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Combined Optimization of Fixed-partition and Integral-ratio Horizon Policy for the Three-echelon Inventory Routing Problem

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Abstract: Inventory and transportation cost the main expenses of logistics. A new combined optimization policy is researched in this study, on the Inventory Routing Problem (IRP) in a three-echelon distribution system, which composed of a vendor, a Distribution Center (DC) and multiple geographically dispersed retailers. In the system, each retailer faces a deterministic, retailer-different rate and same type of product demand. Any retailer's demand must be replenished from the DC, not permitted from the vendor directly. The stocks may be kept at any retailers or the DC. The objective is to determine a combined transportation (routing) and inventory policy to minimize a long horizon average system cost without shortage or delay. After discussing the characteristics of Fixed-Partition and Integral-Ratio Horizon (FP-IRH) method, the model for the IRP of three-echelon system is constructed. Then, a decomposition solution is proved, where the retailers are partitioned into disjoint and collectively exhaustive sets and each partition of retailers is served on a separate route. Given a fixed partition, the original problem is decomposed into two-echelon sub-problems and the efficient algorithms are designed for the three-echelon IRP by developing solution of the famous Vehicle Routing Problem (VRP). The computational results for a testing example problem show that the FP-IRH policy is more effective.

Key words: Combined optimization, inventory routing problem, heuristic algorithms

INTRODUCTION

Inventory and transportation are the most important two functional elements, their consumption accounted for about 2/3 of the total cost of logistics. Inventory Control (IC) is mainly to solve the appropriate time to add the appropriate cargo. The core of transportation research is to solve the Vehicle Routing Problem (VRP), arrange a series of vehicle routing according to the demand.

Inventory and transportation in the actual production has relative independence, resulting in theoretical studies generally conducted separately. However, the two elements have "trade-off" relations in the supply chain and the singly inventory controlling or vehicle routing optimization is often not beneficial to the total cost control of logistics system (Bidhandi, 2011). In order to improve supply chain efficiency, the model of Vendor Managed Inventory (VMI) is put forward (Hemmelmayr *et al*., 2010). Under the premise of ensuring to meet customer's partial or complete demand, the vendor allowed to arrange delivery quantity and period itself and vehicle routing. So, the two problems of inventory and transportation require coordinating to solve at same time. The Inventory Routing Problem (IRP) (Herer and Levy, 1997) is a kind of the hot research topic in such coordination ones.

Although the IC and VRP literature is rich, the IRP receives attention only in recent years. The published IRP literature focuses mainly on two-echelon "one DC-multi retailers" system, the three-echelon IRP research is rare, relatively. Chan and Simchi-Levi (1998) found the boundary of any policy of the three-echelon IRP. Zhao *et al*. (2008) used the "Power-of-Two (POT)" policy for cycling analysis of the three-echelon IRP of Fixed-Partition (FP) policy. Li *et al*. (2011) decomposed the three-echelon IRP into three sub-problems and the design a solving genetic algorithm. Shen and Honda (2009) studied the three-echelon IRP of horizontal transfer transportation problem.

The core work of the literature mentioned above is to integrate the distribution partition (grouping) and the ordering cycle policy. Generally, the cycle period (such as hours) directly get from Economic Order Quantity (EOQ) theory is not feasible in real applications and some decisions should be made in the discrete time point (Zhao *et al*., 2008). The VRP is a famous NP-hard problem, so, the IRP solving is great challenging.

A combined optimization policy, called Fixed-Partition and Integral-Ratio Horizon (FP-IRH) policy is put forward for solving the three-echelon IRP in a long horizon, aiming to coordinate ordering cycle and distribution routing of the IRP. Firstly, the mathematical model is constructed secondly, some analysis of solution on the basis of solving is developed and the heuristic algorithm is design. Finally, the world-wide benchmark examples are used to test the effectiveness of the combined policy and algorithm.

PROBLEM AND ASSUMPTIONS

Problem description: One vendor, one Distribution Center (DC) and multiple retailers make up a logistics system (abbreviated as 1-1-M system). Any retailer's demand without short or delay and must be replenished from the DC, whose goods come from the vendor. The objective is to determine a combined distributing routing and inventory policy minimizing a long horizon average system cost.

Symbols and assumptions: Denote the DC as number 0, retailers as {1, 2, ..., N}, distance between any two points I, $j\in\{0, 1, 2, ..., N\}$ as d_{ij}, inventory cost rate of the DC as h_0, demand rate of retailer $i\in\{1, 2, ..., N\}$ as r_i and inventory cost rate as h_i, h_i-h_0>0.

A big vehicle, such as a train or heavy truck, used between the vendor and DC has a capacity of W. An unchanged cost K_0, is spent in every order of the DC's replenishment. The rreplenishment cycle of DC (called "planning horizon") is t_0 and the homogeneous small vehicle fleet used between the DC and retailers have a capacity of w each vehicle W>>w, w≥ amx r_i.

For simple, the distribution costs of 1-1-M system is denote as fixed costs S and travel costs. Limited by conditions of supply and demand, the allowed maximum and minimum frequency of distributing to retailer i is $f_i^U\le 1$, f_i^L.

MODEL OF FP-IRH POLICY

Partition policy: In order to improve the distribution efficiency, the following steps are designed to cluster the retailers into some partitions, the retailers in same group (sub-area) will be distributed at a same frequency and all partitions do not influence each other.

- **Step 1:** VRP solving. Partitions are coded as $l\in\{1, 2,..., L\}$, the retailers in partition l is denoted as S_l and the total demand in any S_l must no more than w. Then, solve the Traveling Salesman Problem (TSP) between DC and each S_l, to get the optimized route θ_l, for any $l\in\{1, 2, ..., L\}$
- **Step 2:** EOQ solving. Take any S_l as a "supper-retailer", its demand rate is:

$$R_l = \sum_{j\in S_l} r_j$$

and its average inventory cost is

$$H_l = \sum_{j\in S_l}\left(h_j r_j\right)\Big/\sum_{j\in S_l} r_j$$

Then, take $K_l = s+\theta_l$ as the fixed ordering cost of S_l, determine the optimal delivery period t_l and quantity with EOQ theory.

- **Step 3:** Improving. Re-clustering by moving any retailer among the partitions and repeat step 1, 2 to search a satisfactory solution

Period policy: In the inventory literature, integral time point, power-of-two period (retailers ordering), IRH distributing period method of EOQ is relative more effective (Zhao *et al*., 2008), but IRH method is more suitable for processing long-horizon inventory problem (Abdul-Jalbar, 2010).

Method of IRH takes the plan horizon as a basic time unit, the distribution period is an integer multiple of plan horizon, or contrary of that. That is:

$$m_l = \frac{t_0}{t_l} \in \left\{..., \frac{1}{3}, \frac{1}{2}, 1, 2, 3, ...\right\}, \forall l \in \{1, 2, ..., L\}$$

IRH policy may be used in the regional DC, which faces multiple retailers of different demand rate, assuming that the planning horizon is one month (30 day), then, distribution period to a retailer maybe is 1/10 month (3 day), 1/ 4 month (about one week), half a month or a quarter (3 months), etc.

System model: In this case, the vehicle loading capacity and integral planning horizon limitation is ignored firstly, in order to find a simple theoretical optimal policy of $\left(t_0^*, m_1^*, ..., m_L^*\right)$. Then, the policy will be improved by adding the vehicle capacity and integral horizon limitation, for extending to the general case.

Relaxation of vehicle capacity and integral planning horizon constraints: If $m_l\le 1$, the retailers in S_l are replenished at the same time with the DC's replenishment and these goods cost no inventory in the DC because of without being stocked.

If $m_l>1$, some goods need to be stocked in the DC, the average stock level is:

$$\sum_{l:m_l>1} (m_l - 1)R_l t_l / 2$$

so, the total cost of the DC in the planning horizon t_0 is:

$$C_0 = K_0 + h_0 t_0 \sum_{l:m_l>1} \frac{(m_l - 1)R_l t_l}{2}$$

In the distribution period t_l, the average stock level of S_l is: $r_j t_l/2$, its inventory cost is:

$$t_l \sum_{j\in S_l}\left(h_j \frac{r_j t_l}{2}\right) = t_l^2 \sum_{j\in S_l} \frac{h_j r_j}{2}, \forall l \in \{1,2,...,L\}$$

in the planning horizon, the total cost of S_l is:

$$C_l = \left(t_l^2 \sum_{j\in S_l} \frac{h_j r_j}{2} + K_l\right) m_l$$

and the system's unit-time total cost is:

$$C_T = \frac{C_0}{t_0} + \sum_{l=1}^{L} C_l = \frac{K_0}{t_0} + h_0 \sum_{l:m_l>1} \frac{(m_l - 1)R_l t_l}{2} + \sum_{l=1}^{L}\left[\frac{t_l^2 m_l}{t_0} \sum_{j\in S_l}\left(\frac{h_j r_j}{2}\right) + \frac{K_l m_l}{t_0}\right]$$

take $t_l = t_0/m_l$ into the above equation, we get:

$$C_T = \frac{1}{t_0}\left[K_0 + \sum_{l=1}^{L}(K_l m_l)\right] + \frac{t_0}{2}\left[h_0 \sum_{l:m_l>1}\left(R_l(1-\frac{1}{m_l})\right) + \sum_{l=1}^{L}\sum_{j\in S_l} \frac{h_j r_j}{m_l}\right]$$

then, the 1-1-M system IRP model is denoted as:

$$\min\ C_T = \frac{1}{t_0}\left[K_0 + \sum_{l=1}^{L}(K_l m_l)\right] + \frac{t_0}{2}\left[h_0 \sum_{l:m_l>1}\left(R_l(1-\frac{1}{m_l})\right) + \sum_{l=1}^{L}\sum_{j\in S_l} \frac{h_j r_j}{m_l}\right] \quad (1)$$

s.t.

$$m_l \in \left\{..., \frac{1}{3}, \frac{1}{2}, 1, 2, 3, ...\right\}$$

$$\because \frac{\partial^2 C_T}{\partial t_0^2} = \frac{2}{t_0^3}\left[K_0 + \sum_{l=1}^{L}(K_l m_l)\right] > 0$$

$\because$ if $\frac{\partial C_T}{\partial t_0} = 0$, get the optimal replenishment cycle in theory as:

$$t_0^* = \sqrt{\frac{2\left(K_0 + \sum_{l=1}^{L}(K_l m_l)\right)}{h_0 \sum_{l:m_l>1}\left(R_l(1-\frac{1}{m_l})\right) + \sum_{l=1}^{L}\sum_{j\in S_l}\frac{h_j r_j}{m_l}}} \quad (2)$$

Given ρ_l as:

$$\rho_l = \frac{K_l m_l / t_0}{H_l t_0 / (2m_l)} = \frac{2m_l^2 K_l}{H_l t_0^2}, \forall l \in \{1,2,...,L\} \quad (3)$$

take t_0* into the Eq. 1 and 3, were obtained ρ_l and C_T:

$$\rho_l = \frac{m_l^2 K_l\left[h_0 \sum_{l:m_l>1}\left(R_l(1-\frac{1}{m_l})\right) + \sum_{l=1}^{L}\sum_{j\in S_l}\frac{h_j r_j}{m_l}\right]}{H_l\left[K_0 + \sum_{l=1}^{L}(K_l m_l)\right]}, \forall l \in \{1,2,...,L\} \quad (4)$$

$$C_T(m_1, m_2, ..., m_L) = \sqrt{K_0 + \sum_{l=1}^{L}(K_l m_l)} \cdot \sqrt{h_0 \sum_{l:m_l>1}\left(R_l(1-\frac{1}{m_l})\right) + \sum_{l=1}^{L}\sum_{j\in S_l}\frac{h_j r_j}{m_l}} \quad (5)$$

If K_l is fixed, ρ_l is closer to 1 to reflect the distribution volume and distribution of the costs and EOQ policy inventory and distribution (fixed) cost of the gap (Abdul-Jalbar, 2010), then using Eq. 4 and 5 can guide the searching for the optimal policy $(t_0^*, m_1^*, m_2^*, ..., m_L^*)$ in IRH.

Joined the limitation of vehicle capacity and integral planning horizon: Because the Eq. 1-5 above neglected the limitation of vehicle capacity, once the partitions are determined, each partition needs only one vehicle for distribution and their distribution cost are the same as K_l.

Considered the constraints of the vehicle capacity and because of the different t_0, m_l, each planning horizon distributed to the partition l of the trips may be multiple. Therefore:

$$\min\ C_T(t_0, m_1, m_2, ..., m_L) = \frac{1}{t_0}\left[K_0 + \sum_{l=1}^{L}(K_l m_l)\right] + \frac{t_0}{2}\left[h_0 \sum_{l:m_l>1}\left((1-\frac{1}{m_l})\sum_{j\in S_l} r_j\right) + \sum_{l=1}^{L}\sum_{j\in S_l}\frac{h_j r_j}{m_l}\right] \quad (6)$$

s.t.

$$0 < t_0 \le W \Big/ \sum_{i=1}^{N} r_i \quad (7)$$

$$m_l \ge t_0 \sum_{j\in S_l} r_j \Big/ w,\ \forall l \in \{1,2,...,L\} \quad (8)$$

$$t_0 \in \mathbb{Z}^+,\ m_l \in \left\{..., \frac{1}{3}, \frac{1}{2}, 1, 2, 3, ...\right\} \text{ and } S_l = \{\text{retailers in partition } l\} \quad (9)$$

The right side in the objective function (6) denotes the total distributing and inventory cost. The constraint (7) is the planning horizon limited by the large vehicle capacity, constraint (8) is the minimum distributing time limited by the small vehicle capacity over the planning horizon, in any partition:

ALGORITHM DESIGN

Algorithm analysis: If t_0 can be determined a specific value in:

$$\left(0,\ W\Big/\sum_{i=1}^{N} r_i\right]$$

the work of solving is just searching for the best (m_1, m_2, ..., m_L), corresponding partition. In this case, to make:

$$\rho_l = \frac{2K_l}{H_l R_l t_0} \cdot m_l^2$$

tends to 1, three cases is following:

- If:

$$\frac{2K_l}{H_l R_l t_0^2} > 1$$

then:

$$f_l \to \sqrt{\frac{H_l R_l t_0^2}{2K_l}} < 1$$

take $z \in \mathbb{Z}^+$ and meet:

$$\frac{1}{z+1} \le \sqrt{\frac{H_l R_l t_0^2}{2K_l}} \le \frac{1}{z}$$

and meet:

$$m_l \in \left\{\frac{1}{z+1}, \frac{1}{z}\right\}$$

- If $\frac{2K_l}{H_l R_l t_0^2}$<1, then $m_l \to \sqrt{\frac{H_l R_l t_0^2}{2K_l}} > 1$ take $z \in \mathbb{Z}^+$

meet $z \le \sqrt{\frac{H_l R_l t_0^2}{2K_l}} \le z+1$

then, compare the advantages and disadvantages of:

$$m_l \in \{z, z+1\}$$

- If $\frac{2K_l}{H_l R_l t_0^2} = 1$, $m_l = 1$

At the same time, the time of distribution of the above-mentioned methods should also meet the vehicle capacity, as:

If m_l<$R_l t_0$/w<1, then, take m_l = int [w/($R_l t_0$)], where int[•] is expressed on the value of [•] in the round down If m_l<1<$R_l t_0$/w,or $R_l t_0$/w>$m_l \ge 1$, then take m_l = int [$R_l t_0$/w]+1.

For:

$$t_0 \in \left(0,\ W\Big/\sum_{i=1}^{N} r_i\right]$$

and $t_0 \in \mathbb{Z}^+$, not all of the integer t_0 should be searched, it can narrow the searching to [t_{start}, t_{end}], where t_{start} and t_{end} are the starting point and end point respectively.

$$t_{start} = \max\left(1,\ \text{int}\left[\sqrt{2K_0\Big/\sum_{i=1}^{N}(h_i r_i)}\right]\right)$$

$$t_{end} = \min\left(\text{int}\left[2(K_0 + K_{VRP})\Big/h_0 \sum_{i=1}^{N} r_i\right],\ \text{int}\sqrt{W\Big/\sum_{i=1}^{N} r_i}\right)$$

where K_{VRP} is the total cost, assumed that all of the distribution period is movement with the planning horizon and the DC finishes all distribution in one time. The total cost including start-up and VRP travel. If t_{start}> t_{end}, then let t_{start} = t_{end}.

Lower total cost bound of FP-IRH policy in 1-1-M system: IRP of 1-1-M system can be split into a two-echelon IRP and a problem of DC replenishment (Zhao *et al*., 2008; Li *et al*., 2011). For the DC, its demand rate is the sum of all retailers', if the plan period and the distribution period is perfectly synchronized, the DC does not occur inventory costs. In this ideal situation, the DC replenishment is a simple EOQ problem and the lower replenishment cost bound in a unit time is:

$$\sqrt{\frac{K_0}{2}\sum_{i=1}^{N}(r_i h_i)}$$

Table 1: Algorithms Framework

```
Parameter initialization;
Given any distribution partitioning scheme for solving CVRP;
Calculating t_start, t_end
If t_start > t_end, let t_start = t_end;
while t_0 ≤ t_end;
    for l = 1: L;
        Calculating sqrt(1/ρ_l)
        If sqrt(1/ρ_l) < 1, comparing partition of the average total cost, to determine the results of f_l ∈ {1/(z+1), 1/z};
        If sqrt(1/ρ_l) > 1, comparing partition of the average total cost, to determine the results of f_l ∈ {z, z+1};
        If sqrt(1/ρ_l) = 1, let m_l = 1;
        If m_l < R_l t_0/w < 1 let m_l = int[w/R_l t_0];
        If m_l < 1 < R_l t_0/w, or R_l t_0/w < m_l ≥ 1, let m_l = int[w/R_l t_0] + 1;
    end;
    By the Eq. 6 calculate the average total cost of system
    If min C_T(t_0 + 1, m_1, m_2, ..., m_L) > min C_T(t_0, m_1*, m_2*, ..., m_L*) quit while
    t_0 = t_0 + 1;
End.
```

So the lower total cost bound in the 1-1-M system of FP-IRH policy is:

$$Z_{min}^{three} = \sum_{i=1}^{N}\left[\frac{(2d_{0i}+s)r_i}{w} + \frac{1}{2}h_i\, r_i/f_i^U\right] + \sqrt{\frac{K_0}{2}\sum_{i=1}^{N}(r_i h_i)}$$

In fact, is the lower bound of any policy in the 1-1-M system of IRP, with frequency Z_{min}^{three} restrictions. Learn from the definition of Chan (1998), the total cost ratio f_i^U and the actual policy of three-echelon IRP is defined as the efficiency of the actual policy of the three-echelon IRP, to describe effective of the actual policy.

Algorithm description

Main idea: For a given t_0, in any given a partitioning scheme, the distribution problem is a TSP for each partition and the DC and the m_l can be calculated according to the above analysis calculate m_l and the average total cost of system, search t_0 for corresponding optimal partition scheme.

Next, repeat the above process with increasing t_0 in step length of 1, until the system average total cost in t_0*+1 is greater than t_0*. The t_0* and corresponding partition scheme $m_1^*, m_2^*, ..., m_L^*$ are the best solution.

Algorithms framework: Referenced the solution method for Capacity Vehicle Routing Problem (CVRP), the total costs are no longer just a TSP, but are the total cost including inventory cost, distribution cost in a unit time. The neighborhood transformation method of partition in Cheng-Hong and Zhuo (2010). The solving algorithms framework of the three-echelon IRP are in the Table 1.

TEST EXAMPLE

Data and result: In order to test the validity of FP-IRH policy and algorithm, the example (The number of retailers is 50) provided by Zhao *et al.* (2008), just take off NO. 1-6 examples' data because their repeatability to other examples' data). The basic parameters of example are as following.

h_0 = 0.1, h_0 = 0.2 (the same for all retailers), w = 500, s = 200, K_0 = 800, W = 5000.

The algorithm is programmed by MATLAB 6.5, running in the computer with CPU 1.66 G, RAM 1.0 G, repeated 5 times, took the best results in Table 2.

Analysis of results: The actual efficiency of the FP-IRH policy surpasses 80% and the total cost of the FP-IRH policy is lower than the FP-OT policy with an average improvement of 5.5% points.

The examples of 7-11 show that, we should be taken to extend the planning cycle reducing the number of purchase and lower the cost of transportation in order to bring down the total cost when inventory cost of the system is lower than transportation cost.

The examples of 12-13 show that, we should be taken to use small car and increase frequency of the delivery in order to improve the efficiency of system when the Retailer demand is relatively lower than the loading capacity of delivery vehicle.

Table 2: Comparison of the three-echelon IRP solution results

NO.	Parameter adjustment	Frequency restriction: Peak frequency	Frequency restriction: Total cost lower limit	FP-POT solution results (Zhao *et al.*, 2008): Total cost	FP-POT: Efficiency (%)	FP-IRH solution results: Total cost	FP-IRH: Efficiency (%)	t_0	max m_l	CPU (sec)
7		1	776.31	1012.05	76.7	972.1	80.0	5	2	297
8	$h_0 = 0.05, h = 0.1$	1	652.52	877.38	74.4	813.8	80.2	5	1	199
9	$h_0 = 0.01, h = 0.02$	1	543.74	715.93	75.9	618.7	87.9	7	1	138
10	$h_0 = 0.05, h = 0.15$	1/2	710.80	919.30	77.3	878.9	80.9	5	2	363
11	$h_0 = 0.2, h = 0.3$	1/2	960.68	1171.37	82.0	1070.5	89.7	5	2	406
12	w = 200, sec = 80	1/2	923.78	1122.56	82.3	1081.7	85.4	5	2	408
13	w = 1000, sec = 400	1/2	778.96	990.82	78.6	961.0	81.1	5	2	317
14	sec = 800	1/2	1747.52	2064.84	84.6	1969.1	88.7	5	1	348
15	sec = 1600	1/2	2990.76	3464.90	86.3	3250.0	92.0	5	1	360
16	$K_0 = 1000$	1/2	944.01	1192.26	79.2	1120.8	84.2	6	2	358
17	$K_0 = 2000$	1/2	1110.68	1444.97	76.9	1290.0	86.1	6	2	232
18	$K_0 = 1300$	1/2	875.16	1093.66	80.0	1086.1	80.6	6	2	366
19	$K_0 = 1900$	1/2	977.35	1278.91	76.4	1188.5	82.2	6	2	344
20	W = 3000	1/2	844.13	1212.42	69.6	1007.4	83.8	3	1	95
21	W = 10000	1/2	815.16	1015.85	80.2	1010.0	80.7	3	1	102

The parameter without listed in "Parameter Adjustment" of Table 2 is the same as the basic parameters. The lower limit of total cost is the minimum of system total cost when the partition distribution limited by the maximum frequency. CPU (sec): The average time-consuming of 5 times calculations

The examples of 14-15 show that, the average total cost of system increase obviously when the starting cost of delivery vehicles becomes bigger. Simultaneously, the improved efficiency of FP-IRH policy indicates that partitions integration brings the better saving of total cost when inventory cost is obviously lower than delivery cost.

The examples of 16-19 shows that, the fixed purchasing cost of distribution center becomes bigger and be equally allocated each distribution period that thus causing the average total cost increases. The loading vehicle capacity of distribution center purchasing becoming bigger (examples of 20-21) don't has a great influence on the total cost and the efficiency of FP-IRH policy and it indicates that the average total cost depends mainly on the inventory cost of distribution center and delivery cost to retailers when the transport conditions of distribution center purchasing reach a certain level.

CONCLUSION

By coordinating the fixed-partition of distribution and adjusting the rate between planning and distributing cycle, this policy searches the best portfolio program to minimize the total cost. The testing result of example shows that, the total cost of inventory and transportation in long planning cycle of the three-echelon distribution system is too sensitive to changes in the cost rate of stocking and the starting cost of dispatching vehicle and lacks sensitive to the change in the vehicle loading capacity. At the same time, the new policy and algorithm are more efficient than the published FP-POT policy.

Compared with the system of VMI, the problem in this study is relatively simple, without considering the actual situations of retailer's demand replenishing direct from the vendor, the horizontal transfer between different distribution centers. That's the direction of following work.

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