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Optimal supply network with vendor managed inventory in a healthcare system with RFID

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Abstract: We consider a supply network for a medical implant manufacturer within the healthcare system, wherein the manufacturer oversees multi-hospital warehouses under a vendor-managed inventory (VMI) policy and utilizes RFID technology to reduce the network's total costs and enhance customer service. The manufacturer must determine the warehouse locations, inventory policies, and RFID investments to minimize total costs. In this research, we develop a mixed-integer nonlinear program model to formulate the integrated decision problem, which combines the location-inventory problem with the allocation and assignment of RFID technology, including its investment level. A real-world problem is resolved and analyzed using the proposed approach.

Keywords: Supply chain, vendor managed inventory, healthcare system, location-inventory, and RFID.

1. INTRODUCTION

The healthcare sector has witnessed a steady increase in expenditure over the past two decades, with Healthcare Networks (HCNs) experiencing an average annual growth rate of four percent from 2000 to 2009, a trend notably attributed to hospitals, accounting for 29% of the overall increase (Volland et al., 2017). Notably, inventory logistics costs stand as the second highest-cost segment within hospital operations (Ross & Jayaraman, 2009). Over the last twenty years, scholars have increasingly recognized the significance of integrated location and inventory supply chain network optimization in mitigating healthcare expenditure (Tlahig et al., 2013).

Within the healthcare sector, management grapples with multifaceted challenges, including the inherent complexity of healthcare systems, escalating supply chain (SC) costs, the delicate balance between quality and cost, delivery delays, vendor product availability, and the omnipresent unpredictability and uncertainty (Feibert, 2017). These challenges have prompted a critical reassessment of operational strategies among vendors, particularly within the healthcare domain, necessitating a thorough exploration of avenues for optimization.

This study addresses a real-world challenge faced by a manufacturer supplying medical implants to a network of hospitals in Canada. The manufacturer or vendor supplies three distinct types of medical implants - a heart valve, an artificial knee, and a hip - to various hospitals within the healthcare network. Employing a vendor-managed inventory contract as the replenishment system for select hospitals, the manufacturer confronts the pivotal challenge of determining whether to allocate storage facilities at each hospital and how to strategically assign the replenishment system accordingly.

The problem arising in the hospital supply chain differs from other warehouse networks: medical implants are usually very expensive and have expiration dates. Therefore, inventory accuracy and transparency are crucial. Additionally, due to the unique needs of patients, shortages are not allowed. Thus, multiple delivery options are provided in addition to VMI.

RFID technology emerges as a critical enabler in Waste Inventory Reduction (WIR) by effectively managing and identifying defective, lost, and expired items. Leveraging RFID's automated verification, monitoring, and tracking features significantly mitigates the incidence of defective and expired items reaching consumers. Given its potential to reduce inventory waste, the vendor opts to adopt RFID technology to curtail total network costs and enhance profitability, a strategy underscored by Walmart's recent directive to its suppliers (Lee & Lee, 2010). Our research actively studies inventory optimization by integrating RFID technology to enhance ordering and holding efficiencies. This technology plays a pivotal role in reducing healthcare networks' overall costs by streamlining ordering and holding operations.

Previous research on location-inventory supply chain network problems has predominantly focused on the assignment of storage facility locations and replenishment policies under Vendor Managed Inventory (VMI) contracts. While various industries have adopted single replenishment systems such as Direct Delivery by courier under Retailer Managed Inventory (RMI) frameworks, healthcare settings have typically utilized either VMI, Just-In-Time (JIT), or Direct Delivery Policy

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(DDP) independently of storage facility assignments (Pan, 2016).

In our study, we integrate hospital storage facility location assignments with VMI policies and RFID technology allocation decisions alongside their respective investment levels. We formulate this problem as a mixed-integer non-linear program (MINLP) model aimed at minimizing total supply network costs within a VMI supply network.

Our research contributes to the field in three significant ways: firstly, by presenting an optimal integrated location-inventory supply chain network and mathematically modeling it; secondly, by exploring the application of RFID investment factors in holding and ordering operations and developing analytical methodologies to determine optimal RFID investment levels for these factors; and thirdly, by identifying the impact of RFID-related cost savings on storage facility location assignments within hospitals.

The subsequent sections of this paper are structured as follows: a succinct review of pertinent literature is provided in the subsequent section, followed by a detailed exposition of the proposed model in Section 3. Computational analyses are conducted in Section 4 to elucidate findings and benefits, while Section 5 concludes the research and outlines avenues for future investigation.

2. LITERATURE REVIEW

2.1 VMI in the Healthcare Network

Healthcare environments have encountered significant challenges stemming from escalating healthcare costs, intensified competition, and increasingly stringent requirements and regulations. These shifts have accelerated the spotlight on supply chains in healthcare, which have transitioned towards a more demand-driven paradigm (Krichanchai & MacCarthy, 2017). Managing supply chain inventory poses a substantial challenge for numerous firms striving to concurrently minimize costs and enhance customer service in today's fiercely competitive business landscape (Daskin, Coullard, & Shen, 2002). Lotfi et al. (2022) advocate for the integration of hybrid fuzzy and data-driven robust optimization with a Vendor Managed Inventory (VMI) approach to enhance inventory management systems and address uncertainty and disruptions, particularly in the context of COVID-19 conditions.

VMI is characterized as a collaborative replenishment delivery strategy wherein vendors assume responsibility for all replenishment decisions and associated costs, diverging from the traditional model where buyers handle such tasks. It represents a collaborative strategy aimed at optimizing product availability at minimal costs. While VMI policies can vary in terms of frequency, the underlying principle remains the creation of a demand-driven supply chain (Mateen et al., 2015).

Although studies on integrated location-inventory network problems are relatively nascent, recent research endeavors have aimed to address this gap. Liao et al. (2011) introduce a location-inventory model aimed at optimizing service levels while minimizing associated inventory and transportation costs. Similarly, Shang et al. (2022) propose a robust optimization model for healthcare location inventory problems with VMI support. However, notable gaps exist as these studies do not account for the role of RFID technology and its potential impact.

This research seeks to address the challenge of meeting the demands of a chain of hospitals, irrespective of location and demand size, by integrating both VMI and direct delivery policies within the healthcare network, contingent upon the assignment of storage facilities' locations. Additionally, we explore the implementation of safety stock levels for all warehouses assigned at hospitals to mitigate inventory waste. Furthermore, we analyze the potential reduction in inventory waste at hospitals through the adoption of RFID technology.

2.2 RFID Technology in the Healthcare Network

According to recent research and statistics, RFID technology stands out as a premier information technology (IT) investment tool for fostering company growth. Its business value lies in facilitating the easy and cost-effective collection and sharing of information within supply chains, thereby significantly enhancing supply chain visibility (Ivanov et al., 2023; Shams-Shemirani et al., 2023). Improved supply chain visibility correlates with numerous benefits, including reduced stock-out occurrences and lead times, elimination of inventory waste, lower labor costs, decreased transaction expenses, and enhanced customer satisfaction, as well as improved inventory and logistics management (Lee & Lee, 2010; Anand & Fosso Wamba, 2013; Li et al., 2016).

Inaccuracy within the inventory management system often arises from discrepancies in warehouse records, resulting in lost and expired items. This issue can detrimentally affect vendor profits, with lost sales and increased inventory costs averaging around 10%. Addressing the reduction in defective and expired items not only enhances customer service through timely order deliveries but also contributes to improved overall supply chain efficiency (Sarac et al., 2010).

While RFID implementation has proven to lower overall supply chain costs and enhance administrative quality, it is important to acknowledge that the technology entails higher implementation and maintenance service costs compared to traditional tracking technologies like barcodes. Nonetheless, the resultant efficiency gains translate into overall cost savings, manifested through reduced inventory costs, improved labor efficiency, streamlined administrative processes related to material and purchase orders, and minimized waste and rejected items (Feibert, 2017; Lee & Lee, 2010).

Lee and Lee (2010) and Li et al. (2016) introduce RFID technology as an investment evaluation model (IEM) based on Cost-Benefit Analysis (CBA) within an Economic Order Quantity (EOQ) inventory system framework, focusing primarily on continuous replenishment systems without integrating RFID assignment with storage facility location assignments. Abugabah et al. (2023) conduct a systematic literature review, primarily examining real-world experiences of RFID adoption in hospitals, with findings indicating a limited number of cases employing RFID in hospitals as pilot studies, yielding benefits such as improved equipment management, enhanced safety, and better patient flow prediction.

Our study presents an RFID investment evaluation model, and integrates it with the inventory-location assignment problem. We position RFID technology as a tool for cost reduction and inventory waste mitigation. To the best of our knowledge, our study represents the first attempt to integrate the RFID investment evaluation model and its investment level with warehouse location assignment. By examining the relationships between model parameters, variables, and the level of RFID investment within the inventory-location assignment problem, our proposed model not only offers immediate utility but also underscores the feasibility of employing analytical models within healthcare supply networks to assess RFID investments.

3. MATHEMATICAL MODEL

3.1 Problem Statement

In the problem under study, the vendor aims to minimize total costs by addressing three major decision problems simultaneously:

The first pertains to the location assignment problem, a strategic decision where the vendor must determine whether to establish a warehouse at a hospital. This decision hinges on associated costs related to ordering, holding, transportation, fixed costs, and setup costs. Alternatively, the vendor may opt for a direct delivery policy (DDP) with same-day delivery to hospitals lacking assigned warehouses.

The second decision problem involves replenishment inventory decisions, operational in nature. Here, the vendor must determine the size of orders, the number of orders to be delivered to hospitals, and the appropriate safety stock level within hospitals equipped with assigned warehouses.

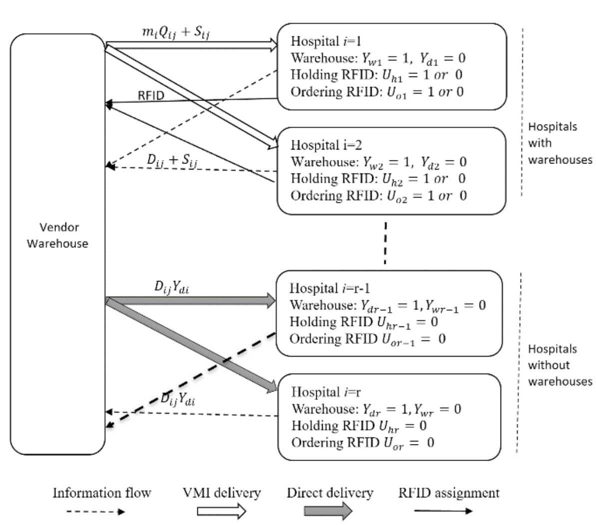

Fig. 1 VMI and RFID assignment chart based on the location-inventory assignment problem.

The third problem concerns the allocation assignment of implementing RFID technology at hospitals with assigned warehouses to enhance ordering and holding efficiencies. Two investment factors, ordering and holding efficiencies, are considered. These efficiencies are realized by minimizing inefficiencies related to ordering and holding activities, and they are largely dependent on the investment intensity of RFID technology. RFID technology enhances both levels, reducing fixed order costs per order and holding efficiencies in various ways. Ordering and holding efficiencies refer to the degree to which the RFID investment cycle impacts holding costs per item in ordering and holding operations. Figure 1 illustrates the VMI and RFID assignment chart, depicting information and material flow based on the location-inventory assignment problem in a chain of hospitals with and without assigned warehouses.

3.2 Model Assumptions

- All hospitals' demands for all products are deterministic.
- The demand should be satisfied without any shortage.
- Ordering and holding efficiencies follow a natural exponential function, with RFID investment costs enhancing these efficiencies (Lee & Lee, 2010; Billington, 1987).
- Transportation costs per item are assumed for delivery to hospitals without assigned warehouses via courier, with rates based on Purolator's rates and service charges for direct same-day delivery.
- Ordering costs are assumed to be fixed.
- A continuous review policy is used for VMI.

3.3 Mathematical Modeling

3.3.1 Indices

i	*an index for hospital; i = 1, 2…, r*
j	*an index for product; j= 1, 2…, n*

3.3.2 Notations

h_{ij}	Holding cost for hospital i for product j
R_i	Rental space cost per f^3 per time unit.
F_i	The total space size of the warehouse at the hospital i per time unit (f^3).
C_{ij}	Transport cost per delivery order to hospital i for product j
FC_i	Fixed setup cost for having a hospital i
CAP_{Truck}	The capacity of truck
D_{ij}	Demand of hospital i of product j per time unit
f_i	The volume of one item of the product j (f^3)
K_i	Unit truck shipment and ordering cost for i
A_i	Ordering costs for hospital i
c_{ij}	Transport cost per item to hospital i for product j
N	The highest ordering efficiency achievable by S_i investment in RFID technology
β	Exponential parameter for ordering efficiency
U	The lowest holding efficiency achieved when there is no investment in RFID technology

Z	The highest holding efficiency achievable by S_i investment in RFID techno
μ	Exponential parameter for holding efficiency

3.3.3 Decisions Variables

Y_{di}	1 if the shipment is delivered directly to hospital i, 0 otherwise
Y_{wi}	1 if hospital i has a warehouse facility, 0 otherwise.
Q_{ij}	The order size quantity of product j delivered to hospital i with assigned warehouse
m_i	The number of shipments to hospital i with assigned warehouse
SS_{ij}	Safety Stock level at the hospital i with assigned warehouse for product j
S_i	RFID technology investment level for ordering efficiency for the hospital i
X_i	RFID technology investment level for holding efficiency for hospital i
V_i	Ordering efficiency which is the degree that the ordering cost at the hospital i reduced by RFID investment S_i (Lee & Lee, 2010; Li et al., 2016).
W_i	Holding efficiency, which is the degree that the inventory holding cost at hospital i reduced by RFID investment X_i.
U_{hi}	1 if RFID technology is installed for holding operation efficiency improvement in the warehouse, the minimal investment is B_h.
U_{Oi}	1 if RFID technology is installed for ordering operation efficiency improvement in the warehouse, the minimal investment is B_O.

3.3.4 Objective Function

$$Min\, TC_{VMI} = \sum_{i=1}^{r}\sum_{j=1}^{n}(A_i + c_{ij})\, D_{ij}Y_{di} + \sum_{i=1}^{r} K_i V_i m_i + \sum_{i=1}^{r}\sum_{j=1}^{n} W_i h_{ij}(\frac{Q_{ij}}{2} + SS_{ij}) + \sum_{i=1}^{r}(FC_i + F_iR_i)Y_{wi} + \sum_{i=1}^{r} X_i + \sum_{i=1}^{r} S_i \quad (1)$$

The objective is to minimize the total cost, which is composed of several terms. The first term encompasses the sum of ordering and courier transportation delivery costs per item for all product demands and all hospitals without assigned warehouses. The second term represents the cost of combined ordering and trucking transportation for all orders delivered to hospitals with assigned warehouses. The third term accounts for the holding cost per item, which includes the summation of the average order quantity and safety stock level for all products at hospitals with assigned warehouses, incorporating the improvement impact of holding efficiency as a function of RFID investment level. The fourth term comprises the total costs of the fixed cost of setting up warehouses at hospitals and the rental rate cost for space assigned by hospitals to vendors for warehousing purposes. The fifth and sixth terms denote the RFID ordering and holding investment costs, respectively.

The main constraints of the model are given as follows.

S.t.:

$$Y_{di} + Y_{wi} = 1 \qquad for\ \forall = 1, \dots, r \quad (2)$$

Network constraints: each hospital has either a warehouse with VMI delivery or a direct delivery with no assigned warehouse.

$$\sum_{j=1}^{n} Q_{ij} \le Cap_{truck} \quad for\ \forall\ i = 1, \dots, r \quad (3)$$

Truck space constraint: the total order size quantities for all products per order that will be delivered to hospital i with assigned warehouse should be equal or less than the capacity of the truck.

$$\sum_{j=1}^{n} (Q_{ij} + SS_{ij}) f_j \le Y_{wi}F_i \quad for\ \forall\ i = 1, \dots, r \quad (4)$$

Warehouse space constraint: the total size of all order size quantities and safety stock level for all products per order should be less or equal than the available space for hospital i with the assigned warehouse.

$$Q_{ij} \le Y_{wi}M \quad for\ \forall\ i = 1, \dots, r\ and\ j = 1, \dots, n \quad (5)$$

There is an order quantity for each product for hospital i only with the assigned warehouse.

$$SS_{ij} \ge Y_{wi}\, g_{ij} \qquad for\ \forall\ i = 1, \dots, r\ \ and\ j = 1, \dots, n \quad (6)$$

Lower bound safety stock level constraint: for hospital i with the assigned warehouse.

$$m_i \le Y_{wi}M \qquad for\ \forall\ i = 1, \dots, r \quad (7)$$

The number of orders shipped to the hospital i should be zero if there is not an assigned warehouse.

$$Q_{ij}m_i \ge D_{ij}Y_{wi} \qquad for\ \forall\ i = 1, \dots, r\ and\ \forall\ j = 1, \dots, n \quad (8)$$

Demand satisfaction constraint: all number of orders of the order quantity of each product j which will be delivered to the hospital i with assigned warehouse should be equal or greater than the demand of the product j at hospital i with the assigned warehouse.

$$W_i = (Z + (U - Z)e^{-\mu X_i})\, Y_{wi} \qquad for\ \forall\ i = 1, \dots, r \quad (9)$$

Holding efficiency and RFID investment constraint: the holding efficiency level responds as an exponential function with RFID holding investment level X_i. Note that a lower value of the holding efficiency means a higher efficiency (Lee & Lee, 2010; Billington, 1987).

$$V_i = \left(N + (M - N)e^{-\beta S_i}\right) Y_{wi}$$

$$for\ \forall\ i = 1, \dots, r \qquad (10)$$

Ordering efficiency and RFID investment constraint: the ordering efficiency level responds as a function of RFID ordering investment level S_i. Note that a lower value of the ordering efficiency means a higher efficiency (Lee & Lee, 2010; Billington, 1987).

It is noted that the above model is incomplete due to the space limit but just presents the main components. The complete model is available upon request. The problem is a mixed-integer nonlinear program model. We use GAMS to solve the problem with the real-world case in the next section.

4. ANALYSIS AND DISCUSSION

In this section, we applied the MINLP mathematical model to a real-world problem and analyzed the performance of various RFID investment strategies. These strategies include having an objective function with no RFID investment (Option A), RFID investment solely in ordering operations (Option B), RFID investment solely in holding operations (Option C), and simultaneous RFID investment in holding and ordering operations (Option D).

Table 1. Performance of simultaneous RFID investment.

Activity	NO RFID Option A	RFID in ordering Option B	RFID in holding Option C	RFID in ordering & holding Option D
Total cost ($)	2,205,299	2,200,909	2,105,938	2,067,082
Avg. ordering efficiency	1	0.215	1	0.316
Avg. holding efficiency	1	1	0.316	0.215
Total RFID investment in ordering operations ($)	0	8000	0	5000
Total RFID investment In holding operations ($)	0	0	6000	17000
Total RFID investment in holding & ordering ($)	0	8000	6000	22000
# of hospitals with VMI	32	32	43	36
# of hospitals with DDP	115	115	104	111
# of hospitals with RFID in holding operations	0	0	6	17
# of hospitals with RFID in ordering operations	0	8	0	5
Cost Reduction	0	0.20%	4.51%	6.27%
GAMS Solver	BARON	BARON	KNITRO	KNITRO
CPU Time (Sec)	3.17	88.71	49996.79	70813.94

The numerical analysis of holding and ordering efficiencies reveals a consistent pattern in total cost reduction. Both the ordering efficiency (Option B) and holding efficiency (Option C) exhibit a minimum demand threshold for RFID investment. This threshold is derived from the experiment that shows no feasible solutions for RFID investment exist at demand levels below 110. Also, we found that as the ordering efficiency V_i improves, the order quantity Q_{ij} decrease; when the holding efficiency X_i improves, the order quantity Q_{ij} increase. Table 1 illustrates the reduction in total cost achieved by simultaneous RFID investment decisions (Option D) compared to sole RFID investment decisions (Option B and C, independently).

RFID investment significantly influences the location assignment of storage facilities within the hospital network chain. The reduction in total costs resulting from implementing RFID technology affects the allocation of warehouses across hospitals. This impact is exemplified in Table 1: when RFID technology is not utilized (Option A), 32 hospitals have warehouses assigned, while the remaining 115 hospitals lack assigned warehouses. However, this arrangement changes with the implementation of simultaneous RFID investment (Option D), where 36 hospitals have warehouses assigned, and the remaining 111 hospitals do not. Similar patterns are observed in the analysis of the impact of sole RFID investment (Option B and C) on the location assignment of storage facilities, mirroring the findings of simultaneous RFID investment (Option D).

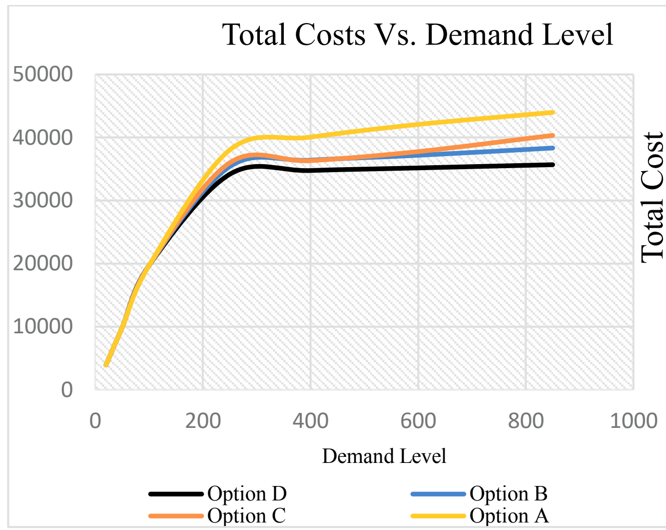

Fig. 2 The impact of demand level on the total costs obtained by different RFID options.

Figure 2 illustrates the correlation between the demand level (annual demand) and the total cost of the objective functions. Option A (No-RFID) exhibits the highest total cost value, while Option D demonstrates the lowest total cost value. Additionally, we conducted further comprehensive numerical analyses to glean managerial insights into the relationship between RFID investment and demand levels.

5. CONCLUSIONS

In our study, we undertake a comprehensive integration of location assignment for storage facilities and corresponding replenishment policies, alongside the allocation assignment of RFID technology and its investment levels. This integration enables us to implement two distinct replenishment policies, namely Vendor-Managed Inventory (VMI) and direct delivery policies, across a network of hospitals, contingent upon the presence of warehouses at each hospital. Strategically positioning the adoption of RFID technology at designated warehouses allows vendors to optimize their inventory management practices, with the aim of mitigating issues related to expired, lost, and defective products.

Our research introduces a novel RFID investment evaluation method intricately linked with the location assignment of storage facilities within the hospital network. This innovative approach considers the RFID investment level as a crucial factor in enhancing ordering and holding efficiencies. By determining optimal RFID investment levels for these efficiencies, our methodology aims to enhance the overall operational performance of the supply chain. We develop a Mixed-Integer Nonlinear Programming (MINLP) model alongside the RFID investment evaluation method to address the location-inventory supply chain network problem. This integrated approach empowers vendors with a comprehensive understanding, enabling informed strategic and operational decisions in managing the complex dynamics of location assignments, inventory policies, and RFID technology integration.

While our research primarily focuses on integrating location-inventory assignment with RFID and its investment level assignment, there are potential avenues for future research. For instance, extending the model to accommodate non-deterministic conditions, such as stochastic or fuzzy demand, could provide valuable insights. In this paper, we assume demand to be deterministic, but stochastic demand offers opportunities to significantly reduce overall network costs by leveraging RFID technology to mitigate shortages and overstock incidents. Additionally, our research assumes RFID technology to be perfect; future studies could explore the implications of imperfect RFID technology on the objective function and decision variables of the study. Another limitation of the research is the assumption of RFID impacts on inventory holding and ordering costs. More investigation about the impacts of RFID technology on inventory under different circumstances is needed.

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