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An Integrated Inventory-Routing and Working Capital Requirement Model for a Two-Echelon Supply Chain

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ABSTRACT

In a context of economic volatility, multiple crises, and growing environmental concerns, the optimization of physical and financial flows has become imperative for businesses. In a classical Inventory Routing Problem (IRP), only the physical flow of goods is considered. This paper introduces a link between a two-echelon Inventory Routing Problem and the financial flows of the Working Capital Requirement, where the products are dispatched from warehouses to fulfill customer demand. We propose a two Echelon Inventory Routing Problem under Working Capital Requirement (2E-IRP-WCR) model which allows us to evaluate the integration of physical and financial flows so as to further reduce the total cost, where the total cost consisting of ordering and inventory costs, transportation costs and financial costs. Numerical tests, established for multi-suppliers, multi-warehouses, multi-customers, single-product and finite capacity cases, are presented to demonstrate the pertinence of our approach.

1. INTRODUCTION

In recent years, there has been significant interest in the literature on supply chain management, with a specific focus on the Inventory Routing Problem (IRP) without considering the financial implications [1-6]. In the realm of financial considerations, the optimization of Working Capital Requirements (WCR) has been relatively overlooked in the literature, despite its crucial role in ensuring the funding of operations. Our research operates at the convergence of two distinct research streams. The first pertains to the IRP, while the second concentrates on financial flows within the supply chain.

In this study, we present a Two-Echelon Inventory Routing Problem (2E-IRP) as an expanded version of the traditional IRP. In this problem, a set of suppliers are required to serve a group of customers exclusively through warehouses, and routes need to be defined in both echelons. The objective is to identify a distribution plan that minimizes the overall cost, calculated as the sum of transportation costs, purchasing costs and inventory holding costs. We explore also how integrating WCR into the management of logistical and financial flows can contribute to overall optimization of the supply chain.

Working Capital Management (WCM), particularly through the lens of the WCR, emerges as a critical indicator in both financial and operational management [7]. WCR signifies the liquid funds needed to cover day-to-day expenses associated with operations and sales. Effective WCM plays a pivotal role in a firm's financial health and stability, as it influences available liquidity for investing in growth and innovation.

Generally, the requirement for the WCR arises when a manufacturer's available capital is insufficient to meet production and inventory expenses. This prompts the company to seek a loan from a bank. By constraining the WCR, the borrowed amount is minimized, thereby lowering associated risks. Consequently, this reduction in risk may incentivize the bank to decrease the interest rate on the loan. Moreover, optimizing WCR also frees up internal capital, offering financial relief to companies facing constraints [8-10].

In this light, our research significantly contributes by proposing an innovative approach to study the synchronization of logistical and financial flows by employing the 2E-IRP-WCR as a bridging tool between economic considerations and operational flows. This integration involves synchronizing financial transactions, such as invoicing, payments, and capital allocation, with logistical processes, such as procurement, production, inventory management, and distribution. By integrating these flows, companies aim to enhance efficiency, reduce costs, improve cash flow management, and ultimately achieve strategic objectives such as maximizing profitability.

The paper follows this structure: Section 2 provides a concise literature review on IRP. Section 3 offers a formal description of the problem, while Section 4 introduces the mathematical model's formulation. Section 5 presents the computational results. Lastly, Section 6 offers concluding remarks and outlines future research directions.

2. LITERATURE REVIEW

The most recent literature review by Cuda et al. [11] show the rise of two-echelon distribution systems in various practical scenarios. A supply chain can be viewed as consisting of various stages, with transportation occurring between every consecutive pair of stages, each representing a level within the distribution network, commonly known as an echelon. In recent years, a significant amount of research papers has been published that concentrate on issues related to different variants two-echelon inventory routing problems [12].

For instance, Shirzadi et al. [13] propose an innovative model to optimize the performance of fresh agri-food distribution, integrating traditional costs and modern environmental considerations. Farias et al. [14] introduce a mathematical formulation and a branch-and-cut algorithm to solve a variant of the problem, accounting for indirect deliveries and routing decisions at both levels. Sanghikian et al. [15] employ a hybrid metaheuristic to solve a maritime routing and inventory management problem, integrating a linear mathematical model into their approach.

Guimarães et al. [16] investigate the implementation of the Vendor-Managed Inventory paradigm, wherein a vendor oversees both their own inventory and that of their customers. The research focuses on a system comprising a supplier, multiple warehouses, and a group of customers, with centralized decision-making at the supplier level. It considers various delivery scenarios, including direct deliveries and deliveries through intermediate locations. Mohamed et al. [17] present the two-echelon stochastic multi-period capacitated location-routing problem (2E-SM-CLRP) dealing with uncertain and time-varying demand and cost. This problem represents a hierarchical decision-making scenario with a temporal hierarchy between design and transportation decisions. The research suggests a logic-based Benders decomposition method to tackle this model, aiming to meet the demand for a solution approach that offers high-quality design solutions along with accurate evaluation, even if it requires more time to run. Finally, the authors present an exact method for a stochastic multi-period location-routing problem, providing valuable insights and solutions for this complex and evolving area of research.

Schenekemberg et al. [18] present a metaheuristic that integrates the branch-and-cut algorithm to address a modified version of the IRP, which includes fleet planning in a two-echelon logistics system. The challenge lies in navigating an intricate supply chain arrangement, with plants positioned centrally and tasked with overseeing inventory management and routing for both material acquisition and final product distribution. Simultaneously, they are responsible for making tactical and operational decisions regarding the fleet. The authors' analysis underscores that expenses associated with rentals, cleaning services, and vehicle returns constitute a substantial share of overall logistics costs. Rohmer et al. [19] introduce a perishable product two-echelon inventory-routing problem, where items are conveyed from a supplier to an intermediary warehouse, where potential storage takes place before being further distributed to customer locations using smaller vehicles. Incurred holding costs are associated with storing these products at the depot. The authors formulate the problem as a mixed integer linear program, resolving it through an adaptive large neighborhood search metaheuristic. The objective is to minimize the total transportation and holding costs.

Integrating Working Capital Requirement into the supply chain is a critical component of managing business operations. WCR, which encompasses the funds required to maintain appropriate inventory levels, manage accounts receivable, and manage supplier debts, plays an essential role in the financial and operational stability of a company. Several studies highlight this importance.

Bian et al. [20] addresse the two-level uncapacitated lot-sizing problem while considering the financing cost associated with the WCR. The lot-sizing problem involves determining the quantities to produce or order for multiple periods to minimize total costs while meeting capacity and demand constraints. Enqvist et al. [9] investigate how working capital management affects firm profitability across different business cycles, using evidence from Finland. Working capital management involves managing a company's short-term assets and liabilities to ensure it maintains sufficient liquidity to meet its operational needs.

Pfohl and Gomm [21] explore the concept of supply chain finance, which involves optimizing financial flows within supply chains. They explore the methods and tools available for streamlining financial processes along the supply chain, focusing on working capital management, reducing financial risks, and improving collaboration among supply chain partners. Singhania et al. [22] examined the relationship between working capital management and profitability, specifically focusing on Indian manufacturing companies. By analyzing empirical evidence, the article aims to shed light on how different aspects of working capital management, such as inventory management, accounts receivable, and accounts payable, impact the profitability of manufacturing firms in India.

From this literature review, it's clear that the financial dimension wasn't considered in the two echelons inventory routing problems, despite the fact that managing financial flows constitutes a vital aspect of supply chain management.

Based on the literature review, the originality of this study can be summarized as follows:

1) The majority of studies on IRPs are based on a distribution structure with a single echelon [20, 23]. However, this study focuses on a two-echelon IRP.

2) Our problem diverges from the majority of existing two-echelon problems in two primary aspects:

- Firstly, we account for inventory levels at the warehouses rather than at the customer locations, which differs from the approach taken in many other papers [3, 14, 24].
- Secondly, while the classic version of the Inventory Routing Problem focuses on a system with a single supplier [19], this study delves into a system with multiple suppliers, warehouses, and customers.

3) We are the first to present a WCR model tailored specifically to the 2E-IRP context. This enables us to accurately gauge the WCR throughout the distribution network.

3. MODELING AND DESCRIPTION OF THE PROBLEM

3.1 Problem description

The examined supply chain comprises S suppliers providing a single product to W warehouses, which in turn serve C customers. Each actor in the supply chain is positioned at a node representing its geographical location. Figure 1 illustrates the suggested supply chain and its corresponding stages. The decision maker should select the suppliers, the warehouses, and quantities to acquire. There are vehicles with unlimited capacity for transporting products from the selected suppliers to warehouses with a limited storage capacity, and from warehouses to customers. Inventory capacities of warehouses and customers must be respected. The operational decision items in the upstream and midstream supply chain examined in this study include the following:

- The chosen suppliers;
- The quantity of products delivered from the suppliers to the warehouses (unit);
- The warehouses operated;
- The product quantities stored (unit);
- The quantity of products delivered from the warehouses to the costumers (unit).

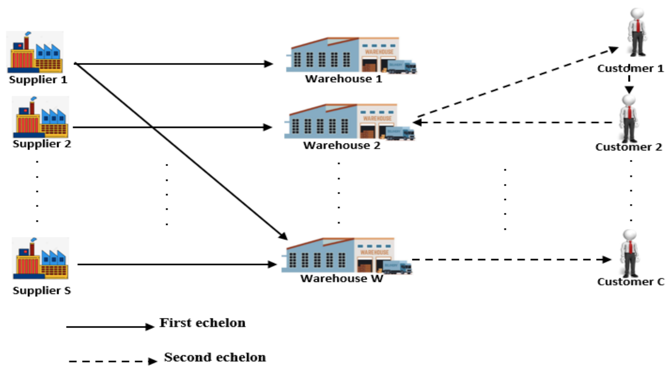

Figure 1. Proposed supply chain

3.2 Assumptions

The formulation of 2E-IRP-WCR and its corresponding model presented in this paper rely on the following assumptions:

- The capacity of all suppliers are equal;
- The warehouse can be supplied by several suppliers at the same time;
- The warehouse can supply several customers at the same time;
- Each warehouse considers an initial stock, but with different carrying costs;
- Supplier assignment will be based on the shortest distance from warehouses.

4. MATHEMATICAL MODEL

In this section, we provide a formalized representation of the mathematical model addressing the synchronization of logistical and financial flows. Our model aims to integrate economic, operational, and environmental aspects, thereby achieving an optimized and balanced solution.

4.1 Model notation

This section shows the notation used in setting the 2E-IRP-WCR model.

4.1.1 Sets and indices

|D|: the number of elements in set D
S: set of suppliers
s: index for suppliers (s=1, 2, …, |S|)
W: set of warehouses
w: index for warehouse (w=1, 2, …, |W|)
C: set of customers
c: index for customers (c=1, 2, …, |C|)

4.1.2 Parameters

Dem_c: demand of customer c
Appro_w: quantity supplied by warehouse w
Cap_w: maximum capacity of warehouse w
Cp_s: maximum capacity of supplier s
$\text{DSW}_{s,w}$: distance between supplier s and warehouse w
$\text{DWC}_{w,c}$: distance between warehouse w and customer c
IO_w: initial inventory of warehouse w
CS_s: unit purchase cost from supplier s
CP_w : unit inventory cost in warehouse w
CT: unit transportation cost
r_c: credit period of customer c
L_s: credit period of supplier s
P_w: product inventory period in warehouse w
β: interest rate for financing WCR per period
Ca_w: turnover of warehouse w
M: a big number
$WCRD$: working capital requirement in number of days
VAT: Value Added Tax

4.1.3 Decision variables

Continuous variables

$Z_{s,w}$: quantity delivered from supplier s to warehouse w
$Y_{w,c}$: quantity delivered from warehouse w to customer c
I_w: inventory level in warehouse w

Binary variables

$B_{s,w}$: binary variable that takes the value 1 if the warehouse w is delivered by the supplier s, otherwise, it takes the value 0

$X_{w,c}$: binary variable that takes the value 1 if the customer c is delivered by the warehouse w, otherwise, it takes the value 0

4.2 The mathematical model

This section delves into the innovative 2E-IRP-WCR mathematical model proposed and each model equation.

4.2.1 Objective function

Eq. (1) gives the total cost function that needs to be minimized. It comprises four terms. These cost terms are, in order, transportation costs, costs of purchasing, inventory holding costs, and financial costs of WCR.

$$\text{Min total cost} = \sum_{s,w}\left(DSW_{s,w} \times B_{s,w} \times CT\right) + \sum_{w,c}\left(\text{DWC}_{w,c} \times X_{w,c} \times CT\right) + \sum_{s,w}\left(CS_s \times Z_{s,w}\right) + \sum_{w}\left(CP_w \times I_w \times P_w\right) + \sum_{w} \frac{Ca_w}{365} \times WCRD \times \beta \quad (1)$$

where,

$$WCRD = \sum_w \sum_c (\frac{Ca_w \times (1 + VAT)}{Ca_w} \times r_c) + \sum_w \sum_s (\frac{Z_{s,w} \times CS_s}{Ca_w} \times P_w) - \sum_w \sum_s (\frac{Z_{s,w} \times CS_s(1 + VAT)}{Ca_w} \times L_s) \quad (2)$$

4.2.2 Constraints

- *Demand Satisfaction Constraint*

Eq. (3) ensures that for each client *c*, the total quantity delivered from warehouses *w* meets or exceeds the demand.

$$\sum_w Y_{w,c} \geq Dem_c \ \forall \text{ c € C} \quad (3)$$

- *Supply Commitment Constraint*

Eq. (4) expresses the supply commitment constraint. For each warehouse *w*, the total quantity supplied from supplier *s* should match the committed supply.

$$\sum_w Z_{s,w} = Appro_w \ \forall \text{ s € S} \quad (4)$$

- *Inventory Balance Constraint*

Eq. (5) maintains a balance between warehouse and supplier inventory.

$$IO_w + Appro_w \geq \sum_c Y_{w,c} \ \forall \text{ w € W} \quad (5)$$

- *Warehouse Capacity Constraint*

Eq. (6) ensures that the total delivery from warehouse *w* to customer *c* does not exceed the warehouse capacity.

$$I_w \leq \text{Cap}_w \ \forall \text{ w € W} \quad (6)$$

I_w is the dynamics of inventory updates. The constraint, given by Eq. (7), ensures that the inventory of warehouse *w* is updated considering initial stock, supplies from suppliers *s*, and customer delivery.

$$I_w = IO_w + \sum_s Z_{s,w} - \sum_c Y_{w,c} \ \forall \text{ w € W} \quad (7)$$

- *Supplier Capacity Constraint*

Eq. (8) ensures that the total delivery from supplier *s* to warehouse *w* does not exceed the supplier capacity.

$$\sum_w Z_{s,w} \leq \text{Cp}_s \ \forall \text{ s € S} \quad (8)$$

- *Binary Variable Logical Constraint*

To ensure a logical linkage between binary variables $Z_{s,w}$ and $B_{s,w}$, the constraint (9) restricts $Z_{s,w}$ to be zero if $B_{s,w}$ is zero.

$$Z_{s,w} \leq M \times B_{s,w} \quad (9)$$

To ensure a logical linkage between binary variables $Y_{w,c}$ and $X_{w,c}$, the constraint (10) restricts $Y_{w,c}$ to be zero if $X_{w,c}$ is zero.

$$Y_{w,c} \leq M \times X_{w,c} \quad (10)$$

5. COMPUTATIONAL RESULTS

5.1 Input data

The mathematical model in Section 4.2 is evaluated using simulated parameters. Importantly, since no real data is accessible for the simulated parameters, a series of parameter values are generated randomly. The values generated for these parameters are reported in Tables 1-4. We further assume that each node, denoted by k ($k \in S \cup W \cup C$), is defined by its randomly generated geographical coordinates (X_k, Y_k) within a 100*100 distance unit grid. Additionally, the distance d_{ij} between any two locations i and j is computed using the Euclidean distance $d_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}$.

This example is designed to illustrate how making integrated decisions regarding the selection of recipients, the quantity of deliveries, and the chosen routes can influence both the WCR and transportation costs.

Table 1. Numerical example parameter values

Parameter	Value
|S|	10
|W|	3
|C|	20
β	0.05
VAT	0.2
CT(€)	2

Table 2. Warehouses' parameter values

W	1	2	3
Appro	100	110	120
Cap	2500	1800	2000
Ca(€)	5000	2500	4000
CP(€)	9	8	11
P	4	10	8
IO	1000	1000	1200

Table 3. Suppliers' parameter values

s	1	2	3	4	5	6	7	8	9	10
Cp	50	50	50	50	50	50	50	50	50	50
CS(€)	3	7	1	5	6	5	3	1	2	4
L	3	2	2	3	5	3	2	2	3	5

Table 4. Customers' parameter values

C	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Dem	70	80	90	100	80	70	110	120	100	90	60	70	80	90	110	90	100	80	70	80
r	1	1	1	2	1	1	1	3	1	1	1	1	5	1	1	1	1	1	1	1

5.2 Results and discussion

This section provides an overview of the computational experiments performed to assess the quality of the obtained solutions. The mathematical model is solved with the ILOG CPLEX optimization Studio 22.1.0 solver. The experiments were conducted on a laptop with an Intel(R) Core(TM) i7-1065G7 @ 1.50GHz processor and 8GB of RAM, operating on Windows 11 Pro. The Table 5 shows the optimal solutions obtained by the CPLEX solver.

The results provided in Figure 2 show which nodes to serve, the quantity to deliver, and the routes for vehicles, with the aim of minimizing the total cost. The Figure 2 indicates that the warehouse 1 is served by the suppliers 2 and 10 with a quantity of 50 units each, and it delivers to customers 6, 1, 4, 2 and 5 the quantities 70, 70, 100, 80 and 80, respectively. It has also an inventory holding equal to 700 units. The warehouse 2 is served by the suppliers 4, 5 and 10 with respectively the quantities of 50, 10 and 50 units, and it delivers to customers 12, 13, 15, 14, 11, 10, 9 and 3 the quantities 70, 80, 110, 90, 60, 90, 100 and 90, respectively. It has also an inventory holding equal to 420 units. Regarding the warehouse 3, it is served by the suppliers 3, 5 and 7 with respectively the quantities of 50, 20 and 50 units, and it delivers to customers 16, 18, 19, 17, 20, 8 and 7 the quantities 90, 80, 70, 100, 80, 120 and 110, respectively. It has also an inventory holding equal to 670 units.

Table 5. The optimal results obtained

Total Cost* (€)			
171 965.296			
Transportation Costs* (€)	**Purchasing Costs* (€)**	**Inventory Holding Costs* (€)**	**WCR* (€)**
52 972	1230	117 697.378	65.918

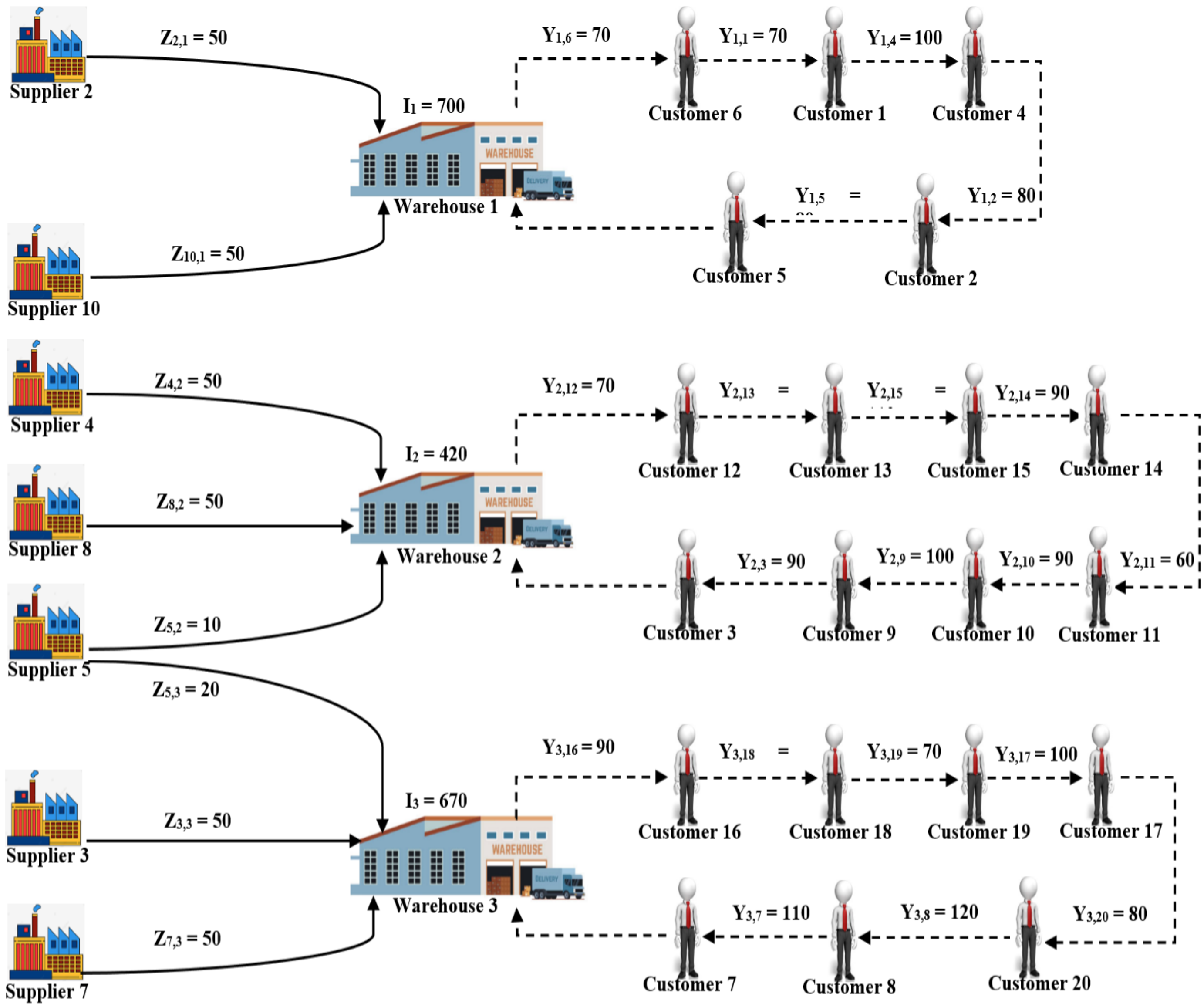

Figure 2. Routing, inventory and shipped product representation

5.3 Sensitivity analysis

Another series of experiments has been carried out to gauge and analyze the sensitivity of the proposed model. The aim of this analysis is to validate the simulation outcomes and examine how the optimal solution reacts to variations in input model parameters. Table 6 presents three different problem sizes (small, medium, and large) alongside their respective configurations and instances. These instances were thoughtfully chosen to represent a wide range of problem sizes and complexities. Each size category underwent three instances; for instance, S1, S2, and S3 represent the three instances of small-sized problems. The effects of varying these parameters from the basic case are presented in Table 7.

In summary, the findings presented in Table 7 offer valuable insights into the performance of the CPLEX solver and underscore the challenges encountered when tackling large optimization problems. Examining the results of total, transportation, and inventory costs allows for a deeper understanding of the solver's performance. Figure 3 presents the evolution of all these costs, for the different instance sizes. By incorporating the financing cost of the WCR, we particularly observe the trade-off between total cost and inventory costs, as evidenced by the nearly identical appearance of the corresponding curves. An increase in customer orders not only reduces warehouse inventory costs but also the WCR (as indicated in the last column of Table 7), resulting in decreased financial costs. On the other hand, transportation costs fluctuate as the number of customers increases from one instance to another and so the routes taken by vehicles will automatically change.

The integration of financial indicators such as the WCR directly impacts cash flow management. A reduced WCR indicates improved cash liquidity, which can be allocated strategically for growth opportunities or invested to generate higher returns.

The integration of logistical and financial flows yields several managerial insights and practical implications:

- Improved Cost Management: By aligning logistical and financial processes, companies can gain better visibility into the costs associated with each stage of the supply chain.
- Enhanced Decision-Making: Integration enables managers to make more informed decisions by considering both logistical and financial implications simultaneously. For example, when selecting suppliers or transportation routes, managers can evaluate not only logistical efficiency but also the financial impact on working capital, inventory costs, and cash flow.
- Optimized Inventory Management: Integrating logistical and financial flows facilitates better inventory management practices. Companies can minimize excess inventory levels, reduce carrying costs, and improve inventory turnover rates by aligning inventory levels with financial objectives and customer demand patterns.
- Efficient Cash Flow Management: Integration helps optimize cash flow by synchronizing financial inflows and outflows with logistical operations. This allows companies to better manage working capital, reduce the need for external financing, and improve overall liquidity.
- Competitive Advantage: Companies that successfully integrate logistical and financial flows gain a competitive advantage by operating more efficiently, reducing costs, and improving customer service levels. This integration allows them to adapt quickly to changing market conditions and customer demands, positioning them for long-term success.

Table 6. Characteristics of the different instances

Classification	Instance	Problem Size (|S|×|W|×|C|)
	S1	10×2×10
Small	S2	10×2×15
	S3	10×2×20
	M1	15×3×15
Medium	M2	15×3×20
	M3	15×3×25
	L1	30×3×20
Large	L2	30×3×25
	L3	30×3×30

Table 7. Results of sensitivity analysis

Instance	Total Cost* (€)	Transportation Costs* (€)	Purchasing Costs* (€)	Inventory Holding Costs* (€)	WCR* (€)
S1	106 318.24	40 338	710	65 280	-9.75
S2	87 435.34	36 204	710	50 520	0.53
S3	98 129.50	62 012	710	35 400	3
M1	193 500.59	41 404	1340	150 840	-33.36
M2	159 168.04	40 142	1340	117 760	-29.58
M3	145 358.83	41 512	1340	102 560	-21.26
L1	151 271.54	32 902	1160	117 760	-550.45
L2	137 462.34	34 272	1160	102 560	-529.66
L3	153 389.35	62 822	1160	89 920	-512.65

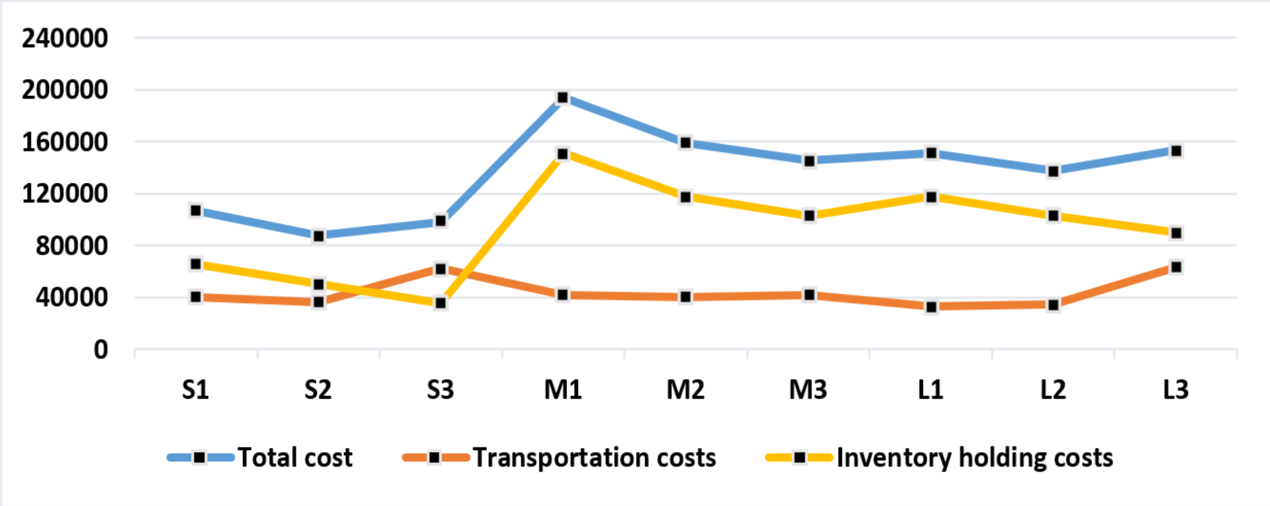

Figure 3. Evolution of total, inventory and transportation costs for the different instance

6. CONCLUSION

In this paper, we have dealt with the two echelons inventory problem by considering the financial dimension. We introduce a novel generic model for assessing working capital requirements related to IRP. Such a model enables the tracking of WCR variations throughout the routing horizon. It is designed to accommodate scenarios involving multiple suppliers, warehouses, and customers. Numerical experiments are conducted to demonstrate the efficacy of our 2E-IRP-WCR model. The results highlight the diminished incentive for inventory holding, attributed to the significant escalation in financial costs.

The synchronization of logistical and financial flows offers a transformative approach to supply chain management that goes beyond operational efficiency. The presented model for synchronizing logistical and financial flows offers a multitude of advantages that extend beyond the optimization of operational and financial metrics. By aligning inventory management, transportation decisions, and financial considerations, organizations can achieve a holistic perspective on their supply chain dynamics. The model's consideration of the WCR in tandem with logistical decisions further emphasizes the interconnected nature of supply chain and financial performance. This approach not only aids in the effective allocation of resources but also contributes to enhanced decision-making capabilities.

Future research could prioritize integrating environmental impact considerations into the proposed mathematical model by minimizing CO_2 emissions. Additionally, further investigation could explore the implementation of a two-echelon closed-loop supply chain.

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