

[Field Research]

Model and Heuristics for the Heterogeneous Fixed Fleet Vehicle Routing Problem with Pick-Up and Delivery*

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Abstract

Purpose – This paper discusses the heterogeneous fixed fleet vehicle routing problem with pick-up and delivery (HFFVRPPD), for vehicles with different capacities, fixed costs, and travel costs.

Research Design, data, methodology – This paper made nine assumptions for establishing a mathematical model to describe HFFVRPPD. It established a practical mathematical model, and because of the non-deterministic polynomial-time hard (NP-hard), improved the traditional simulated annealing algorithm and tested a new algorithm using a certain scale model.

Result – We calculated the minimum cost of the heterogeneous fixed fleet vehicle routing problem (HFFVRP) with a single task and, on comparing the results with the actual HFFVRP for the single task alone, observed that the total cost of HFFVRPPD reduced significantly by 46.7%. The results showed that the new algorithm provides better solutions and stability.

Conclusions – This paper, by comparing the HFFVRP and HFFVRPPD results, highlights certain advantages of using HFFVRPPD in physical distribution enterprises, such as saving distribution vehicles, reducing logistics cost, and raising economic benefits.

Keywords : Vehicle Routing Problem, VRP with Pick-Up and Delivering, Simulated Annealing Algorithm, HFFVRP, HFFVRPPD.

JEL Classifications : C51, C93, D23, L92.

1. Introduction

Anily(1996) concluded that the Vehicle Routing Problem (VRP) is

one of the most studied combinatorial optimization problems and is concerned with the optimal design of routes to be used by a fleet of vehicles to serve a set of customers. "VRPPD (VRP with Pick-Up and Delivering) as the expansion of VRP need to consider goods distribution and recovery and it is also an important part for an optimal logistics system" introduced by Angelelli and Mansini(2002). VRPPD can be traced back to the 1980s, when the concept of reverse logistics was put forward, as everyone's concern of reverse logistics, the recovery services of forward logistics, and reverse logistics distribution blended together, forming a VRPPD problem.

The VRP with Pickup and Delivery (VRPPD), a heterogeneous vehicle fleet based at multiple terminals must satisfy a set of transportation requests. Each request is defined by a pickup point, a corresponding delivery point, and a demand to be transported between these locations. The requested transport could involve goods or people. This latter environment is called dial-a-ride. The objective function generally minimizes system costs.

Researches on the VRPPD are carried out by assuming that vehicles that used to provide the pick-up and delivering service are homogeneous. That means all the vehicles have the same capacity, the same fixed cost, the same maximum distance that allowed in each service plan and so on. Furthermore, the number of vehicles that can be use is also infinite. But in real distribution, the vehicles of the company are always a fleet with heterogeneous, and the vehicles have a different capacity, the different unit cost for travel, and different fixed cost. Because of the constraints a capital, numbers of each kind of vehicles are also different. Therefore the problem we studied in this paper was proposed: Heterogeneous Fixed Fleet Vehicle Routing Problem with Pick-Up and Delivering, (HFFVRPPD).

This case is the problem we have been come across, and thus in this work, we consider a new version of the VRP problem. We decided to work on its exact real world formulation, without any concession to judicious simplification, which would have probably allowed us to borrow results from existing successful solution techniques.

The paper is organized as follows: Section 2 we present the problem description Section 3 we discuss Algorithm design Section 4 shows the experimental analysis Finally, Section 5 we draw some conclusions and discuss future work.

* It has been verified that this paper from 2012 winter international academic conference, KODISA, was the modified version after considering the genuine opinions of both authors and all of three anonymous reviewers.

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2. Problem description and model foundation

The Vehicle Routing Problem was first introduced by Dantzig and Ramsey (1959) in what they called The Truck Dispatching Problem. It was formulated as a branch of the Traveling Salesman Problem (TSP) with multiple vehicles and routes. Subsequently, many other extensions that include time windows, different depots, pick-up and delivery options, heterogeneous fleet and periodic routing have been developed by Toth and Vigo(2001). As Liu and Xuan(2005) concluded that most of the researches are focus on improve the algorithm, transforming constraint conditions and the uncertainty of customer information, etc. We review here the articles in the literature that deal with those variants of the HFFVRPPD that are the closest to our problem. Baldacci & Battara (2007) gave an overview of approaches to solve the case of a fleet of vehicles characterized by different capacities, the HVRP (H for Heterogeneous). Some recent construction heuristics for the HFFVRPPD include the ones based on column generation methods by Tailard(1999).

2.1. Problem description

From the graph theory, HFFVRPPD can be defined as follow: Assuming that there is a digraph $G=(V,E)$, where $V=\{0,1,2,...,I\}$ defines the node-set where '0' is stands for the logistics center and $E=(i,j), i,j \in V, i \neq j$ defines the edge-set. $V'=\{1,2,...,I\}$ is defined the node-set of customers that need service and their requirements pick-up d_i and delivering p_i are known. The distance from customer i to the neighboring customer j is D_{ij} . A fleet of vehicles start from the depot and provide pick-up and delivering service to the customers. $\varphi=\{1,2,...,K\}$ is defined the kinds of vehicles, vehicles of kind k have the capacity Q_k and the maximum travel distance L_k , and the fixed cost is f_k . The variable costs of vehicles of type k between the couple-node (i,j) is v_k . The number of vehicles in each type is fixed to n_k . The objective of the optimal in HFFVRPPD is that: Arrange the best vehicles routes to provide service to all the customers who need both of the pick-up and delivering service, so that the total cost is a minimum. The total cost contains all the vehicles' fixed cost, travel cost and routes must satisfy the following requirements: (1) The service vehicles must start from the logistic center, and back to the logistics center after the service has been to the customers one by one; (2) Each demand point can only be serviced once, as a service stop, can meet pick-up and delivery requirements; (3) The load capacity of a vehicle at any customer load points cannot exceed vehicle capacity (4)The length of each delivery path does not exceed the maximum travelled distance of the vehicle.

2.2. Model assumption

In order to establish the mathematical model to describe

HFFVRPPD, the article made the following assumptions:

- (1) There is only one logistic center;
- (2) Coordinates and required volume of the logistic center and demand points are already known;
- (3) The numbers of various types of vehicles are already known and the fixed cost, travel cost and the capacity of various types of vehicles are already known.
- (4) There are no time constraints for customers;
- (5) One vehicle service, a loop, starting from the logistic center and eventually back to the logistic center;
- (6) The weight in a moving vehicle does not exceed vehicle capacity volume restrictions;
- (7) The distribution distance of each vehicle is not more than the maximum travel distance;
- (8) Each demand point can only be serviced once, as a service stop can meet pick-up and delivery requirements;
- (9) Other hypothesis: Assume the goods in transit will not be damaged; they do not take the working hours of the drivers into account, do not take the prevailing road conditions into account, regardless of rules and regulations of transportation, etc.

2.3. Symbol description and Model foundation

It is necessary to make the description of the symbols, as follows:

$\varphi=\{1,2,...,K\}$: The set of vehicle types, a total of K types;

m_k : The number of vehicles type k , total number of vehicles is

$$M = \sum_{k=1}^K m_k$$

ϕ_k : The set of vehicles type k , where $\phi_k = \{1,2,...,m_k\}$

Q_k : Capacity of vehicles, that is, maximum load of distribution vehicles;

f_k : Fixed costs in traveling;

v_k : Average cost of vehicle type k per kilometer of distribution;

L_k : The maximum travel distance of vehicle of type k

kl : The l -th vehicle type k

I : Total number of customers demand points

$V=I \cup \{0\}$: The set of the entire demand points and logistics center, node 0 stands for the logistic center;

$V'=\{1,2,...,n\}$: The set of customers demand points

D_{ij} : Distance between customer i and customer j ,

$$D_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

d_i : Distribution volume of customer i ($0 \leq i \leq I$) required,

$$(0 \leq d_i \leq Q_k)$$

P_i : Pick-up of customer i ($0 \leq i \leq I$) required ($0 \leq p_i \leq Q_k$)

U_{ikl} : Load weight of after leaving the customers i , ($0 \leq U_{ikl} \leq Q_k$)

n_{kl} : The number of customers the l -th vehicle type k served

n_{klj} : The j -th customer that the l -th vehicle type k served, ($0 \leq n_{klj} \leq n_{kl}$) for example, n_{423} represents the third customer that the second vehicle of type 4 served;

$x_{ijkl} = \begin{cases} 1, & \text{the } l\text{-th vehicle of type } k \text{ through node } i \text{ to customer } j \\ 0, & \text{otherwise} \end{cases}$

$y_{ikl} = \begin{cases} 1, & \text{customer } i \text{ was served by the } l\text{-th vehicle of type } k, i \in I, k \in \varphi, l \in \phi_k \\ 0, & \text{Otherwise} \end{cases}$

This paper proposed the mathematized model of HFFVRPPD as follows:

$$\min F(x) = \sum_{k=1}^K \sum_{l=1}^{m_k} \left(f_k \cdot \sum_{i=1}^I x_{0ikl} \right) + \sum_{i=0}^I \sum_{j=0}^K \sum_{k=1}^K \sum_{l=1}^{m_k} x_{ijkl} \cdot D_{ij} \cdot v_k \quad (1)$$

s.t.

$$\sum_{k=1}^K \sum_{i=0}^I \sum_{l=1}^{m_k} x_{ijkl} = 1 \quad \forall j \in V \quad (2)$$

$$\sum_{i=0}^I x_{ipkl} - \sum_{j=0}^I x_{pjkl} = 0 \quad \forall p \in V, \forall k \in \varphi, \forall l \in \phi_k \quad (3)$$

$$\sum_{i=1}^I d_j y_{ikl} \leq Q_k \quad \forall k \in \varphi, \forall l \in \phi_k \quad (4)$$

$$\sum_{i=1}^I p_j y_{ikl} \leq Q_k \quad \forall k \in \varphi, \forall l \in \phi_k \quad (5)$$

$$0 \leq U_{ikl} - \sum_{j=1}^I x_{ijkl} (d_i - p_i) \leq Q_k \quad \forall i \in V, \forall k \in \varphi, \forall l \in \phi_k \quad (6)$$

$$\sum_{i=0}^I \sum_{j=0}^I x_{ijkl} d_{ij} \leq L_k \quad \forall k \in \varphi, \forall l \in \phi_k \quad (7)$$

Equation (1) is the objective function, denoting the minimum total cost which is composed of fixed cost and travel cost. The constraint (2) is that every customer is visited by exactly one vehicle of one type, and the vehicle is used to serve at the most one route. The constraint (3) is the flow conservation formula, where every vehicle that arrives to a customer must leave that customer. The constraint (4) and (5) means the total recovery of all vehicles should not exceed capacity of the vehicle, and the total distribution of any one route delivery vehicles cannot exceed the total vehicle capacity. The constraint (6) explains that the pick-up volume of every vehicle must not exceed the capacity in any customer point. The constraint (7) ensures that the length of each delivery path does not exceed the maximum travelled distance of the vehicle.

3. Algorithm design

3.1. SA procedure

As HFFVRPPD is an NP-hard problem, an accurate algorithm, even if to the HFFVRP or VRPPD is almost impossible for large-scale problems. So the heuristic algorithm was used to solve the problem. The basic principle of simulated annealing algorithm comes from the fact that a solid will collapse from the solid structure into liquid structure if it is heated to a certain temperature, and by controlling its cooling process can make the molecules re-ranked as our expected steady state when they revert to the solid structure. Simulated annealing algorithm has been theoretically proven to be a probability of 1 converges to the global optimal solution of the global optimization algorithm, furthermore, because the best result is of less dependence than the initial solution which used to research a new VRP.

The HFFVRPPD studied in this paper could be described by the simulated annealing algorithm as a solution of the problem and its objective function $f(i)$ is separately equivalent with a micro state i and its energy $E(i)$.

Steps of the simulated annealing algorithm (takes minimizing the objective function) for example:

Step 1 Get an initial feasible solution x_0 randomly, set t_0 as the initial temperature, the current solution $x_i = x_0$, the current iteration step $k = 0$, the current temperature $t_k = t_0$

Step 2 If the temperature satisfies the loop stop condition, go to Step 3; otherwise, choose a neighborhood solution x_j randomly from the neighborhood $N(x_i)$ and calculate $\Delta E_{ij} = E(x_j) - E(x_i)$. If $\Delta E_{ij} \leq 0$, then $x_i = x_j$ otherwise, if $\exp(-\Delta E_{ij}/t) > \text{rand}(0,1)$ (a random number between 0 and 1), go to Step 2;

Step 3 $k = k + 1$, $t_{k+1} = y(t_k)$ (temperature control function), If it meets the termination conditions, go to Step 4; Otherwise, go to Step 2;

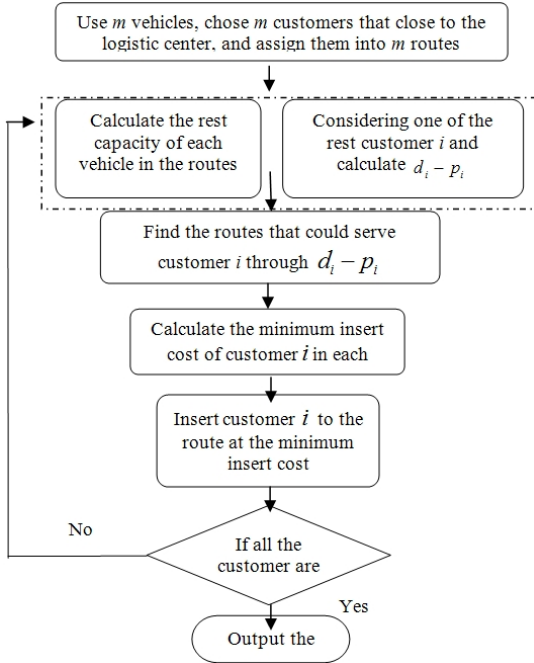
Step 4 Output the results, terminate the SA algorithm. Step two is the inside circle, which indicates a random search at the same temperature. The outer loop includes the temperature decreased changes, the increase of iterations times, and the stopping criteria in Step 3.

3.2. Algorithm optimizing and algorithm flowchart

Considering the characteristics of Heterogeneous Fixed Fleet Vehicle Routing Problem with Pick-Up and Delivering, we optimized the conventional simulated annealing algorithm, and constructed a new simulated annealing algorithm for solving this problem. The improvements are as follows:

(1) Initial solution generation.

The solution is described as $R=(0-1-2-3-0-4-5-6-0-...-0)$, where 0 represents the logistics center, a loop starts with 0 and ends with 0, in the middle of which are the customer nodes. We get the initial solution following the flow chart as follows:



<Figure 1> Algorithm of Initial Solution Generation

The minimum insert cost is calculated as follows:

$$c_i^k = (d_{i_1,i} + d_{i,i_2} - d_{i_1,i_2}) \times v_k \quad (8)$$

Where i_1 and i_2 represent the customer before and after the insert location separately.

(2) Neighborhood and a feasible solution.

The traditional neighborhood operation method of the simulated annealing algorithm is $2-Opt$ ex-change. This exchange method is simple and exchange two nodes at one time, but the ability to search the solution space is not strong. So at each temperature, it takes a long time to search the solution space to ensure getting an optimal solution of the temperature. When the temperature slowly decreases, the number of the outer loop increases, the algorithm's time increase multiplies, leading the search time of the algorithm too long. To improve the ability of search solution space, we considered four operators: SWAP operator, the RELOCATE operator, the operator $2-Opt$ and the $2-Opt^*$ operator. Every time there is neighborhood operation, one of the four operators will be chosen to be used randomly.

Though this method didn't increase the number of solutions iterations, but the search solution space increases the scope of many, together with a memory array, which can assure of a more satisfactory optimal solution, so you can to a large extent, reduce the length of Markov chain, thereby saving time algorithm.

When it comes to the new solution, we judged if it is a feasible solution by following steps:

Step 1: Decode the new solution, calculate the total number of vehicles used M' . if M' is bigger than M , the number of vehicles that the logistics center has, turned to step 7, otherwise, turned to step 2.

Step 2: Calculate the total weight of pick-up P_j and the total weight of delivery D_j , if $D_j > \max(Q_k)$ or $P_j > \max(Q_k)$, turned to step 7, otherwise, turned to step 3.

Step 3: Sort the total weight of delivering D_j and the capacity of each vehicle types Q_k by descend, and assigned the types of vehicle by capacity. If the number of routes which the total weight is more than the vehicles capacity is more than the number of vehicles with the capacity bigger than the given vehicles capacity, turned to step 7, otherwise, turned to step 4.

The total length of each route is L_j , if there is one or more route that the total length is larger than the maximum distance of the vehicle, use L_k , turned to step 7, otherwise, turned to step 5.

Step 5: Calculate the weight of each vehicle at every customer point. If there exist a situation that load weight of the vehicle is bigger than the maximum capacity of vehicle of this type, turned to step 7.

Step 6: If the solution is a feasible solution, calculate the value of the objective function, and the evaluated solution, if this satisfies the determinate principle, algorithm end, otherwise, turned to step 7.

Step 7: repeat the neighborhood operation, get a new solution, then turn to Step 1.

(3) Memory device design.

In the traditional simulated annealing algorithm, the output cannot guarantee to be the best solution. So we set a memory array S in the algorithm, which records the best solution as the algorithm progresses. At the beginning of the algorithm, S is initialized to be the initial solution, that is, $S = \Omega$, $E(S) = E(\Omega)$. When the next optimal solution Ω' is found, compare the objective functional value of $E(S)$ with $E(\Omega')$, and if $E(S) > E(\Omega')$, then $S = \Omega'$. Improving S constantly, we can get the best solution of this search.

(4) The determination of the termination criteria.

Adopt mixed-stopping criterion, that is, when the temperature is below a certain value, or the memory array of consecutive does not change for g times, the algorithm is terminated. With the initial temperature t_0 , temperature coefficient α , it is easy to control the number of iterative steps, and easy to get the global optimal solution. g is

used to eliminate unnecessary iteration in order to reduce the number of iterative steps and improve the algorithm efficiency. The value of g varies according to the size of the node, the larger the scale, the relatively larger is the value.

4. Computational experiments

Based on the data of the example in reference, assume that a single logistics center served 27 customers, each customer need both of the pick-up and delivering service. We need to decide the types of vehicle must use, route of each vehicle to provide service to all the customers with the minimum cost. The information of customers is list in <Table 1>, the distance matrix of customers and logistics center are the same with the research result of Lin et al.(2009) and the information of the vehicles are list in <Table 2>.

<Table 1> Information of Customers' Pick-up and Delivering

Id	0	1	2	3	4	5	6	7	8	9	10	11	12	13
d_i	-	160	260	100	400	120	160	120	200	350	650	180	240	420
p_i	-	130	270	125	333	112	185	157	226	433	467	118	130	222
Id	14	15	16	17	18	19	20	21	22	23	24	25	26	27
d_i	420	180	120	400	270	200	80	220	240	360	280	280	150	500
p_i	400	109	235	406	238	124	106	150	160	305	229	151	109	640

<Table 2> Property of Distribution Vehicles

Vehicle types	Number of vehicles	Load age/Kg	Fixed cost	Travel cost
A	3	1100	100	1.2
B	2	1115	110	1.5
C	1	2000	95	1.1
D	1	850	100	1.6
E	4	990	80	1.3
F	1	900	120	1.4

Used the algorithm we designed in this paper, we get the minimum cost is 912.1, and the details of the results are list in <Table 3>. To compare the cost of HFVRP and HFFVRPPD, we calculate the minimum cost of heterogeneous fixed fleet vehicle problem with the single task only, and the results are compared in <Table 4>.

From <Table 4>, we find that compared to the heterogeneous fixed fleet vehicle problem with the single task only, total cost of HFFVRPPD was reduced by 46.7%. It greatly reduced the cost, so it is very useful to research the HFFVRPPD.

5. Conclusions

Vehicle routing problem forms an integral part of supply chain management, which plays a significant role for productivity improvement in organizations through efficient and effective delivery of goods/services to customers. In this paper, an attempt has been made to survey the recent developments in the vehicle routing problem (VRP) and its variants.

<Table 3> The Best Computational Results

Number	Vehicle types	Load age	total weight of delivering	total weight of pick-up	Route distance	Route
1	C	2000	1980	1891	179	0-12-14-9-8-10-16-0
2	A	1100	1040	982	163	0-3-1-2-5-6-22-0
3	A	1100	1010	1054	47	0-23-26-27-0
4	A	1100	1100	730	40	0-15-19-11-13-7-0
5	E	990	970	900	50	0-17-18-20-21-0
6	E	990	960	713	21	0-25-4-24-0
Sum d_i	7060			Fixed cost	555	
Sum p_i	6270			Travel cost	357.1	
Total cost	912.1					

<Table 4> Comparing the Results of HFVRP and HFFVRPPD

	HFVRP		HFFVRPPD
	Delivering	Pick-up	
A	2	3	3
B	0	1	0
C	1	1	1
D	0	0	0
E	3	0	2
F	0	0	0
Fixed cost	535	505	555
Travel cost	332.1	337.9	357.1
Total cost	1710		912.1

From the delivering practice, we have proposed a more realistic heterogeneous fixed fleet vehicle routing problem with pick-up and delivery (HFFVRPPD) model, considering vehicles have different capacity, largest travel distance, fixed cost and travel cost.

As Doris et al.(2008) appointed that the HFFVRPPD is an NP-hard problem, we used heuristic approach to get the solution. Based on the analysis of the advantages and disadvantages of the algorithm, we improve the algorithm: we designed the initial solution generation of HFFVRPPD, proposed the neighborhood operation with four operators selected randomly in each research, memory device and multi-termination criteria are also included.

Computational experiments show that the model and algorithm are useful to the delivering company, it helps reduce the cost by reduce the number of vehicles need to use and the distance the vehicles travelled.

And we plan to take forward this research as follows.

1. Incorporate the findings of our analysis to an improved solution algorithm. Such a method may only allow splitting customers with the characteristics described in the previous section. This way, we have a good chance of still having the optimum solution within the feasible set, but not doubling the number of customers the method should work faster and have a better chance of finding good solutions.

2. Extend the scope of our analysis to the HFFVRPPD, allowing customers' delivery and pick-up needs to be served in several visits. In particular, we are interested in whether the theoretical properties of the VRPS observed carry over to the HFFVRPPD and It we will try our best to increase the customer data in the further study.

3. Merging our lines of research in this paper, we wish to investigate the HFFVRPPD with Restricted Mixing. This model, forces customers to be served separately to avoid situations where there is a mixture of delivery and pickup goods on board but not enough space to have access to both kinds of goods.

Received: October 22, 2012.

Revised: November 14, 2012.

Accepted: December 17, 2012

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