Inventory Routing Optimization with Working Capital Requirement consideration

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***Abstract*— Integrating Working Capital Requirement (WCR) into supply chain decision-making is essential for balancing operational efficiency with financial sustainability. This study presents an Inventory Routing Problem (IRP) model tailored to healthcare supply chains, incorporating WCR considerations to optimize overall costs. By aligning inventory levels with financial considerations, our approach provides a more integrated perspective on supply chain management. The results highlight the significant impact of WCR optimization on decision-making, offering a framework for developing cost-effective and financially sustainable supply chains.**

***keywords*—Inventory Routing Problem, Two-echelon, Working Capital Requirement, Healthcare.**

I. INTRODUCTION

Efficient inventory and distribution management is critical in supply chain optimization. The Inventory Routing Problem (IRP), introduced by Bell et al. in 1983 [1], addresses the challenge of coordinating inventory replenishment and transportation decisions to minimize total costs while ensuring that customer demand is met. As a special case of the Vehicle Routing Problem (VRP), the IRP is classified as NP-hard [1], [2], making it computationally complex.

Despite the extensive research on the IRP, the financial implications of Working Capital Requirement financing costs have been largely overlooked in Supply Chain Management (SCM) [3]. Traditional models focus primarily on logistic costs. However, integrating financial and physical flows is crucial for a more holistic optimization approach, particularly in cost-sensitive environments like hospital supply chains [4].

In this article, we propose a Two-echelon IRP tailored to the hospital supply chain, incorporating Working Capital Requirement (WCR) considerations. Inspired by the work of Farias et al. [8], our model integrates WCR costs into the objective function of a mono-product formulation, offering a more realistic depiction of financial constraints in supply chain operations.

The structure of this paper is as follows: Section 2 provides a literature review, followed by the mathematical formulation of the problem in Section 3. Section 4 presents the computational results. Finally, Section 5 concludes the study and offers directions for future research.

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II. LITERATURE REVIEW

We present an overview of the latest developments in IRP and WCR research and solution methodologies.

A. *IRP LITERATURE REVIEW*

In 2018, Alvarez et al. [6] addressed the IRP by incorporating the logistic ratio as an additional objective, alongside minimizing total costs. This ratio, obtained by dividing the total travel cost by the total quantity delivered to customers, reflects the efficiency of the distribution process. The authors developed two metaheuristic approaches—Simulated Annealing (SA) and Iterated Local Search (ILS). Computational experiments showed that both methods effectively produced high-quality solutions.

In 2018, Timajchi et al. [7] proposed an innovative approach specifically focusing on hazardous and deteriorating pharmaceutical items. They introduced a bi-objective Mixed-Integer Linear Programming (MILP) model with two key objectives: minimizing total logistics costs and reducing the maximum accident loss during distribution. The model also included the option for transshipment between hospitals, helping to mitigate shortages and optimize inventory distribution. The results highlighted the advantages of transshipment.

In 2021, Goodarzian et al. [17] developed a simulation-optimization model to enhance medical supply chain sustainability during COVID-19. They used three hybrid metaheuristic algorithms (HFSA-VNS, HFA-VNS, HACO-VNS) to minimize logistics costs and CO2 emissions, with HFSA-VNS performing the best. A Tehran case study highlighted the importance of inventory control and sustainability in healthcare logistics.

Farias et al. [8] presented in 2021 a comprehensive study on the two-echelon inventory routing problem (2E-IRP), integrating inventory management and vehicle routing to optimize urban distribution via distribution centers. They proposed a mixed integer linear programming formulation under various replenishment policies and evaluated solution methods, including a branch-and-cut algorithm and a two-phase heuristic. Computational experiments on generated instances demonstrate the effectiveness of the proposed approaches and valid inequalities.

In 2022, Chen et al. [9] proposed a genetic algorithm to optimize fresh product supply chains, addressing climate impacts, late deliveries, and production constraints. The model improved customer satisfaction and cost efficiency, as confirmed by simulation results.

Achamrah et al. [10], in 2022, introduced a two-phase metaheuristic combining Genetic Algorithm (GA) and Simulated Annealing (SA) to optimize inventory routing for a fashion distribution company. The model addressed inventory sharing, vehicle routing, and minimizing costs related to stock imbalances and transshipment. Results showed significant cost reductions and improved service levels.

Dorgham et al. [5] in 2022 applied a fuzzy chance-constrained programming approach to address a two-echelon IRP in the healthcare sector, specifically for Territorial Hospital Groups. The model, involving multiple products, suppliers, warehouses, and customers, was solved using a combination of a constructive heuristic and an adaptive variable neighborhood search (AP-GVNS) algorithm.

Rejeb et al. [18] presented in 2024 a multimodal freight transport optimization model which integrates cost, time, and CO2 emissions across air, road, rail, and sea modes. Using Genetic Algorithms and Tabu Search, the study identified efficient transport strategies under realistic constraints. The work offered a robust framework for sustainable and cost-effective freight planning.

Alonso-Pecina et al. [11] tackled in 2024 the IRP with their focus on optimizing the transportation of liquid oxygen. The goal was to minimize the logistic ratio, which is the operating cost per unit of delivered product, considering factors like driver expenses, travel distance, and layover costs. They introduced an Iterated Local Search algorithm that first identifies a feasible solution and then iteratively improves it using neighborhood search methods like simulated annealing.

However, existing inventory routing optimization models rarely incorporate financial metrics, leaving a gap in understanding its financial implications. WCR is a key financial metric that quantifies the short-term liquidity required to manage working capital efficiently throughout a company's core operational cycle [13].

Our analysis aims to optimize the management of operational cash flows, a crucial integration for businesses seeking to enhance both cash flow efficiency and overall supply chain profitability. Integrating WCR into these models would enable a more comprehensive assessment of the trade-offs between operational and financing costs [3].

B. WCR LITERATURE REVIEW

WCR represents the capital required to cover the gap between cash outflows (expenses) and inflows (revenues), providing a precise measure of the firm's operating investment cycle [16].

Bian et al. [12], [13], [14] contributed to integrating the financing cost of WCR into tactical decision-making, particularly in lot-sizing problems.

In Bian et al. [12], they proposed a single-level, single-product, dynamic lot-sizing model that integrates WCR financing costs, focusing on maximizing the present net value of profit by considering cash inflows and outflows. Using a dynamic programming-based algorithm with the Zero-Inventory-Ordering (ZIO) property, the model simplified production planning. A computational study highlighted the advantages of incorporating financial factors, improving liquidity and responsiveness.

In 2020, Bian et al. [13] integrated the financial cost of WCR into a two-level supply lot-sizing problem involving a supplier and manufacturer. They used dynamic programming to maximize profit and propose two approaches: the sequential approach, focusing on the manufacturer's profit, and the centralized approach, maximizing the overall profit. Numerical tests showed that WCR significantly impacted production plans, with the centralized approach reducing financial costs by balancing inventory, while the sequential approach lowered inventory at the manufacturer level.

Bian et al. [14] explored the integration of WCR financing costs into the classic Economic Order Quantity (EOQ) model. They illustrated how financial factors impact production decisions in a single-product, single-level system. The model extended the traditional EOQ by including WCR financing costs in the total cost objective function, alongside logistic costs.

In 2024, Daldoul et al. [15] integrated WCR financing costs into the Inventory Routing Problem, creating the 2E-IRP-WCR model. This model optimizes logistical and financial flows by minimizing costs, including ordering, inventory, transportation, and WCR. Numerical tests showed how financial factors impact inventory decisions. Using ILOG CPLEX, optimal solutions were found. Sensitivity analysis showed how higher customer orders decrease inventory and WCR costs, improving cash flow and financial decision-making.

Chairat et al. [3] emphasized that, despite progress in supply chain management, the integration of WCR for assessing organizational health and cost reduction remains insufficient.

Table I classifies various studies on WCR integration in IRP. Our research advances this domain by incorporating WCR directly into the IRP objective function, an aspect not previously explored in healthcare and multi-period models. By incorporating WCR, our approach provides a holistic view and addresses a critical gap in the literature. This integration enhances the financial realism of the model, ensuring cost optimization while maintaining a stable hospital supply chain.

III. MATHEMATICAL MODEL

Our approach follows the approach of Farias et al. [8], who developed a mathematical model to optimize logistic costs (holding, ordering, and transportation costs) in a Two-echelon supply chain. We adapted their model to a mono-product version using the maximum-level replenishment policy. We incorporated additional parameters, such as purchasing cost, to integrate the WCR financing cost into the model. The primary goal is to minimize both WCR financing and logistic costs, enhancing the financial efficiency of the supply chain. This modification allows our model to simultaneously address operational and financial optimization for a more comprehensive approach to supply chain management.

A. Model Assumptions

In this model, lead time is not considered. It is assumed that suppliers have sufficient capacity to meet all customer demands in each period, and the vehicle fleet is adequate

Paper	WCR	Objective	Approach	Echelon	Multi-period	Context
Alvarez et al. [6]		Min Total cost / Min logistic ratio	Local search, Simulated annealing	1	✓	IRP
Timajchi et al. [7]		Min Total cost and accidents	GA	1	✓	IRP
Goodarzian et al. [17]		Max social factors, Min Total costs	HACO-VNS, HFSA-VNS, HFA-VNS	4	✓	IRP
Farias et al. [8]		Min total cost	B&C and two-phase heuristic	2	✓	IRP
Chen et al. [9]		Max green appraisal, Min transportation time	GA	3		IRP
Achamraha et al. [10]		Min Total costs	CH, Two-phase metaheuristic (GA+SA)	2	✓	IRP
Dorgham et al. [5]		Min Total costs	VNS	2	✓	IRP
Alonso-Pecina et al. [11]		Min Logistic Ratio	Iterated Local Search	2		IRP
Bian et al. [12]	✓	Max Profit	Exact method	1	✓	Lot sizing
Bian et al. [13]	✓	Max Profit	Exact method	1	✓	Lot sizing
Bian et al. [14]	✓	Min Total cost	Exact method	1	✓	Lot sizing
Daldoul et al. [15]	✓	Min Total costs	Exact method	2		IRP
Our approach	✓	Min Total costs	Exact method	2	✓	IRP

TABLE I: Models discussed in IRP literature

to transport the required product quantities. The routing problem is addressed only on the downstream side. Each warehouse takes into account an initial stock, but the carrying costs vary between warehouses. Additionally, warehouses are assumed to have sufficiently large capacities to meet all supply and demand requirements.

B. Sets and Indices

Various sets are defined to represent the key elements in this model. The index s refers to the suppliers, and t represents the planning periods. The customer index is denoted by c, while w is used for the warehouses. and vehicles are indexed by k. The set of warehouses, denoted as W. The set T encompasses all planning periods, and S represents the set of suppliers. Additionally, K denotes the set of vehicles, while C represents the customers. Each set is indexed in terms of the number of elements it contains.

C. Input parameters

The following parameters are introduced to define the essential data and input values required for the model:

- $d_{c,t}$: is the demand of customer c at period t
- $Cmax_c$: is the maximum inventory level of customer c
- $C0_c$: is the initial inventory level of customer c at $t = 0$
- $Imax_{\text{w}}$: is the maximum inventory level of warehouse w
- $I0_w$: is the initial inventory level of warehouse w at $t = 0$
- Cap: Vehicle capacity
- h_c: is the unit holding cost at customer c
- h_w: is the unit holding cost at warehouse w
- Cs_s: is the unit purchasing cost at supplier s
- $c_{i,j}$: is the routing cost associated with edge i, j, where $i, j \in C \cup W$
- OC_1^w: is the fixed ordering cost at warehouse w
- OC_2^c: is the fixed ordering cost at customer c
- b: is the fixed transportation cost related to the use of a vehicle
- β: is the interest rate for financing WCR
- α : is the profit margin
- VAT: is the Value Added Tax

D. Decision variables

The model includes 9 decision variables: 4 integer variables and 5 binary (Boolean) variables:

- $C_{c,t}$: is the inventory level of customer c at the end of period t
- $I_{w,t}$: is the inventory level of warehouse w at the end of period t
- $x_{w,k,c,t}$: is the quantity delivered from warehouse w to customer c by vehicle k at period t
- $y_{s,w,t}$: is the quantity delivered from supplier s to warehouse w at period t
- $r_{w,k,c,t}$: takes 1 if vehicle k from warehouse w visits customer c at period t, 0 otherwise
- $vec_{k,w,t}$: takes 1 if vehicle k from warehouse w performs delivery at period t, 0 otherwise

- $q_{w,k,i,j,t}$: takes 1 if vehicle k starting from warehouse w travels directly from vertex i to vertex j at period t, 0 otherwise
- $sw_{s,w,t}$: takes 1 if supplier s serves warehouse w at period t, 0 otherwise

E. Objective function

These are the cost components defined as follows:

Ordering cost:

$$\text{Ordering Cost} = \sum_{t \in T} \sum_{s \in S} \sum_{w \in W} OC_1^w sw_{s,w,t} + \sum_{t \in T} \sum_{m \in w} \sum_{c \in C} OC_2^c r_{w,k,c,t} \quad (1)$$

Holding cost:

$$\text{Holding Cost} = \sum_{t \in T} \sum_{w \in W} h_w I_{w,t} + \sum_{t \in T} \sum_{c \in C} h_c C_{c,t} \quad (2)$$

Transportation cost:

$$\text{Transportation Cost} = \sum_{t \in T} \sum_{s \in S} \sum_{w \in W} c_{s,w} sw_{s,t} + \sum_{(i,j) \in C \cup W} \sum_{w \in W} \sum_{t \in T} \sum_{k \in K} c_{i,j} q_{w,k,i,j,t} + \sum_{t \in T} \sum_{k \in K} \sum_{w \in W} b.vec_{k,w,t} \quad (3)$$

WCR financing cost:

The WCR financing cost is computed as the difference between inventory value (equation 4) and supplier payables (equation 6), plus customer receivables (equation 5). This value is then multiplied by a financing rate β to reflect capital cost [3].

Inventory Value:

$$\text{IV}_{w,t} = I_{w,t} \cdot CSM \quad (4)$$

Customer Receivables:

$$\text{CR}_{w,t} = \sum_{c \in C, k \in K} x_{w,k,c,t} \cdot CSM \cdot (1 + \alpha) \cdot (1 + \text{VAT}) \quad (5)$$

Supplier Payables:

$$\text{SP}_{w,t} = \sum_{s \in S} y_{s,w,t} \cdot CS_s \cdot (1 + \text{VAT}) \quad (6)$$

WCR Financing Cost:

$$\text{WCRCost}_{w,t} = \sum_{w \in W} \sum_{t \in T} \left(\text{IV}_{w,t} + \text{CR}_{w,t} - \text{Sp}_{w,t}\right) \cdot \beta \quad (7)$$

Where CSM is the average purchasing cost calculated as in Equation 8 :

$$CSM = \frac{\sum_s CS_s}{|S|} \quad (8)$$

The total cost to be minimized, as defined in Equation 9, is composed of the following components: ordering costs (Equation 1), holding costs (Equation 2), transportation costs (Equation 3), and financing costs related to WCR (Equation 7).

Minimize

$$\text{Ordering Cost} + \text{Holding Cost} + \text{Transportation Cost} + \text{WCR Financing Cost} \quad (9)$$

F. Constraints

The constraints formulation builds upon the work of Farias et al. [8], which provides a solid basis for our model. They ensure the feasibility and practicality of the Two-echelon IRP model.

They enforce inventory balance at both warehouses and customer locations by accounting for incoming shipments, outgoing deliveries, and demand satisfaction. Warehouse and customer inventories are restricted by maximum capacity limits to avoid overstocking.

Vehicle capacities are considered to limit the quantity delivered per route, while delivery constraints ensure only active assignments and valid warehouse connections are utilized.

Our model contains routing constraints that guarantee that each vehicle is assigned to at most one route per period and that the routes are feasible and connected.

All inventory levels, shipment quantities, and assignment variables are constrained to be non-negative, ensuring logical and operational consistency.

IV. COMPUTATIONAL RESULTS

The computational experiments were performed on a laptop equipped with an Intel Core i5-11320H processor (3.20 GHz) running Windows 11. The optimization problem was solved using the ILOG CPLEX Optimization Studio 22.1.0 solver.

The computational results presented below are based on the instance composed of 3 suppliers, 2 warehouses, 4 clients, 2 vehicles, and a 12-period planning horizon.

Table II shows that incorporating the WCR cost (WCRC) into the model reduces the total cost from €2124.93 to €2063.067. While holding and ordering costs remain constant, the WCR cost decreases significantly from €321.43 to €247.57. This confirms the effectiveness of the model in minimizing the financial expenses related to WCR with a reduction of approximately 22.98 %.

Table III and IV demonstrate that the consideration of the WCR impacts customer inventory management decisions. This leads to changes in how inventory is allocated and replenished throughout periods, to optimize costs related to working capital requirements while still meeting demand.

In tables III and IV, it is noticeable that certain customers, like C1 and C3, have adjusted stock levels, reflecting the impact of WCR on their product allocation and replenishment strategies. These adjustments help avoid stockouts while maintaining the financial balance required by WCR constraints.

[redacted]	Total Cost	Holding	Ordering	Transportation	WCR Cost
Without WCRC	2124.93	765	740	298.5	321.43
With WCRC	2063.07	765	740	310.5	247.57

TABLE II: Comparison of total costs in euros and cost components with and without WCR consideration.

The holding cost is affected by the fluctuation of stock levels over the periods. As stock levels decrease due to optimized allocations (especially for customers like C3), holding and WCR costs are minimized

These results are also influenced by changes in warehouse inventory levels, which adjust in response to WCR considerations. As warehouses adapt their stock to minimize holding and WCR financing costs, these decisions directly impact cost optimization.

T	1	2	3	4	5	6	7	8	9	10	11	12
C1	30	46	26	11	22	0	19	0	20	0	14	25
C2	20	15	0	26	12	0	18	0	19	0	19	10
C3	40	41	16	20	26	0	0	21	23	0	0	21
C4	10	38	28	23	14	6	0	23	11	0	26	12

TABLE III: Customer inventory levels at the start of each of the 12 periods, considering the WCRC

T	1	2	3	4	5	6	7	8	9	10	11	12
C1	30	37	17	2	22	0	19	0	20	0	0	25
C2	20	15	0	26	12	0	18	0	19	0	19	10
C3	40	50	25	0	26	0	0	21	23	0	0	21
C4	10	38	28	23	14	6	0	23	11	0	14	12

TABLE IV: Customer inventory levels at the start of each of the 12 periods, without considering the WCRC

Figures 1 and 2 illustrate the difference in routing and allocation when WCR is considered. With WCR, figure 1 shows that the second warehouse is served by the third supplier, and the routing starts from the fourth client, moves to the third, then the first client, and returns to the warehouse using the first vehicle.

Without considering WCR, figure 2 shows that a different configuration is used. The fourth customer was served before the third, contrary to what was planned, when considering the WCR. The second warehouse is served by the first supplier, and the second vehicle is used to service the third client, then the fourth, and finally the first client, before returning to the warehouse. In some cases, there is no routing plan in certain periods because the stock is sufficient.

This highlights how WCR influences vehicle allocation and routing decisions, leading to different configurations for minimizing financial and operational costs.

V. SESITIVITY ANALYSIS

We applied a sensitivity analysis on customer demand, β, and α to evaluate their impacts on costs.

A. Varying customer demand

Table V shows that increasing customer demand by 1% in scenario Sc1, holding and WCR costs decreased, confirming

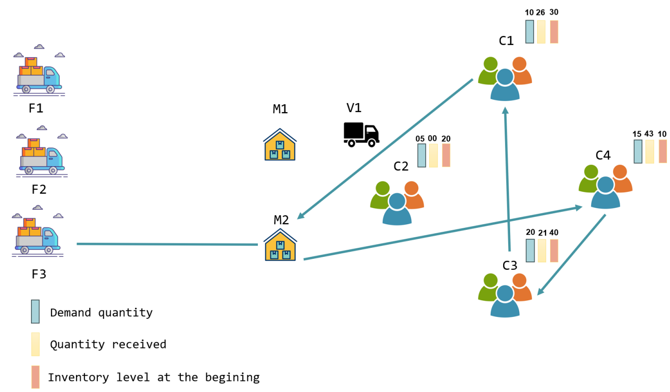

Fig. 1: Routing and allocation of suppliers, warehouses, and vehicles per period (t1) with WCR cost

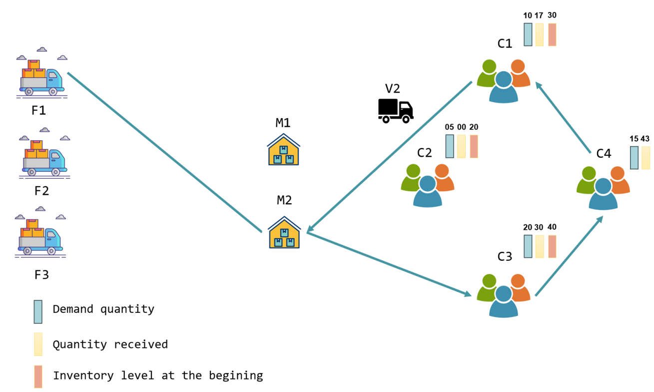

Fig. 2: Routing and allocation of suppliers, warehouses, and vehicles per period (t1) without WCR cost

Daldoul et al. [15]. However, transportation and ordering costs increased due to higher delivery frequency and volume. The system reduces overstocking, lowering holding costs. Less inventory means reduced capital lock-up, improving cash flow. This highlights how small demand changes can enhance both operational and financial efficiency.

β	Total Cost	Holding	Ordering	Transportation	WCR
Sc 1	2185.173	661	920	405.8	199.37
Sc 0	2063.067	765	740	310.5	247.57

TABLE V: Costs sensitivity to changes in demand

B. Varying β and α

Tables VI and VII highlight how variations in the parameters β and α directly affect total and WCR-related costs. As β decreases, total cost and WCR cost decrease significantly, reflecting reduced financial pressure on inventory holding.

Similarly, lowering α results in lower WCR costs and overall expenses. However, higher values α and β increase these costs, leading to greater capital tied up and higher overall expenses. This demonstrates how minor changes in parameter values can lead to substantial cost savings.

β	Total Cost	Holding	Ordering	Transportation	WCR
0.10	2294.433	783	760	336.3	415.13
0.05	2063.067	765	740	310.5	247.57
0.025	1939.283	765	740	310.5	123.78

TABLE VI: Sensitivity of Total Cost to the Parameter β

α	Total Cost	WCR
0.4	2090.867	275.37
0.3	2063.067	247.57
0.2	2035.267	219.77

TABLE VII: Sensitivity of Total Cost to the Parameter α

VI. Discussion

In real-world applications, adapting the model to incorporate practical constraints such as lead times and variable demand is essential to ensure its usability. These factors introduce complexity, but they reflect the operational realities that firms face daily.

The inclusion of WCR financing costs enhances the model's realism, especially for companies with limited liquidity, by capturing the financial implications of inventory and receivables. Optimizing WCR influences key decisions related to inventory allocation, delivery scheduling, and fleet management.

Our model remains adaptable and capable of addressing various supply chain configurations and operational contexts. Ultimately, the integration of financial and logistical dimensions supports more sustainable and informed decision-making in supply chain operations.

VII. CONCLUSIONS

This study demonstrates the significant impact of optimizing the WCR costs. By incorporating the WCR into the IRP, our findings demonstrate significant cost reductions and show how WCR financing costs influence supply chain operations. This integration leads to more realistic inventory management. Additionally, the inclusion of WCR improves decision-making in supplier-to-warehouse allocation, warehouse-to-customer allocation, and vehicle routing. This optimizes resource allocation across periods for better overall supply chain performance.

The inclusion of the WCR financing cost in supply chain optimization bridges the gap between operational and financial decision-making. Taking into account these financial considerations, we contribute to the development of more financially sustainable supply chain strategies, offering a more comprehensive view of resource flows.

Future research should further explore the role of WCR in supply chain optimization, particularly within the IRP framework, and focus on developing metaheuristic approaches to address the complexity of large-scale supply chain problems.

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