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Optimizing Vendor-Managed Inventory in Multi-Tier Distribution Systems

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ABSTRACT

This paper addresses the concept of the vendor-managed inventory (VMI) problem, focusing on the replenishment policy and the vehicle routing problem (VRP) model. These components are integrated to tackle a three-echelon distribution issue comprising a single plant, multiple depots, and multiple retailers, with the primary objective of minimizing transportation and inventory costs within this complex distribution network. A three-phase methodology is proposed to optimize the entire supply chain, from the plant to the final retailer, and its performance is evaluated through computational experiments. This research is motivated by a real-life supply network, highlighting its practical relevance and applicability. To extend the capabilities of existing methods for solving the combined inventory and routing problem, an insertion heuristic is incorporated to enhance vehicle utilization, thereby reducing total costs. Computational results demonstrate the effectiveness of the improved algorithm, indicating that it is sufficiently robust for practical application. Significant cost savings can be achieved with the proposed approach, making it a valuable contribution to the field of supply chain optimization.

1. Introduction

With growing awareness among companies about the significance of effective supply chain performance and its enhancement, inventory and distribution have emerged as the primary functional components in supply chain management [1,2]. These elements account for approximately two-thirds of the overall logistic costs [3]. From this perspective, the coordination and integration of inventory and distribution play a crucial role in assessing the effectiveness of a supply chain management system [4,5].

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The Vendor Managed Resupply policy is a solution in product transportation that effectively addresses various transportation issues, enhances efficiency, and minimizes costs [6]. This policy operates on the premise that supplying parties, who possess superior knowledge of goods production capacities and lead times, are better equipped to manage inventory [7,8]. Furthermore, this approach is grounded in the notion that granting suppliers the responsibility of inventory management leads to a decrease in the number of intermediaries involved in the supply chain, hence enhancing the visibility of available stock and diminishing the overall quantity of inventory.

Prior research mostly focused on a two-tier system, often comprising either a 1-M (one depot and multiple retailers) or M-M (multi depots and multiple retailers) configuration [9,10]. Recently, the three-echelon IRP has garnered significant attention from researchers [11]. This paper focuses on a distribution system consisting of three levels: a central plant, multiple depots, and a group of retailers. Every depot must replenish certain retailers and meet their demands, resulting in the formation of a sub distribution cluster consisting of the depot and the stores located nearby [12].

The 1-M-M distribution system involves transportation cost as well. Since vehicle capacity is limited, all retailers' demands may not be fulfilled in one trip with one vehicle. The travelling distance of vehicles and the number of trips obviously affect transportation cost [13]. The objective is to minimize travelling distance so that vehicle capacity is utilized with inventory requirements being satisfied [14].

This paper is organized as follows. In section 2, research objectives and related research are formally described. For the sake of improvement, we focus on multiple non-identical items. In section 3 a mathematical model for it is formulated. Consequently, the basic procedure involving three phases is proposed. The algorithm in detail is presented with main steps in each phase. Experimental study with these heuristics is presented in section 4, giving evaluation of different developed solution methods. Finally, conclusions are formulated in section 5.

2. Research Objectives and Related research

2.1. Research Objectives

The goal of the 1-M-M IRP problem is to identify optimal replenishment policies that determine the right delivery quantities, delivery intervals, and vehicle routes. These policies aim to reduce the costs associated with inventory and transportation throughout the whole supply chain system. Due to the unique requirements of each retailer, the vendor must provide them with varying quantities at different times and using different routes. Meanwhile, the plant at the beginning of the supply chain keeps track of depot inventory and restocks them based on their inventory levels. This ensures that the retailers further down the supply chain can be satisfied. To address this distribution issue, the three-echelon system needs to be divided into two separate two-echelon subsystems: the Depot-Retailer distribution system (M-M) and the Plant-Depot distribution system (1-M). These subsystems should be integrated with both the inventory problem and the vehicle routing problem.

2.2. Related Research

In the past decade, vendor managed inventory has gained increased attention both from a research and a practical point of view [15]. Managerial interest has been garnered through the claims of significant savings in terms of stock reduction, shorter lead times, a better match of the supply chain to the customer needs, and the improved responsiveness of the supply chain. According to several sources, the performance benefits predicted have been disappointing. Research focusing on the definition is at best inconsistent, at worst confused and contradictory. Therefore, different types of vendor managed inventory models have been proposed, using a wide variety of assumptions regarding the decision level, the nature of the contract, the type of product, lead time, etc. This research first contributes to the theoretical literature by developing a classification scheme for these models that is based on the concepts of the Newsvendor and EOQ problems, while taking into account distinct goals, decision levels, information sharing and contracting instruments [4].

Vendor Managed Inventory (VMI) is a supply chain technique in which the vendor or supplier takes responsibility for managing the inventory levels of the customer. The vendor oversees the customer's inventory and restocks it as necessary, guaranteeing that the customer never experiences a shortage of items. Conversely, CS stands for inventory that is owned by a supplier but is physically located at the customer's premises. Customers have the ability to access and make use of the commodities as required, but they are only needed to pay for the items that have been used or sold. The combination of VMI and CS results in a synergistic approach to inventory management. The vendor maintains ownership of the goods, but they have access to the customer's inventory levels and restock it accordingly. This arrangement has the potential to optimize the supply chain, enhance operational efficiency, and decrease expenses for all parties involved.

Lotfi *et al.,* [16] combined fuzzy logic and robust optimization to address uncertainty and disruption in Resilience and Sustainable Health Care Supply Chains using the VMI approach. They proposed three stochastic programming models, each varying in effectiveness based on decision-maker conservatism. Malleeswaran and Uthayakumar [17] assessed sustainability investments and carbon policies in a two-level supply chain, finding VMI methods reduced costs and emissions more effectively than classical methods. Golpîra *et al.,* [18] introduced a tri-objective robust MILP model for two-echelon supply chains, optimizing visibility, product quality, and costs. Salas-Navarro *et al.,* [19] developed a VMI model for three-layer supply chains, incorporating defective and deteriorated products, and demonstrated its practical application in the Dairy Industry. Gharaei *et al.,* [20] optimized a VMI approach for multiple products using a stochastic MINLP model and Generalized Benders Decomposition, determining effective joint replenishment policies.

3. Methodology

3.1. A Mathematical Model

The three-echelon inventory and distribution routing system in this research uses a single facility to produce several goods. To meet deterministically known demand over a planning horizon, plant trucks must deliver made products to depots. However, each depot will restock stores with various supplies brought by vehicles. The plant or depot has limited storage and a truck for delivery. These vehicles' transportation costs depend on journey time, not quantity. Vehicle use has no fixed cost. It is expected that each truck can make many trips (a trip is a sequence of retailer locations a vehicle visits from a depot to the same depot) during each period as long as it can return to the base depot. The goal is to meet demand without raising inventory or transportation costs and minimize shortages.

To give a formal presentation of the Integrated **I**nventory and **D**istribution **R**outing **P**roblem in VMI system, we consider a supply chain environment with the following assumptions:

i. Single plant
ii. Multiple depots
iii. Multiple retailers
iv. Multiple non-identical products
v. Multiple time periods within a planning horizon
vi. A number of vehicles at plant
vii. A number of vehicles at each depot
viii. Each vehicle can visit more than one customer during a trip, and can make multiple trips within one period if possible

ix. Each vehicle returns to its base plant or depot at the end of each period

Parameters of the model are defined in Table 1, and variables are defined in Table 2 as follows.

Table 1
Parameter Definitions for the IRP Model

Symbol	Definition
t	distribution cycle (t=1,2,3……m)
T:	distribution cycle time
H	Simulation horizon (H:1,2,3….t)
p	plant
d	distribution center ($d=d_1,d_2,\ldots\ldots d_l$)
r	retailers (r=1,2,3…..n)
i	product (i=1,2….N)
D_{irt}	demand of retailer r for product i
I_{irt}	inventory level of retailer r for product i
I_{idt}	inventory level of the depot for product i
I_{ipt}	inventory level of the plant for product i
K_d	quantity of vehicles at depot
V_d	capacity of vehicles at depot
K_p	quantity of vehicle at plant
V_p	capacity of vehicles at plant
q_{irt}	quantity of product i distributed from depot to retailer r
q_{idt}	replenished quantity of product i from plant to depot
q_{ipt}	produced quantitiy of product i at plant
$\alpha_{dt}(q_{idt})$	1 or 0, when $q_{idt}>0$ or otherwise
$\beta_{rt}(q_{irt})$	1 or 0, when $q_{irt}>0$ or otherwise
C_{hip}	unit inventory holding cost for product i at plant
C_{hid}	unit inventory holding cost for product i at depot
C_{hir}	unit inventory holding cost for product i at retailer
D_{xy}	distance between depots and retailers (x=0,1,2……n, y=0,1,2……n)
D_{pd}	distance between plant and depots.($d= d_1,d_2,\ldots\ldots d_l$)
C_v	variable transportation cost in unit distance
C_f	fixed transportation cost (vehicle depreciation cost, premium, driver salary)

Table 2

Variable Definitions for The IRP Model

Symbol	Definition
C_{Thp}	total holding cost for plant
C_{Thd}	total holding cost for depot
C_{TTd}	total transportation cost for depot
C_{Thr}	total holding cost for retailer
C_{TTr}	total transportation cost for retailer

The integrated inventory and distribution routing problem can then be formulated as follows.

$$\text{Min} \sum_{t=1}^{m}\sum_{i=1}^{N} C_{hip}T_{ip}\frac{Iipt\text{-}1+Iipt}{2} + \sum_{t=1}^{m}\sum_{i=1}^{N} C_{hid}T_{id}\frac{Iidt\text{-}1+Iidt}{2} + \sum_{i=1}^{m}\sum_{d=1}^{l} 2C_v d_{pd}\alpha_{dt} + \sum_{t=1}^{m} C_f K_{pt} + \sum_{t=1}^{m}\sum_{i=1}^{N}\sum_{r=1}^{n} C_{hir}T_{ir}\frac{Iirt\text{-}1+Iirt}{2} + \sum_{t=1}^{m}\sum_{x=0}^{n}\sum_{y=0}^{n} C_v d_{xy}\beta_{rt} + \sum_{t=1}^{m} C_f K_{dt} \tag{1}$$

s.t.

Total holding cost for plant:

$$C_{Thp} = \sum_{t=1}^{m}\sum_{i=1}^{N} C_{hip}\,T_{ip}\frac{Iipt\text{-}1+Iipt}{2} \tag{2}$$

$$I_{ipt} = I_{ipt-1} + q_{ipt} - \sum_{d=1}^{l} q_{idt} \quad \forall\, i, t,\ i \in N,\ t \in T\ p=1 \tag{3}$$

Total holding cost for depot:

$$C_{Thd} = \sum_{t=1}^{m}\sum_{i=1}^{N} C_{hid}\,T_{id}\frac{Iidt\text{-}1+Iidt}{2} \tag{4}$$

$$I_{idt} = I_{idt-1} + q_{idt} - \sum_{r=1}^{n} q_{irt} \quad \forall\, i, t,\ i \in N,\ t \in T \tag{5}$$

Total transportation cost for depot

$$C_{TTd} = \sum_{i=1}^{m}\sum_{d=1}^{l} 2C_v\, d_{pd}\,\alpha_{it} + \sum_{t=1}^{m} C_f K_{pt}$$

$$K_{pt} \geq 0,\quad \alpha_{it} \in \{0,1\} \quad \forall\, i, t,\ i \in N,\ t \in T \tag{6}$$

Total holding cost for retailer

$$C_{Thr} = \sum_{t=1}^{m}\sum_{i=1}^{N}\sum_{r=1}^{n} C_{hir}T_{ir}\frac{Iirt\text{-}1+Iirt}{2} \tag{7}$$

$$I_{irt} = I_{irt-1} + q_{irt} - D_{irt} \quad \forall\, i, t,\ \forall\, i, t,\ i \in N,\ t \in T,\ r \in n \tag{8}$$

Total transportation cost for retailer

$$C_{TTr} = \sum_{t=1}^{m}\sum_{x=0}^{n}\sum_{y=0}^{n} C_v\, d_{xy}\,\beta_{rt} + \sum_{t=1}^{m} C_f K_{dt}$$

$$K_{dt} \geq 0,\quad \beta_{rt} \in \{0,1\} \quad \forall\, t,\ t \in T,\ r \in n \tag{9}$$

Storage capacity and safety stock requirement constraints

$$0 \leq I_{ipt} \leq I_p^{max} \quad \forall\, i, t,\ i \in N,\ t \in T \tag{10a}$$

$0 \leq I_{idt} \leq I_d^{max} \quad \forall\, i, t, i \in N, t \in T$ (10b)

$0 \leq I_{irt} \leq I_r^{max} \quad \forall\, i, t, i \in N, t \in T$ (10c)

vehicle capacity constraints

$$K_{dt} V_d \geq \sum_{r=1}^{n} q_{irt} \quad \forall\, i, t, i \in N, t \in T \tag{11}$$

$$K_{pt} V_p \geq \sum_{d=1}^{l} q_{idt} \quad \forall\, i, t, i \in N, t \in T \tag{12}$$

Non-negative and integer requirement

$q_{irt} \geq 0 \; q_{idt} \geq 0 \;\; q_{ipt} \geq 0 \;\; \forall\, i, t, i \in N, t \in T$ (13)

$K_{dt} \geq 0\, ,\; K_{pt} \geq 0 \quad \forall\, t\, , t \in T$ (14)

The objective function (1) of the model includes inventory cost (at plant, depots and retailers, respectively), and transportation cost (both plant and depots owned vehicles).

Constraints (2) and (3) balance plant production, inventory, delivery, and depot demand fulfillment. Plant average inventory is constraint (2). The plant inventory balance constraint (3) requires that inventory and current production can cover plant distribution in that period. Restocking, inventory, delivery, and merchant demand fulfillment are balanced at the depot by constraints (4) and (5). Constraint (4) is depot inventory average. Depot inventory balance constraint (5) needs depot distribution to be met from inventory and plant replenishment in that time. When one delivery is made from plant to depot, constrain (6) includes variable and fixed depot transportation costs. Constraints (7) and (8) ensure retailer replenishment, inventory, delivery, and customer demand fulfillment. The average store inventory level is constraint (7). Retailers' inventory balance constraint (8) demands inventory and depot replenishment to meet customer demand. When one replenishment is made from depot to retailers, constrain (9) is the variable and constant transportation costs for retailers. Inventory limitations (10a, 10b, and 10c) meet plant, depot, and retailer storage capacity and inventory needs. Constrain (11) and (12) limit plant and depot vehicle capacity. Finally, constraints (13) and (14) are non-negative.

3.2. Replenishment Process

This research investigates a three-phase methodology, Route-Route-Cluster, to address the Multi-Depot and Multi-Retailer (M-M) problem. Initially, a schematic representation of the system is utilized to illustrate the functioning of this methodology (Figure 1). Subsequently, a detailed explanation of the main steps is provided.

The Route-Route-Cluster methodology consists of three distinct phases designed to optimize the distribution process in a supply chain with multiple depots and retailers. The first phase involves routing from the central plant to the depots, ensuring efficient allocation of resources and minimizing transportation costs. The second phase focuses on routing from the depots to the various retailers, maintaining consistency in delivery schedules and reducing travel distances. Finally, the clustering phase groups retailers based on geographic proximity and demand patterns, further enhancing the efficiency of the distribution network.

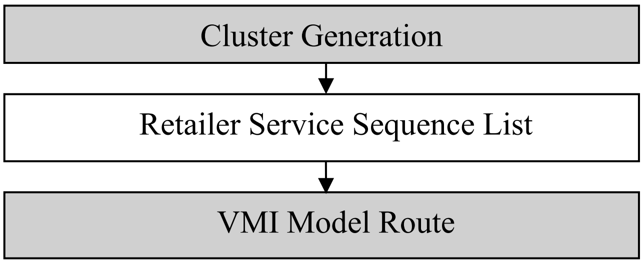


Fig. 1. A Schematical Model of The Distribution System

As shown in Figure 2, this method is divided into three stages including specific steps respectively.

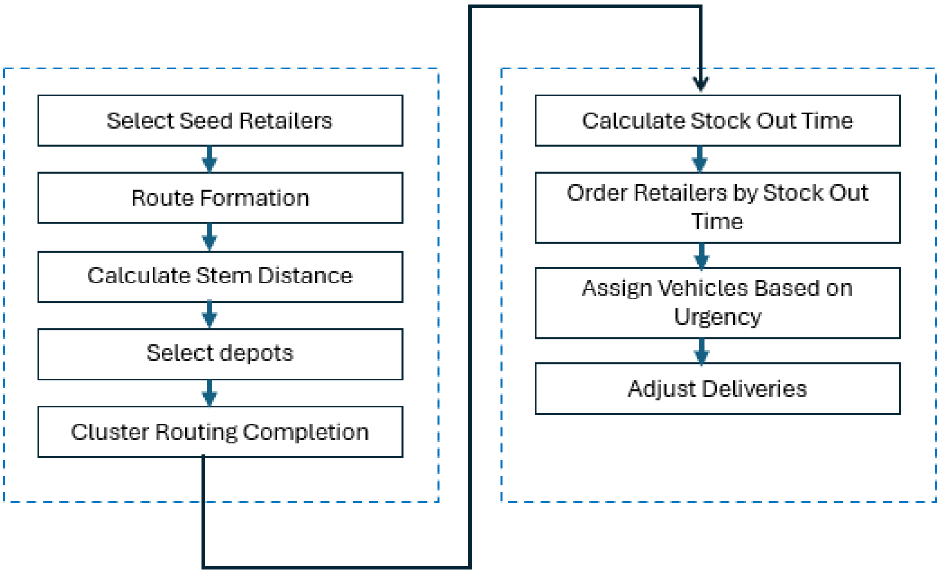


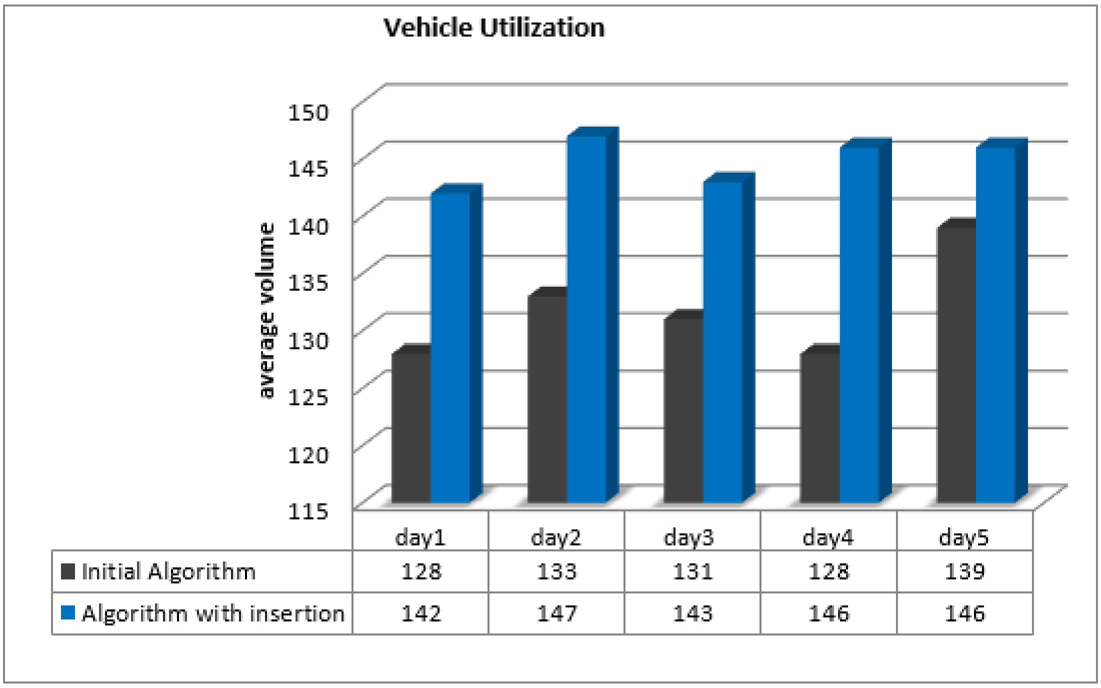
Fig. 2. General Flowchart For M-M Algorithm

4. Experimental Study and Evaluation

This section examines the effectiveness of the developed models. As stated previously, there are two components involved in the distribution system: the inventory problem and VRP. Therefore, in this experiment, we compare the initial solutions from model 1, each truck delivers only one product, and model 2, each truck delivers three items simultaneously, to the improved solutions from model 3, delivery quantity depends on the time that vehicle arrives at retailer, to the model with insertion algorithm, by varying the inventory factor and VRP factor, which are the inventory level and transport distance, in case unit holding cost and unit transport cost are constant.

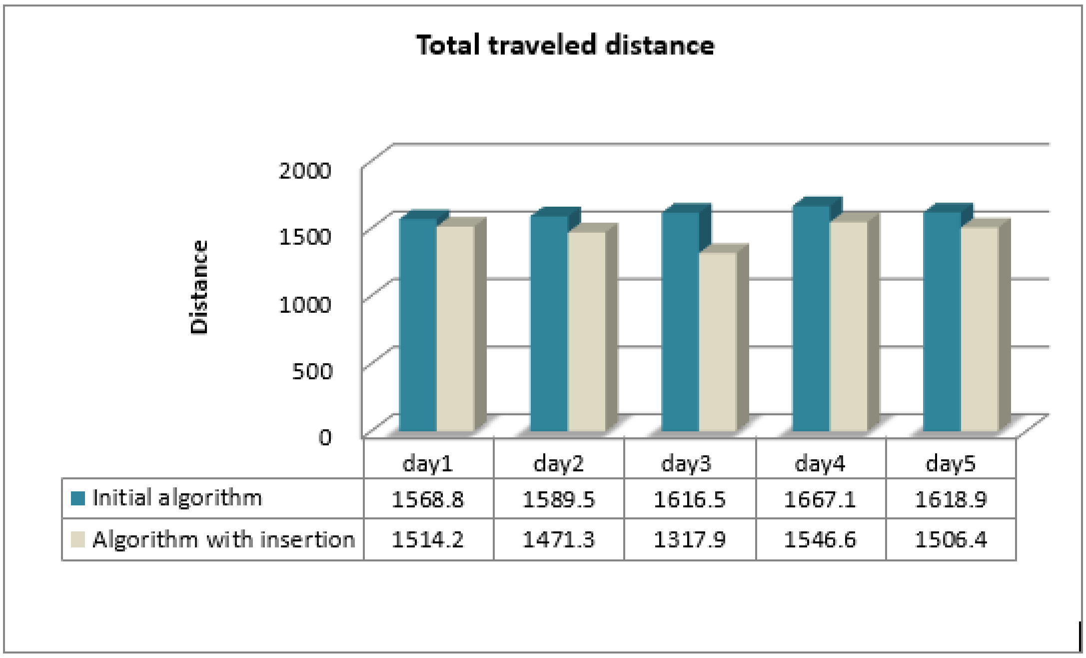
For the comparison of simulation results, the following information will be taken into research:

i. Vehicle utilization (Figure 3);
ii. Total traveled distance (Figure 4);
iii. Total cost (Figure 5).



	day1	day2	day3	day4	day5
■ Initial Algorithm	128	133	131	128	139
■ Algorithm with insertion	142	147	143	146	146

Fig. 3. Comparison Of Vehicle Utilization



	day1	day2	day3	day4	day5
■ Initial algorithm	1568.8	1589.5	1616.5	1667.1	1618.9
■ Algorithm with insertion	1514.2	1471.3	1317.9	1546.6	1506.4

Fig. 4. Comparison Of Total Traveled Distance

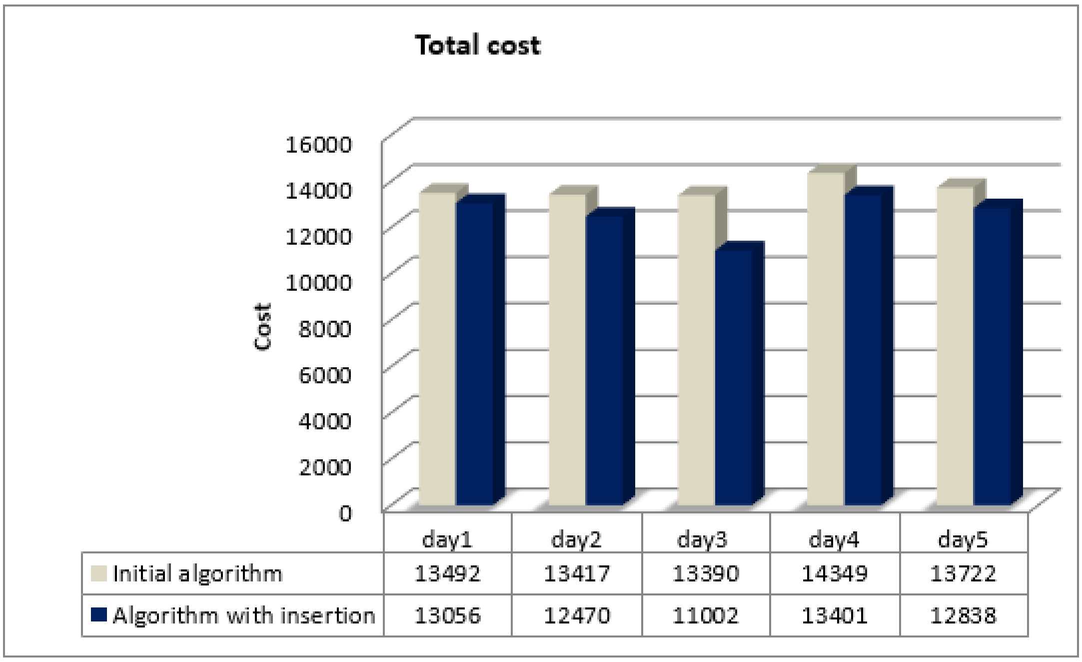


Fig. 5. Comparison Of Total Cost

In conclusion, the objective cluster demonstrates that the algorithm with insertion achieves a substantially lower travel distance, higher volume per mile, higher average utilization, and lower total cost compared to the initial algorithm, despite a larger total volume delivered. This insertion approach optimizes vehicle capacity by incorporating deliveries to retailers near imminent delivery points, thereby reducing transportation costs, particularly fixed transportation costs. When fixed transportation costs are high, this approach minimizes the number of trips and the distance a vehicle must travel, significantly lowering transportation expenses. Furthermore, allowing imminent retailers to be replenished based on the remaining truck capacity increases the total system inventory cost. However, the reduction in transportation costs offsets the increased inventory costs, resulting in a minimized total system cost.

5. Conclusion

This paper explores the integration of the vendor-managed inventory problem, replenishment policy, and vehicle routing problem model to address a three-echelon distribution system composed of a single plant, multiple depots, and multiple retailers. Unlike previous studies that typically consider either the inventory problem or the transportation problem separately within a two-level system, this research combines both aspects in a three-level context. The developed models demonstrate how integrating inventory and vehicle routing can solve the 1-M-M distribution system using approaches adapted from existing models. It is important to note that the solutions derived from these models are not always optimal, as they depend on the specific conditions and factors involved in the system.

The developed models first group retailers and depots into clusters based on consumption rates and capacities using the nearest neighbor and stem distance algorithms, applying a route-first, cluster-second approach. After routing all retailers, a service sequence list is created for each cluster according to the urgency of each retailer. Subsequent route assignments are made based on this list. Initial solutions for the inventory routing problem (IRP) are provided by Models 1 and 2, with Model 2 performing better, though both are deemed impractical. Model 3, incorporating stochastic demand, offers more practical solutions. An insertion heuristic, introduced to improve Model 3, aims to maximize vehicle capacity utilization without increasing total costs, demonstrating significant progress. These models can guide companies in making replenishment decisions regarding timing and quantity.

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Conflicts of Interest

The authors declare no conflicts of interest.

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