8-3-9-5-7-0 Depot 2: 0-4-10-6-1-0 customer 2 is served by LTL
	Heuristic solution	Depot 1: 0-8-7-5-3-9-0 Depot 2: 0-4-1-6-10-0 customer 2 is served by LTL
2-1-5	Optimal Solution	Depot 1: 0-8-7-6-4-0 Depot 2: 0-2-3-1-9-10-0 Customer 5 is served by LTL
	Heuristic solution	Depot 1: 0-4-6-7-8-0 Depot 2: 0-2-3-9-10-1-0 customer 5 is served by LTL

Table 8. Detailed results for test problems with ten customers.

2-2-1	Optimal Solution	Depot 1: 0-2-4-7-8-5-0 Depot 2: 0-6-10-9-3-0 customer 1 is served by LTL
	Heuristic solution	Depot 1: 0-2-6-4-7-8-0 Depot 2: 0-5-3-9-10-0 customer 1 is served by LTL
2-2-2	Optimal Solution	Depot 1: 0-4-9-10-6-8-3-0 Depot 2: 0-1-2-5-0 customer 7 is served by LTL
	Heuristic solution	Depot 1: 0-2-4-5-6-9-10-0 Depot 2: 0-1-3-8-0 customer 7 is served by LTL
2-2-3	Optimal Solution	Depot 1: 0-5-7-2-6-4-0 Depot 2: 0-10-1-9-8-0 customer 3 is served by LTL
	Heuristic solution	Depot 1: 0-5-4-3-1-6-0 Depot 2: 0-10-8-2-9-0 customer 7 is served by LTL
2-2-4	Optimal Solution	Depot 1: 0-8-4-3-9-0 Depot 2: 0-6-10-1-5-7-0 customer 2 is served by LTL
	Heuristic solution	Depot 1: 0-8-1-7-3-9-0 Depot 2: 0-4-5-6-10-0 customer 2 is served by LTL
2-2-5	Optimal Solution	Depot 1: 0-4-2-3-1-9-10-0 Depot 2: 0-8-7-6-0 customer 5 is served by LTL
	Heuristic solution	Depot 1: 0-4-6-7-8-1-10-0 Depot 2: 0-3-2-9-0 customer 5 is served by LTL

From Tables 3 and 4, we find that the heuristic algorithm obtains the optimal or near-optimal solutions. The average percentage deviation from the optimum for the twenty test problems is 1.74% and the execution time for all test problems is less than a second.

The results are encouraging as our algorithm obtains the optimal or near-optimal solutions in an efficient way in terms of time and accuracy. Due to time constraint, only twenty examples are test in this research. In the future, a wide range of examples should be tested. In order to test whether the solution time of the algorithm is not sensitive to larger size of problem, we will solve additional test problems with the customer size of 50, 75 and 100 in the future research. From Table 4, we can find that the solution quality for our heuristic algorithm decreased with the size of the problem. In order to improve the solution quality for our heuristic algorithm, we should dedicate to enhance the solution quality of the initial solution.

Our proposed mathematical model and heuristic algorithm extend the current research by integrating the outsider carrier into the model. This scenario has not been considered in the literature. Hence, the results of the current research will be a special case of our research. The main advantage of our proposed mathematical model and heuristic algorithm can handle the situation that the total demand of the customers is greater than the whole capacity of owned trucks.

VI. CONCLUSIONS

A multi-depot vehicle routing plays a central role in logistics management. In this paper, we considered a multi-depot vehicle routing problem with simultaneous pickup and delivery and the possible use of an outside carrier to satisfy customer demands. To the best of our knowledge, this scenario has not been considered in the literature. Our research fills the research gap and solve the real world problem.

We developed both the mathematical model and the heuristic algorithm. A variety of test problems were examined with our heuristics. The results are encouraging as our algorithm obtains the optimal or near-optimal solutions in an efficient way in terms of time and accuracy.

As for future research, a wide range of examples should be tested. Furthermore, it would be interesting to see if other intelligent optimization techniques, such as Tabu Search, Genetic Algorithms, Ants Colony, Simulated Annealing and Neural Networks, can be used to solve this problem and even provide better results. Furthermore, a multi-depot vehicle routing problem with multiple trips and selecting less-than-truckload carriers is worthwhile to explore in the future. It is an extension of this research since our proposed mathematical model and heuristic algorithm in this research will be only a special case of the suggested future research.

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APPENDIX: TESTING PROBLEMS

Problem 1-1-1 and Problem 1-2-1

No.	(X, Y)		q(x)	p(x)
1	37	52	5	7
2	49	49	25	30
3	52	64	17	16
4	20	26	18	9
5	40	30	10	21
	20	20		
	30	40		

Problem 1-1-2 and Problem 1-2-2

No.	(X, Y)		q(x)	p(x)
1	21	47	27	15
2	17	63	13	19
3	31	62	11	23
4	52	33	16	11
5	51	21	10	5
	20	20		
	30	40		

Problem 1-1-3 and Problem 1-2-3

No.	(X, Y)		q(x)	p(x)
1	42	41	8	19
2	31	32	8	29
3	5	25	16	23
4	12	42	10	21
5	36	16	28	10
	20	20		
	30	40		

Problem 1-1-4 and Problem 1-2-4

No.	(X, Y)		q(x)	p(x)
1	52	41	6	15
2	27	23	9	3
3	17	33	15	41
4	13	13	14	9
5	57	58	7	28
	20	20		
	30	40		

Problem 1-1-5 and Problem 1-2-5

No.	(X, Y)		q(x)	p(x)
1	62	42	6	8
2	42	57	9	8
3	16	57	15	16
4	8	52	14	10
5	7	38	7	28
	20	20		
	30	40		

Problems 2-1-1 and 2-2-1

No.	(X, Y)		q(x)	p(x)
1	22	22	37	18
2	36	26	16	26
3	21	45	12	11
4	45	35	31	30
5	55	20	8	21
6	33	34	19	19
7	50	50	20	15
8	55	45	13	16
9	26	59	15	29
10	40	66	22	26
	20	20		
	30	30		

Problems 2-1-2 and 2-2-2

No.	(X, Y)		q(x)	p(x)
1	10	17	7	27
2	21	10	30	13
3	5	64	16	11
4	30	15	9	16
5	39	10	21	10
6	32	39	15	5
7	25	32	19	25
8	25	55	23	17
9	48	28	11	18
10	56	37	5	10
	20	20		
	30	30		

Problems 2-1-3 and 2-2-3

No.	(X, Y)		q(x)	p(x)
1	62	42	11	8
2	42	57	12	8
3	16	57	23	16
4	8	52	26	10
5	7	38	17	28
6	27	68	6	7
7	30	48	9	15
8	43	67	15	14
9	58	48	14	6
10	58	27	7	19
	20	20		
	30	30		

Problems 2-1-4 and 2-2-4

No.	(X, Y)		q(x)	p(x)
1	42	41	27	19
2	31	32	13	29
3	5	25	11	23
4	12	42	16	21
5	36	16	10	10
6	52	41	5	15
7	27	23	25	3
8	17	33	17	41
9	13	13	18	9
10	57	58	10	28
	20	20		
	30	30		

Problems 2-1-5 and 2-2-5

No.	(X, Y)		q(x)	p(x)
1	37	52	15	7
2	49	49	19	30
3	52	64	14	16
4	20	26	11	9
5	40	30	5	21
6	21	47	19	15
7	17	63	23	19
8	31	62	12	23
9	52	33	10	11
10	51	21	10	5
	20	20		
	30	30		

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