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Optimal Supply Network with Vendor Managed Inventory in a Healthcare System with RFID Investment Consideration

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Optimal Supply Network with Vendor Managed Inventory in a Healthcare System with RFID Investment Consideration

by

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Optimal Supply Network with Vendor Managed Inventory in a Healthcare System with RFID Investment Consideration

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DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis is a joint research wherein all key ideas, primary contributions, experimental designs, data analysis, and interpretations were performed by the author and Dr. Guoqing Zhang as the advisor.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have optained written permission from each of the co-author(s) to include the above material(s) in my thesis.

I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

II. Previous Publication

This thesis includes three original papers that have been previously submitted for publications in peer reviewed journals, as follows:

Thesis Chapter	Publication title/full citation	Publication status
Chapter 2	Almanaseer, M., Zhang, G., 2019. Optimal supply network with vendor managed inventory in a healthcare system with RFID investment consideration.	Submitted to Expert Systems with Applications
Chapter 3	Almanaseer, M., Zhang, G., 2019. Optimal supply network with vendor managed inventory in a healthcare system with stochastic demand	Will be submitted soon
Chapter 4	Almanaseer, M., Zhang, G., 2019. VMI as Preferable to a Traditional RMI System in an Optimal Healthcare Supply Network: A Comparative Study	Will be submitted soon

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ABSTRACT

Supply Chain Management in the healthcare sector faces several significant challenges, including complexity in healthcare systems, high supply chain costs, balancing quality and costs, delay in delivery, product availability from vendors, inventory waste, and unpredictability and uncertainty. Among those challenges, having an effective inventory management system with an optimal supply network is important to improve the match between supply and demand, which would improve the performance of for healthcare firms.

Vendor Managed Inventory (VMI) system is a replenishment solution in which the vendor monitors and decides the time and the quantity of the inventory replenishment of their customers subject to their demand information exchange. A VMI contract in the location-inventory assignment problem is a decision tool for management in the healthcare industry, in which it enables the management to have a cost and service effective decision tool to critically re-evaluate and examine all areas of operations in a SC network looking for avenues of optimization.

This dissertation is based on a real-world problem arising from one of the world's leading medical implant supply company applied to a chain of hospitals in the province of Ontario. The chain of hospitals under study consists of 147 hospitals located in Ontario, Canada. The vendor is a supplier of three types of medical implants (a heart valve, an artificial knee, and a hip).

In Chapter 2 of this dissertation, we present an optimal supply healthcare network with VMI and with RFID consideration, in which we shed light on the role of the VMI contract in the location-inventory assignment problem and integrate it with both the replenishment policy assignment and the Radio Frequency Identification (RFID) investment allocation assignment in healthcare SC networks using both VMI and direct delivery policies. A numerical solution approach is developed in the case of the deterministic demand environment, and we end up with computational results and sensitivity analysis for a real-world problem to highlight the usefulness and validate the proposed model.

We extend our research of integrating the VMI contract in the location-inventory assignment problem with the replenishment policy assignment under a deterministic demand environment to include the stochastic demand environment. The impact of the

uncertainty of the demand as a random variable following two types of distributions, normal and uniform distributions, is studied in Chapter 3.

Motivated by the lack of investigations and comparative studies dealing with the preference of dealing with VMI contracts to other traditional Retailer Managed Inventory (RMI) systems, we provide in Chapter 4 of this dissertation a comparative study in which we compare the total cost of the VMI system with another two situations of traditional RMI systems: first, a traditional RMI system with a continuous replenishment policy for all hospitals and with assigned storage facilities and second, a traditional RMI system with a direct delivery policy for all hospitals without assigning a storage facility.

Computational results, managerial insights, sensitivity analysis, and solution methodologies are provided in this dissertation.

Keywords: Vendor Managed Inventory, healthcare system, location-inventory, RFID technology, supply-chain network, stochastic demand, location-inventory assignment problem, and retailer managed Inventory.

DEDICATION

To the souls of my mother, father and my mother-in-law, to my brothers, sisters, and my entire both families, especially my father-in-law Dr. Yousef Ghidan. To my extraordinary wife Dr. Sumar Ghizan and to my lovely kids: Ala, Abdullah, and my baby Adam.

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I would like to extend my thanks to the other members of my committee, Dr. Walid Abdul-Kader, Dr. Michael Wang, and Dr. William Anderson for their honest remarks. Their insightful comments were crucial for positively improving this dissertation.

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TABLE OF CONTENTS

LIST OF TABLES

.

LIST OF FIGURES

LIST OF ABBREVIATIONS/SYMBOLS

VMI: Vendor Managed Inventory

SC: Supply Chain

RFID: Radio Frequency Identification

RMI: Retailer Managed Inventory

MINLP: Mixed Integer Non-Linear programming

SMINLP: Stochastic Mixed Integer Non-Linear programming

MIP: Mixed Integer Programming

GAMS: General Algebraic Modeling System

HCN: Health Care Network

WIR: Waste Inventory Reduction

JIT: Just-In-Time

DDP: Direct Delivery Policy

LIAP: Location-Inventory Assignment Problem

MOLIP: Multi-Objective Location–Inventory Problem

SOO: Single Objective Optimization

MOO Multi-Objective Optimization

LRPA: Location-Replenishment Policy Assignment

RFIDILB: RFID Investment Lower Bound

CBA: Cost-Benefit Analysis

EOQ: Economic Order Quantity

EIEF: Efficiency-Investment Exponential Function

IEM: Investment Evaluation Model

ESC: Expected Shortage per Cycle

CSL: Cycle Service Level

RMI-CR: RMI system with a Continuous Replenishment policy

RMI-DD: RMI system with a direct delivery policy

GPS: Global Positional System

IT: Information Technology

ERP: Enterprise Resource Planning

CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

The healthcare business is considered one of the major industries in most economies, as per the United States Department of Labor (2010). They announced that the healthcare sector in the USA had 14.3 million jobs in 2008 with the ability to create another 3.2 million jobs within the coming ten years (Wamba, Anand, & Carter, 2013). The healthcare expenditure in Canada in 2000 almost reached six percent of its GNP (Gross National Product) and the estimated value in 2020 is expected to reach around 7.1% (Anand & Fosso Wamba, 2013; Han, Brimacombe, Lee, & Yang, 2001). Healthcare expenditures at Organization for Economic Co-operation and Development (OECD) have been escalating year by year with an average of four percent linked to supply chain and logistics costs due to a number of reasons: increasing operations costs, a higher number of medical errors, and the aging population (Nachtmann & Pohl, 2009).

Supply chain (SC) logistics indoors and outdoors are responsible for almost 30 percent of hospital costs and are considered the second-highest cost of hospital activities after personnel and labour costs (Nachtmann & Pohl, 2009). Poulin (2003) mentions that half of such expenditures initiated by indoor and outdoor logistics related to hospital activities can be eliminated if we implement an optimal supply chain and cost-effective logistics tools.

SC and optimal logistics approaches at hospitals can offer some meaningful solutions to be responsive through enhancing the quality level of healthcare and cost reduction using effective tools. Supply chain and logistics networks consist of having long and short-term planning for storage facilities, and the inventory management decisions can manage the flow of the products and services within a healthcare network between the vendor and the hospitals to meet the customer expectations. SC and logistics management are considered to be a competitive tool that can bring added value and advantages that can improve the long and short-term operational performance (Li, Li, & Zhang, 2016).The SC and logistics approach can be a challenge due to the complexity of healthcare operations and its constraint of matching and satisfying all demand regardless of the order size and the location of the hospitals with no assigned warehouses.

A high level of efficiency is needed to match the high-quality level of healthcare treatment with the high expectations of the patient (De Vries, 2011). Supply chain and logistics techniques applied in healthcare have not always ended up with the expected outcome due to the complexity of the healthcare network. As a result, supply chain and logistics have not been a familiar tool used in the healthcare network; management did not consider such tools and may prefer to depend on their accumulative experience to manage the strategic and operational decisions (Volland, Fügener, Schoenfelder, & Brunner, 2017). Burt (2006) suggests applying supply chain and logistics tools applied in other industries to inventory management aspects to be implemented in the healthcare sector wherever it is applicable.

Supply chain and logistics optimization in healthcare networks has started to be considered recently by management in the healthcare sector and by scholars as an important and value-adding tool in that they provide a significant reduction in the total cost of supply chain and logistics activities (Jarrett, 1998).

Many relevant publications have been published on the topic of supply chain and logistics activities related to the flow of handling pharmaceuticals and medical-surgical products from a quantitative point of view, in which 70% to 80% account for medical pharmaceutical products and the rest account for medical-surgical products (Rego, Claro, & de Sousa, 2014). Most of the healthcare material management studies consider three areas: first, hospital material management through outsourcing networks using either VMI by using a supplier integration system, or stockless inventory by using just-in-time or direct delivery from the supplier to the hospitals. The second topic is related to increasing purchasing power based on increasing the size of the bundle and quantity by aggregation of multiple orders in one order to have a significant discount. The third topic is related to demand forecasting.

Motivated by the lack of investigations dealing with integrating the RFID technology in the location-inventory assignment problem using VMI contract to reduce the total network cost and enhance its profitability by reducing the waste inventory, our research is actively engaged in studying implementing RFID technology to enhance the ordering and holding efficiencies in order to reduce the waste inventory by handling and identifying the defective, lost, and expiry date items. RFID automated verification, monitoring, and tracking features lead to reducing the cost of defective and expired items by enhancing the information sharing and engancing the collaboration between supply chain parties.

This dissertation sheds light on the first topic and discusses the role of VMI contract in healthcare supply chain management and integrates it with both the replenishment policy assignment and the RFID investment allocation assignment in healthcare SC networks using both VMI and direct delivery policies.

1.2 Problem Statement

Management in the healthcare sector faces several significant challenges, including complexity in healthcare systems, high SC costs, balancing quality and costs, delay in delivery, product availability from vendors and unpredictability and uncertainty. The total spending on healthcare has increased by an average of four percent per year; out of that increase, 29% accounts for hospitals. Inventory logistics costs are the second highest-cost segment in hospitals. Inventory logistics and network allocation decisions have been recognized in the last twenty years as an important tool to manage healthcare expenditures.

Many medical supply vendors rely on VMI contracts to design their inventory management systems and have solutions for their critical strategic and operational decisions. In spite of the considerable amount invested in the VMI system and location-inventory assignment problem, a number of negative issues are not yet resolved:

- Integrating the location-inventory assignment problem with the replenishment policy allocation assignment.
- Integrating the location-inventory assignment problem with the RFID investment allocation assignment.
- The impact of cost saving obtained by RFID investment on the setup and the layout of the healthcare SC network.
- Introducing the RFID Investment Lower Bound to enhance the viability and reliability of implementing RFID technology in real-world problems.
- Out-of-stock: Gruen et al. (2005) mention that the out-of-stock figure varied between 7.9% in the US and 8.6% in Europe.
- A comparative study for the performance of VMI contracts based on the suggested integrated location-inventory assignment problem to the performance of other replenishment systems such as RMI system in case of a continuous review and direct delivery policy simultaneously.

- Inventory visibility to enhance the inventory waste management by using RFID technology: by implementing RFID technology to enhance the inventory visibility in the supply chain network, the management can have better outcomes about reducing the inventory waste level due to the defective, lost, misplaced and expired items.

The main issues considered in this thesis are the impact of the VMI contract and RFID technology on the location-inventory assignment problem in improving the performance of the inventory system and the layout of the healthcare SC network. Three major keywords can describe the context of the thesis:

1. The first keyword is VMI contract: Vendor Managed Inventory (VMI) contract has been defined as a collaborative and replenishment delivery strategy in which all replenishment decisions and associated costs are covered by the vendors instead of the buyers in the traditional replenishment system. VMI is a collaborative strategy to optimize the availability of products at minimal costs.
2. The second keyword is RFID: Radio-Frequency Identification (RFID) is an emerging technology to enhance the inventory visibility and more accurate in real time, resulting in reducing the inventory waste, processing time and workforce. Such reduction brings opportunities for improving the ordering and holding inventory operations.
3. The third keyword is a location-inventory problem: it is a problem concerning location assignment of a storage facility to optimize the service level with minimal associated inventory and transportation costs. The location-inventory model, in general, is based on a trade-off between the cost and service responses level.

1.3 Research Question

One of the major objectives of this thesis is to demonstrate a quantitative analysis through mathematical modelling to measure the role of the VMI contract on the location-inventory assignment problem, and the impact of RFID investment on the layout of the healthcare SC network and on inventory waste.

In this thesis, the following research gaps and questions are to be solved:

1. How should the role of the VMI contract on the location-inventory assignment problem with deterministic demand be modelled?

2. How should the location-inventory assignment problem integrated with the replenishment policy allocation assignment be modelled?
3. Is there any impact for RFID investment through its ability to reduce cost on the layout of the healthcare SC network?
4. What is the role of RFID technology on the reduction of inventory waste?
5. How should the role of the VMI contract on the location-inventory assignment problem with stochastic demand be modelled?
6. Is the integrated location-inventory assignment problem under the VMI contract in the case of the real-world problem the best solution against other traditional inventory systems such as traditional retailer managed inventory (RMI) systems?

1.4 Scope of the Thesis

This research is motivated by a real-world problem arising from one of the world's leading medical implants supply companies applied to a chain of hospitals in the province of Ontario. The chain of hospitals under study consists of 147 hospitals located in Ontario, Canada. The vendor is a supplier of three types of medical implants (a heart valve, an artificial knee, and a hip). The vendor implements a VMI contract as a replenishment system for the selected hospitals in the healthcare network. The vendor faces a challenge of whether or not to allocate a storage facility at each hospital and to assign the replenishment system accordingly.

As a response to the first, second and fifth research questions mentioned above, we formulate the problem as a Mixed Integer Non-Linear Programming (MINLP) model to minimize the total supply network cost for a VMI supply network in deterministic and stochastic demand environments. In addition, this model gives the vendor adequate understanding to make different strategic and operational decisions. The third research question is answered by providing analytical analysis for the impact of cost-saving generated by RFID implantation on the final layout and setup of the healthcare SC network and affects the location assignment of the warehouses at the hospitals. Considering RFID technology in the VMI contract enables us to answer the fourth research question: two investment factors of ordering and holding efficiencies are considered and lead to minimizing any inefficiency related to the ordering and holding activities with regards to the inventory waste reduction; those two investment factors are typically dependent on the investment intensity of the RFID technology.

Concerning the recent research, we also contribute in extending the research of VMI contracts in healthcare networks by presenting a comparative study of the VMI contract with other common and traditional inventory systems by comparing total costs of the systems and analyzing the impact of the cost variations of the parameters on the total cost. This comparative study enables us to respond to the sixth research question and to give insights into the other traditional inventory systems against the role of the VMI system in the location-inventory assignment problem.

1.5 Research Contribution

To the best of our knowledge, this dissertation contributes in a novel way to the existing literature.

In Chapter 2, our first contribution to this research is threefold: first, we provide an optimal integrated location-inventory supply chain network with a deterministic demand environment and model it mathematically. Second, we discuss applying two RFID investment factors in holding and ordering operations and developing analytical procedures to derive optimal RFID investment levels for these factors. Third, we identify the impact of RFID cost savings on the location assignments of the storage facilities at the hospitals.

In Chapter 3, the contribution for this dissertation is integrating the role of VMI contract in the location-inventory assignment problem within a healthcare SC network in a stochastic demand environment and modelling it mathematically. The research explores integrating the location assignment of the storage facility with the replenishment policy (using either VMI policy or direct delivery policy per hospital). In addition, we present a flexible safety stock system that can respond effectively and efficiently, in which we assigned a local safety stock level at each hospital with an assigned warehouse, and a safety stock level at the vendor’s warehouse to cover any expected shortages at the hospitals with no warehouses. In this research, we present a comparison between the performance of the SMINLP model with the uncertainty of the demand as a random variable following normal and uniform distributions, in which we define the expected shortage as a function of the safety factor in case of the demand following the normal distribution. For the demand following the uniform distribution, we define the expected shortage as a function of the reorder point. The total supply chain cost and the layout of the healthcare network are both used as the measure of the comparison.

In Chapter 4, this research is the first comparative study to analyze numerically the power of proposed model of the VMI contract in cost saving with the comparison of the other traditional RMI systems in the healthcare SC, in which we find that using our proposed model based on the integration of the location-inventory assignment problem can motivate both the vendor and hospitals to adopt it; in this way, the vendor will gain a significant cost saving, and the hospital will benefit by eliminating the inventory operation stress and having better pricing for the medical implants due to the cost savings obtained by the vendor.

1.6 Solutions Approach

1.6.1 Deterministic Programming

Deterministic programming is one of the main approaches that we used to program the mathematical model of case one in Chapters 2 and 4, in which I assume that all related parameters and inputs associated with the decision variables and objective function are well defined and precise. Deterministic programming's outcomes are well defined and with no random variations and uncertainty level in the case of having fixed known inputs, in which the objective function with a given fixed input will produce the same specific outcomes in any run. In Chapters 2 and 4, we minimize the objective function of the total cost, and all parameters related to demand are known and well defined.

1.6.2 Stochastic Programming

Stochastic programming is one of the main approaches used to program the mathematical model in Chapter 3, in which some or all of the input parameters have random variations and uncertainty. Stochastic programming is a way of calculating the probability distribution of the objective outcomes by considering a random variation and uncertainty level of some or all input parameters. The random variation in input parameters is defined as fluctuations observed in historical data given per known time by implementing standard time-series approaches. The objective function's outcomes in stochastic programming should be feasible and have an optimal solution that can achieve the best solution criteria, which in our case is to minimize the total costs of the healthcare network that can be obtained under such uncertainty and the variation of the parameters. In Chapter 3, we present the performance of the VMI contract under a stochastic environment with the uncertainty of the demand as a random variable following the normal and uniform distributions.

1.6.3 Mixed Integer Non-Linear Programming (MINLP)

Mixed Integer Non-Linear Programming (MINLP) is an optimization tool for a problem, in which some of the decision variables are constrained by taking integer and non-negative values, and the objective function of the problem can be classified through non-linear functions; the regions of the feasible solutions are a non-linear function too. MINLP is the best approach to handle real-world problems and applications. We formulate the mathematical models in Chapters 2, 3 and 4 as an MINLP model. Using the MINLP approach is somewhat challenging to optimize the problems, in that we need to deal with two complex issues: one dealing with optimizing the integer decision variables and the other one dealing with the non-linear functions.

1.7 Structure of the Thesis

The dissertation is composed of three major chapters (Chapter 2, 3 and 4), in addition to the introduction (Chapter 1), and conclusion and future research (Chapter 5):

- Chapter 2: We first study the optimal supply network with VMI in a healthcare system with RFID investment consideration under a deterministic demand environment. In addition, we deal with the case in which the RFID technology is deployed in order to eliminate the inventory waste due to lost, expired, and rejected items by enhancing the ordering and holding efficiencies. In this chapter, we provide analytical solutions for solving the location-inventory assignment problem under the VMI contract by integrating the location assignment of the storage facility and its replenishment policy with the allocation assignment of RFID technology with its investment level; such integration allows us to have a flexible inventory system by having two types of replenishment policies (VMI and direct delivery policies) in a chain of hospitals subjected to the availability of the warehouse at the hospital. In particular, we show that there is a significant cost saving by implementing the MINLP model and show that RFID investment impacts the storage facilities' layout of the healthcare SC network. This chapter ends with deducing an elegant mathematical analysis of the optimal healthcare SC network decisions, including RFID investment settings.

- Chapter 3: this chapter extends the research of Chapter 1 in the case of a stochastic demand environment without RFID consideration. The chapter analyzes a real-world problem with stochastic demand in which a single vendor supplies multiple medical products to a chain of hospitals, and in which the inventory replenishment policy assignment is subjected to the storage facility location assignment. A Stochastic Mixed-Integer Non-Linear Program (SMINLP) is developed to determine the location of the warehouses, the quantity of products, and the number of orders, the size of the safety stock at the hospitals' warehouses and the vendor's warehouse so that the total cost of transportation, inventory, and other associated operating costs are minimal. In this chapter, we compare the performance of VMI systems under a stochastic environment with the uncertainty of the demand as a random variable following two types of distributions: normal and uniform distributions.
- Chapter 4: This chapter provides a comparative study in which we compare two inventory systems: in the first situation, the VMI contract with continuous replenishment policy, we developed a mathematical model as a MINLP and solved by GAMS. The second situation deals with a traditional RMI system in which the vendor, and the chain of hospitals act as different parties and do not cooperate. The RMI situation is developed under two scenarios: the first scenario is with a continuous replenishment policy in which we consider all hospitals as having a storage facility with a continuous replenishment policy, and we develop a mathematical model as a MINLP and solved by GAMS. In the second scenario, we consider all hospitals within the healthcare network as having no storage facilities and the chain of hospitals are using direct delivery policy with the same day delivery; we developed a mathematical model as a mixed integer programming (MIP) and solved using GAMS. The computational results and sensitivity analysis in this chapter for this real-world case study in specific show that the application of VMI systems is more justified and works better in terms of lowering cost than traditional RMI systems.

All solution methodologies, computational results, managerial insights, sensitivity analysis, and conclusion and future research topics are provided in this dissertation.

CHAPTER 2: OPTIMAL SUPPLY NETWORK WITH VENDOR MANAGED INVENTORY IN A HEALTHCARE SYSTEM WITH RFID INVESTMENT CONSIDERATION

2.1 Introduction

We consider a supply network for medical implants in the healthcare system, where the vendor manages multi-hospital warehouses under a vendor managed inventory (VMI) policy and uses RFID technology to reduce the network's total costs and enhance customer service. A real-world problem arising within a medical implant supply company is the impetus for the research. The vendor needs to determine the location of the warehouses, the inventory policy, and the RFID investment level in the healthcare network so that the total cost of transportation, inventory, and other associated operating costs are minimal. In this research, we develop a mixed integer non-linear program model to formulate the integrated decision problem that combines the location-inventory problem with the allocation assignment of RFID technology and its investment level. In addition, we present the RFID investment evaluation model and provide a basis for enhancing our understanding of the RFID impact on allocation assignment of the supply network. The real-world problem is resolved and analyzed with the proposed approach. The computational results and sensitivity analysis are provided.

The total spending on Health Care Network (HCN) has increased by an average of four percent per year from 2000 to 2009; out of that increase, 29% is accounted by hospitals (Volland, Fügener, Schoenfelder, & Brunner, 2017). Inventory logistics costs are the second highest-cost segment in hospitals (Ross & Jayaraman, 2009). Researchers have recognized that integrated location and inventory supply chain network problems have been recognized in the last twenty years as an important tool to minimize the healthcare expenditures (De Vries, 2011; Tlahig, Jebali, Bouchriha, & Ladet, 2013).

Management in the healthcare sector faces several significant challenges, including complexity in healthcare systems, high supply chain (SC) costs, balancing quality and costs, delay in delivery, product availability from vendors, and unpredictability, and uncertainty. Those challenges force many vendors, especially in the healthcare sector, to re-examine their operations, and critically re-evaluate all areas of operations looking for avenues of optimization. (Feibert, 2017).

This research is based on a real-world problem arising from a world's leading medical implants supply company applied to a chain of hospitals in the province of Ontario. The chain of hospitals under study consists of 147 hospitals located in Ontario, Canada. The vendor is a supplier of three types of medical implants (a heart valve, an artificial knee, and hip). The vendor implements a vendor managed inventory contract as a replenishment system for the selected hospitals of the healthcare network. The vendor faces a challenge either to allocate or not a storage facility at each hospital and to assign the replenishment system accordingly.

RFID technology plays an essential role in Waste Inventory Reduction (WIR) by handling and identifying the defective, lost, and expiry date items. Using RFID automated verification, monitoring, and tracking features lead to reducing the cost of defective and expired items reaching consumers. Due to the ability of RFID technology in reducing the rate of the inventory waste, the vendor decides to adopt this technology to reduce the total network cost and enhance its profitability as evidenced by Wal-Mart's recent RFID direct its suppliers to the benefit of its significant potential for process improvement and cost reduction (Lee & Lee, 2010; Kumar & Budin, 2006).

Considering the large number of the hospitals within the healthcare network, the vendor needs to extend supply chain activities to cover all hospitals' demand regardless of the size of the demand or the location of the hospitals. Also, the vendor needs to implement an effective inter-firm information technology system with the most advanced technology for supply chain integrity and traceability, such as RFID technology by enhancing information sharing and collaboration between supply chain parties.

The vendor is striving to achieve total joint effectiveness across the entire chain network by having strategic decisions represented by the location assignment of the storage facilities with a VMI policy to manage the inventory at the assigned hospitals and with the option of implementing RFID technology with its investment level, otherwise, using a direct delivery policy instead at the hospitals without storage facilities. Also, the vendor is seeking to have operational decisions represented by the order size, the number of orders, and the safety stock level of the inventory supply that will be maintained at the assigned warehouses of the hospitals.

Our research is actively engaged in studying the inventory problem by implementing RFID technology to enhance the ordering and holding efficiencies. This technology plays a significant role in reducing the total costs of the healthcare network by enhancing the efficiency of the ordering and holding operations. The discussion and analysis section explain the cost saving generated by implementing RFID technology and its impact on the location assignment of the storage facilities at the chain of the hospitals. In our research, we have identified a two-supply chain RFID investment factors of ordering and holding efficiencies and developed quantitative procedures to have an optimal RFID investment level for these factors.

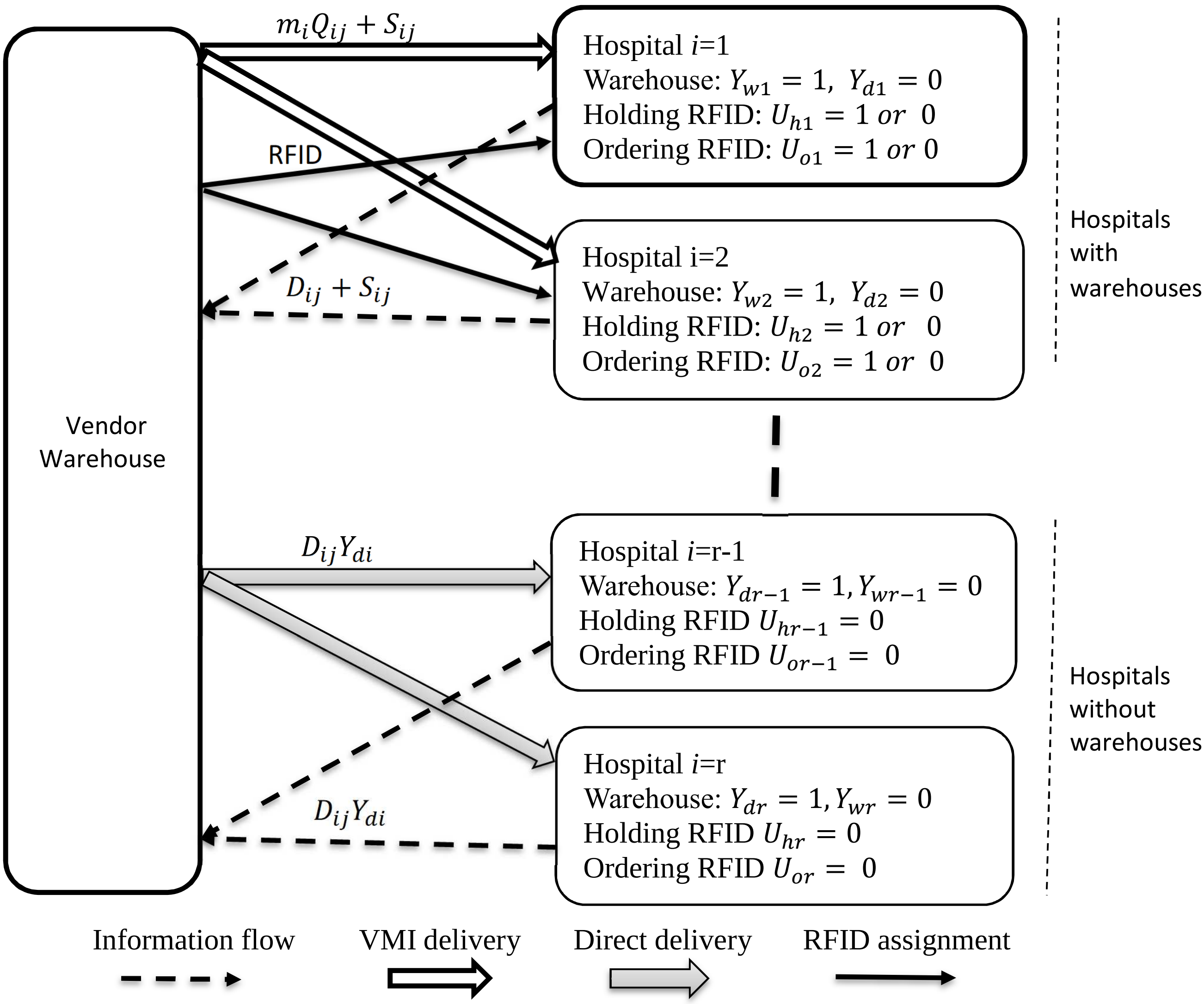
Previous research on location-inventory supply chain network problem, in terms of location assignment of the storage facility and the type of the replenishment policy under VMI contract, focused on using either a VMI policy or Just-In-Time (JIT) policy or Direct Delivery Policy (DDP) sequentially regardless the location assignment of the storage facility in the network, other industries implemented the direct delivery by courier as a single replenishment system under Retailer Managed Inventory (RMI) system, in which the hospitals play the retailer role (Hariga, Gumus, & Daghfous, 2014; Pan, 2016).

In our research, we integrate the location assignment of the warehouse at the hospital with a VMI policy and allocation assignment of implementing RFID technology with its investment level. We formulate the problem as a mixed integer non-linear program (MINLP) model to minimize the total supply network cost for a VMI supply network. Fig. 2.1 eliustrates the VMI and RFID assignmnet chart including the information and material flow based on the location-inventory assignment problem in a chain of hospitals with and without assigned warehouses.

Our contribution to this research is threefold: First, we provide an optimal integrated location-inventory supply chain network and model it mathematically. Second, we discuss applying two RFID investment factors in holding and ordering operations and developing analytical procedures to derive optimal RFID investment levels for these factors and third, we identify the impact of RFID cost savings on the location assignments of the storage facilities at the hospitals.

The remainder of this paper is organized as follows: a review of the relevant literature is presented in the next section, followed by a presentation of the proposed model in Section 3. Computational results have been carried out to analyze and illustrate the findings, benefits, and sensitivity analysis in Section 4. The last section contains concluding remarks and some avenues for future research.

Fig. 2.1 VMI and RFID assignment chart based on the location-inventory assignment problem in a chain of hospitals with and without assigned warehouses.



2.2 Literature Review

In this research, we consider two streams of literature: First, Vendor Managed Inventory (VMI) contract, including the healthcare network, the definition and its role in the Location-Inventory Assignment Problem (LIAP). Second, RFID technology in the healthcare network.

2.2.1 VMI Contract Including the Healthcare Network

Healthcare environments have experienced challenges due to increased healthcare costs, high competition, and sophisticated requirements and regulations. Such changes have hastened the focus on supply chains in healthcare, which is now more demand-driven (Krichanchai & MacCarthy, 2017). Managing Supply Chain inventory is a significant challenge for many firms that have simultaneously endeavored to minimize costs and enhance customer service in the current competitive business environment (Daskin, Coullard, & Shen, 2002). To overcome the gap of managing inventory in the healthcare sector, several programs of supply-chain coordination, which include vendor managed inventory (VMI), have recently been implemented to support the supply-chain software (Sui, Gosavi, & Lin, 2010).

VMI has been defined as a collaborative and replenishment delivery strategy in which all replenishment decisions and associated costs are covered by the vendors instead of the buyers in the traditional replenishment system. VMI is a collaborative strategy to optimize the availability of products at minimal costs. In general, VMI policy can be either a frequent, or it can be infrequent replenishment system, but the main point is that VMI strategy is a demand-driven supply chain (Govindan, 2015; Haavik, 2000; Mateen, Chatterjee, & Mitra, 2015)

Studies concerning the integrated location-inventory network problem are relatively new Liao, Hsieh, & Lai, (2011), Jayaraman (1998) developed a mathematical model examined the impact of the integration of facility location on inventory decisions and transportation modes. Erlebacher and Meller (2000) presented a location-inventory model to optimize the service level with minimal associated inventory and transportation costs. Nozick and Turnquist (2001) presented a location -inventory model based on a trade-off between the cost and service responses level. Miranda and Garrido (2004) integrated the facility location problem with inventory decisions and presented a MINLP model by introducing the inventory decisions in facility location models. Sabri and Beamon (2000) used a multi-objective function to resolve strategic and operational planning decisions such as fill rate cost and flexibility for a sub-module model. Recently the Liao et al. (2011) studied an integrated location–inventory distribution network problem by integrating the impact of the facility location, distribution, and inventory issues under VMI contract on the inventory decisions; they presented a Multi-Objective Location–Inventory Problem (MOLIP) model and they tested the multi-objective evolutionary algorithm to solve MOLIP, they used a multi-objective approach to present the location assignment as strategic decision and inventory management assignment as operational decisions with VMI policy as single replenishment policy,

In this paper, We use a Single Objective Optimization (SOO) to integrate the inventory-location assignment problem as a Mixed-Integer Non-Linear Problem (MINLP) to present the strategic and operational decisions instead of using a Multi-Objective Optimization (MOO) as most previous works have focused on. In addition, our model builds upon assigning the replenishment policy for each hospital based on the storage facility location assignment, in which, we use a VMI policy for the hospitals with assigned warehouses and a direct delivery policy with the rest of hospitals with no assigned warehouses.

The healthcare sector has compromised the costs of the inventory and logistics costs using Vendor Managed Inventory (VMI) to reduce cost and waste, eliminating supply and transportation distribution and take advantage of better pricing offered by suppliers. VMI has been tested and adopted in various industries since the late 1980s, by Wal-Mart, Procter & Gamble, HP, Shell, and other big firms popularized the concept to attract customers. Scholars are actively engaged in studying aspects related to VMI, including replenishment decisions, contracts, relationships, as well as strategic implications (Mateen et al., 2015).

In this research, we highlighted the constraint of fulfillment all demand of the chain of hospitals regardless the location and the demand size by integrating both VMI and direct delivery policies in healthcare network based on the location assignment of the storage facilities and by assigning safety stock level for all warehouses assigned at the hospitals. Also, we highlighted the challenge of reducing inventory waste at the hospitals by implementing RFID technology.

A thorough literature review of VMI contract in healthcare network was conducted as elaborated in Table 2.1, which summarizes the most related publications to VMI contract and presents our research contribution of VMI in the healthcare network.

2.2.2 RFID Technology in the Healthcare Network

According to the latest research papers and statistics, RFID technology is considered the best Information Technology (IT) investment tool for the growth of companies. The RFID technology business value by enabling supply chains to easily and inexpensively collecting and sharing information, thus playing a significant role in enhancing supply chain visibility. By enhancing supply chain visibility leads to reduced stock-out and lead time, eliminate inventory waste, lower labor costs, reduce transaction costs, and improve both customer satisfaction and inventory and logistics management (Lee & Lee, 2010; Anand & Fosso Wamba, 2013; Li, Li, & Zhang, 2016; Wamba, Anand, & Carter, 2013).

The inaccuracy problem happens in inventory management system due to inaccurate accounts in the warehouses, which leads to having such lost and expired items. Vendor profits can suffer an average of 10% as lost sales and an increase in inventory cost. A reduction in the rate of defective and expired items improves customer service due to timely order deliveries (Sarac et al., 2010). In our research, we consider implementing RFID technology as a promising solution in dealing with inventory waste problem by enhancing the efficiency of ordering and holding operations.

Table 2.1 Literature review summary for VMI contract.

Reference	VMI[1]	DDP[2]	LIAP[3]	RFID[4]	HCN[5]	LRPA[6]	LP/IP[7]	NLP[8]	MINLP[9]
• Rivard-Royer, Landry, and Beaulieu (2002)		√			√				
• Liao et al. (2011)		√	√		√				
• Govindan (2015)	√				√				
• Uthayakumar and Priyan (2013)	√				√			√	
• Kannan, Grigore, Devika, and Senthilkumar (2013)	√				√				
• Danese (2006)	√			√	√				
• Kiesmüller and Broekmeulen (2010)	√			√					
• Ben-Daya and Hariga (2004)	√							√	
• Guan and Zhao (2010)	√						√		
• Turhan and Vayvay (2012)	√			√	√				
• Achabal, McIntyre, Smith, and Kalyanam (2000)	√				√		√		
• Darwish and Odah (2010)	√							√	
• Priyan and Uthayakumar (2014)	√				√			√	
• Bijvank and Vis (2012)		√			√			√	
• Hong, Chunyuan, Xu, and Diabat (2016)	√				√			√	
• Shu, Li, Shen, Wu, and Zhong (2012)	√		√					√	
• Szmerekovsky and Zhang (2008)	√			√	√			√	
• Sarac, Absi, and Dauzère-Pérès (2010)	√			√	√				
• Volland et al. (2017)	√				√				
• Liao et al. (2011)	√			√	√				
• Pan (2016)	√			√	√				
• Epstein and Dexter (2000)	√			√	√				
• Machado Guimarães and Maia (2013)	√				√				
• ÇAkıCı, Groenevelt, and Seidmann (2011)	√		√	√					
• Park, Yoo, and Park (2016)	√				√		√		
Our Model	√	√	√	√	√	√			√

[1] Vendor managed inventory (VMI), [2] direct delivery policy (DDP), [3] location-inventory assignment problem (LIAP), [4] radio frequency identification (RIFD), [5] healthcare network (HCN), [6] location-replenishment policy assignment (LRPA), [7] linear programming/integer programming (LP/IP), [8] non-linear programming (NLP), and [9] mixed-integer non-linear programming (MINLP).

RFID implementation lowered the overall costs of supply and improved administrative quality. Although, that RFID technology is more costly with regards to implementation and maintenance service follow-up compared with other traditional tracking technology such as barcodes. Still, the outcomes and enhancement in efficiency create overall cost savings; this efficiency comes in the form of reduction in the inventory costs due to the inventory visibility, the reduction in labour costs, the improvement in shortening the administration works regarding the readiness of material orders and purchase orders and minimizing waste and rejected items (Feibert, 2017; Romero & Lefebvre, 2015; Wamba et al., 2013; Lee et al., 2011).

In light of the debate on the best measurement methods for RFID investment, this study provides an overview of existing evaluation studies presents the RFID investment evaluation model and integrates it with the inventory-location assignment problem. We considered having RFID technology as a tool of cost and inventory waste reduction. In addition, our research introduces a RFID Investment Lower Bound (RFIDILB) to be viable and reliable, in which we assigned constraints in MINLP model to limit the lower bound investment in RFID technology equals to or greater than the specific value of the investment ($1000).

Lee and Lee (2010); Li et al. (2016); Cui, Wang, and Deng, (2014) presented RFID technology as an investment evaluation model (IEM) based on a Cost-Benefit Analysis (CBA) for Economic Order Quantity (EOQ) inventory system which represents a continuous replenishment system without integrating the assignment of RFID with location assignment of the storage facility.

The efficiency improvement gained by RFID implementation and its direct and indirect investment costs plays a significant positive role in enhancing the inventory operations level based on Efficiency-Investment Exponential Function (EIEF) (Lee & Lee, 2010; Wamba et al., 2013; Chong & Chan, 2012). The ordering and holding efficiencies represented the RFID outcomes accurately by better inventory management by using the tracking and monitoring capabilities of RFID technology Table 2.2 summarizes the cost categories related to supply chain inefficiency activities and RFID benefits (Lee & Lee, 2010).

Table 2.3 summarizes the most related publications to RFID technology as a cost-benefit analysis tool.

To the best of our knowledge, our study is the first study integrate the RFID investment evaluation model and its investment level with the warehouse location assignment; we integrate the RFID investment evaluation model by examining the relationships between model parameters, variables and the level of RFID investment within inventory-location assignment problem. The presented model is not only useful in its own right, but it also underscores the feasibility of using an analytical model in healthcare supply network in the field of RFID investment.

Table 2.2 The cost categories of supply chain inefficiency activities and RFID outcomes.

Inventory Operations	Cause costs of SC inefficiency	RFID outcomes
Ordering Operations	Unmatched units within vendor SC network.	Improve the inventory data by RFID automated feature.
	Resolve the defective units in orders and expiry date items.	Enhance the verification process by the RFID feature.
	Resolve inaccurate invoicing of due to disputes.	RFID reconciliation automated disputes.
	Having fake and counterfeit units.	Enhancing the put-away process by the RFID feature.
	Resolve the inaccurate ordering counts and any count discrepancy.	Enhancing the time of the counting process of the order.
	Inaccurate ordering inquiries with available stock.	Enhance the balance reconciliation of disputes by merging RFID & ERP.
	Resolve inaccurate time to track the orders from plants to warehouses.	Enhance the timely delivery process of orders using GPS with RFID technology.
Holding operations	Unbalanced excess inventory and safety stock level.	Enhance the number of stock balance reviews.
	Managing backorders from customers.	Enhancing inventory visibility and matching it with demand.
	Inaccurate inventory counts at vendor and customers' warehouses.	Enhancing the time reduction in inventory counts.
	Inaccurate time reporting of inventory loss.	Automated real-time tracking & reporting system by RFID.
	Resolve the inaccurate labeling and misallocating units at the warehouse.	The automated tagging system eliminates mistake in location or labeling of units.
	Manage the Inaccurate counting of the discrepancy in the vendor's inventory.	Enhance the automated reconciliation process by merging RFID with ERP systems.
	Inaccurate accounts of defective, lost, out stock, and obsolete units.	Enhance the monitoring and tracking process of the inventory records.
	Error in tracing the units on shelves and misidentifying the defective units on shelves	Reduce the rate of defective units on shelves that can be accessed by the customer.

Table 2.3 Literature review summary RFID as a cost-benefit analysis tool.

Reference	RFID[1]	IEM[2]	WIR[3]	CBA[4]	EIEF[5]	HCN[6]
• Lee and Lee (2010)	√	√	√	√	√	
• Li et al. (2016)	√	√	√	√	√	
• PG (1998)		√		√	√	
• Sarac et al., (2010)	√	√	√	√		√
• Bendavid, Boeck, and Philippe (2012)		√		√	√	√
• Cui, Deng, Liu, Zhang, and Xu (2017)		√		√	√	
• Wamba et al. (2013)	√		√	√		√
• Chircu, Sultanow, and Saraswat, (2014)	√		√	√		√
• Camdereli and Swaminathan (2010)	√		√	√		
• Lee and Özer (2007)	√	√		√		
• Guan and Zhao (2010)	√		√	√		
• Volland et al. (2017)	√	√	√	√		√
• Cui, Wang, and Deng, (2014)	√	√		√	√	
• Chong and Chan, 2012	√					√
• **Our Model**	√	√	√	√	√	√

[1] Radio frequency identification (RIFD), [2] investment evaluation model (IEM), [3] waste inventory reduction (WIR), [4] cost-benefit analysis (CBA), [5] efficiency-investment exponential function (EIEF), and [6] healthcare network (HCN).

2.3 Mathematical Model

2.3.1 Problem Statement

In this paper, the vendor's objective function is to minimize the total cost by resolving three major decision problems simultaneously as follows:

The first is related to the location assignment problem as a strategic decision, the vendor should decide whether to open a warehouse at a hospital *i* based on associated costs connected with ordering, holding, transportation, fixed and setup costs, or implement a direct delivery policy (DDP) with same day delivery to the hospitals with no assigned warehouses.

The second is related to replenishment inventory decisions as operational decisions. The vendor should decide the size of the order, the number of orders that should be delivered to the hospitals, and the safety stock level to be maintained within the hospitals with assigned warehouses.

The third problem is related to the allocation assignment of implementing RFID technology at the hospitals with assigned warehouses to enhance the ordering and holding efficiencies. Two investment factors of ordering and holding efficiencies are considered. Holding and ordering efficiencies are realized by minimizing any inefficiency related to the ordering and holding activities, and they are typically dependent on the investment intensity of the RFID technology. RFID technology improves both ordering and holding efficiencies in various ways. Ordering and holding efficiencies are defined as the degree to which the RFID investment levels reduce the fixed order cost per order cycle and holding cost per item in ordering and holding operations.

2.3.2 Model Assumptions:

- All hospitals' demands for all products are deterministic.
- The demand should be satisfied regardless of the size of the demand or the location of the hospitals.
- The ordering and holding efficiencies are a natural exponential function where the RFID investment costs, improve the ordering, and holding efficiencies (Lee & Lee, 2010; Billington, 1987).
- The transportation cost per item is assumed to be delivered to the hospitals with no assigned warehouses by courier; the rate applied is based on Purolator's rates and service charges for direct same-day delivery due to the specialty of the medical implants that will be delivered.
- Ordering cost is assumed to have a fixed cost regardless of the type of the product or the quantity shipped per order, as all the administrative costs related to setting up the order inquiry, issuing a local purchase order and the inspection of the order are the same regardless of the quantity and the weight.
- A continuous review policy is used for VMI.

2.3.3 Mathematical Modeling

2.3.3.1 Indices

i — an index for hospital; $i = 1; 2\ldots, r$

j — an index for product; $j=1, 2\ldots, n$

2.3.3.2 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 assigned warehouse at the hospital *i* per time unit. (f^3)
C_{ij}	Transportation cost per delivery order to hospital *i* for product *j*
FC_i	Fixed setup cost for having a warehouse at the hospital *i*
CAP_{Truck}	The capacity of Truck used for delivery to hospital *i*
D_{ij}	Demand rate of hospital *i* of product *j* per time unit
f_i	The volume of one item of the product *j* (f^3)
BigM	Integer number representing a very high value
K_i	Unit truck shipment and ordering cost for hospital *i*
g_{ij}	Minimal Safety Stock level for product *j* at the hospital *i* with assigned warehouse
A_i	Ordering costs for hospital *i*
c_{ij}	Transportation cost per item to hospital *i* for product *j*
M	The lowest ordering efficiency achieved when there is no investment in RFID technology
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 technology
μ	Exponential parameter for holding efficiency
B_O	The minimal level of RFID investment to enhance the ordering efficiency at the assigned warehouse
B_h	The minimal level of RFID investment to enhance the holding efficiency at the assigned warehouse

2.3.3.3 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} The 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* with the assigned warehouse.

X_i RFID technology investment level for holding efficiency for hospital *i* with the assigned warehouse.

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 the hospital *i* reduced by RFID investment X_i (Lee & Lee, 2010; Li et al., 2016).

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.

2.3.3.4 Objective function

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

The object is to minimize the total cost. The first term represents the sum of ordering and courier transportation delivery costs per item for all products' demands and all hospitals with no assigned warehouses. The second term represents the cost of the combined ordering and trucking transportation cost for all orders delivered to all hospitals with assigned warehouses. The third term represents the holding cost per item of the summation of average order quantity and the safety stock level for all products at the hospitals with assigned warehouses and the improvement impact of holding efficiency as a function of RFID investment level. The fourth term represents the sum of the totals costs of the fixed cost of setting up the warehouse at hospitals and the rental rate cost for the assigned space by hospitals for the vendor for warehousing purpose. The fifth and sixth terms are the RFID ordering and holding investment costs, in order, for all hospitals with assigned warehouses.

S.T.

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

Network constraints, each hospital *i* either having a warehouse with VMI delivery or having a direct delivery with no assigned warehouse.

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

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.

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

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.

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

Upper bound order quantity constraint, the maximum number of each order quantity for each product is equal to or less than the bigM value for the hospital *i* with the assigned warehouse.

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

Lower bound safety stock level constraint, to limit the lower bound of the safety stock level equal to the minimal value represented by g_{ij} for hospital *i* with the assigned warehouse.

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

Upper bound of the number of orders constraint, the maximum number of orders shipped to the hospital *i* with assigned warehouse should be equal to or less than the bigM value.

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

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 product j of hospital *i* with the assigned warehouse.

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

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).

$$V_i = \left(N + (M - N)e^{-\beta S_i}\right) Y_{wi} \qquad for\ \forall\ i = 1, \dots, r \qquad (10)$$

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).

$$X_i \le Y_{wi} M \qquad for\ \forall\ i = 1, \dots, r \qquad (11)$$

Holding upper bound of RFID investment constraint, the maximum value of RFID holding investment level at the hospital *i* with assigned warehouse should be equal to or less than the bigM value.

$$S_i \le Y_{wi} M \qquad for\ \forall\ i = 1, \dots, r \qquad (12)$$

Ordering upper bound of RFID investment constraint, the maximum value of RFID ordering investment level at the hospital *i* with assigned warehouse should be equal to or less than the bigM value.

$$X_i \ge U_{hi}\, B_h \qquad for\ \forall\ i = 1, \dots, r \qquad (13)$$

The minimum level of RFID investment constraint in holding operations, the minimal level of RFID investment to enhance the holding efficiency should be greater or equal to a minimal RFID investment of B_h .

$$X_i \le U_{hi}\ \mathrm{M} \qquad for\ \forall\ i = 1, \dots, r \qquad (14)$$

Holding RFID investment assignment at the storage facility constraint, the RFID investment level in holding efficiency should be less than or equal to bigM value.

$$S_i \geq U_{Oi}\, B_O \qquad for\ \forall\ i = 1, \ldots, r \qquad (15)$$

The minimum level of RFID investment constraint in ordering operations, the minimal level of RFID investment to enhance the ordering efficiency should be greater or equal to a minimal RFID investment of B_O .

$$S_i \leq U_{Oi}\, \mathrm{M} \qquad for\ \forall\ i = 1, \ldots, r \qquad (16)$$

Ordering RFID investment assignment at the storage facility, the RFID investment level in ordering efficiency should be less than or equal to bigM value.

$$U_{hi} \leq Y_{wi} \qquad for\ \forall\ i = 1, \ldots, r \qquad (17)$$

Holding RFID minimal investment assignment for assigned warehouse constraint, the minimal level of RFID investment for enhancing the holding efficiency is implemented at the assigned warehouse at the hospital *i*.

$$U_{Oi} \leq Y_{wi} \qquad for\ \forall\ i = 1, \ldots, r \qquad (18)$$

Ordering RFID minimal investment assignment for assigned warehouse constraint, the minimal level of RFID investment for enhancing the ordering efficiency is implemented at the assigned warehouse at the hospital *i*.

$$Q_{ij}, m_i, X_i, S_i, SS_{ij} \geq 0 \qquad for\ \forall\ i = 1, \ldots, r\ \ and\ j = 1, \ldots, n \qquad (19)$$

Non-negativity constraint, the order quantity, number of orders, RFID ordering and holding investments levels, and the safety stock level for product *j* at a hospital *i* are all non-negative values.

$$Y_{di}, Y_{wi}, U_{hi}, U_{Oi}, \in [0,1] \qquad (20)$$

Binary constraint, the location and allocation variable decisions are binary decisions.

The problem given by (1)-(20) is a mixed integer nonlinear program model. We use GAMS to solve the problem with the real-world case in the next section.

2.4 Analysis and Discussion

2.4.1 Real-World Problem

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

We conduct sensitivity analyses to understand model behaviors of the RFID investment decisions by changing base parameter values. Base parameter values assumed are presented in Table 2.4.

The numerical analysis of the holding and ordering efficiencies shows a similar pattern in the total cost reduction. A minimum level of demand for the RFID investment in the ordering efficiency (Option B) and in the holding efficiency (Option C) are both derived from Fig. 1, in which no feasible solutions for RFID investment can exist at demand level less than 110. Also, we found that as the ordering efficiency V_i improves, the order quantity Q_{ij} decrease, also, when the holding efficiency X_i improves, the order quantity Q_{ij} increase. Table 2.5 expresses the improvement in total cost made by the simultaneous RFID investment decisions (Option D) over the sequential RFID investment decisions (Option B and C independently). In the sequential RFID investment decisions, the two investment decisions are made independently. Fig. 2.2 shows that while the demand level increases, the cost saving of the simultaneous RFID investment (Option D) becomes greater than those of the sequential RFID investment. The input data for the real-world problem designed based on a practical approach which represents the actual data for real-world calculations, Table 2.4 demonstrate the base parameters that we used as input for this problem.

Table 2.4 The base parameters and scalars values used in the computational results and analysis

Parameter	Value	Parameter	Value
M	1	N	0.2
U	1	Z	0.3
β	0.004	μ	0.0038
B_o	\$1000	B_h	\$1000
A_i	\$100	h_{ij}	10% of the average cost per item
D_{ij}	0.0009 city population	R_i	Subjected to the zone's location

Although, the overall investment level for the simultaneous RFID investment (Option D) is the highest compared with the investment level of the sequential RFID investment

(Option B and C), but the total cost of the objective function obtained in option D is the least, which represents the significant cost saving obtained by simultaneous RFID investment (Option D).

Table 2.5 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

Fig. 2.2 shows the impact of demand size on the cost saving; the cost saving is the highest in case of the simultaneous RFID investment (Option D) comparing with the cost saving obtained by sequential RFID investment (Option B and C).

RFID investment plays a significant role on the location assignment of the storage facilities at the chain of hospitals network, in which the reduction in total cots obtained by implementing RFID technology affects the location assignment of the warehouses at the hospitals, an example for such impact can be tracked from Table 2.5 , in case of having no RFID technology (Option A), a 32 hospitals assigned with warehouses and the rest of 115 hospitals with no assigned warehouse, such arrangement changed when we implement simultaneous RFID investment (Option D) where 36 hospitals assigned with warehouses and the rest of 111 hospitals with no warehouses. The analysis of the impact of sequential RFID investment (Option B and C) on the location assignment of the storage facility shows a similar pattern to the previous analysis with simultaneous RFID investment (Option D).

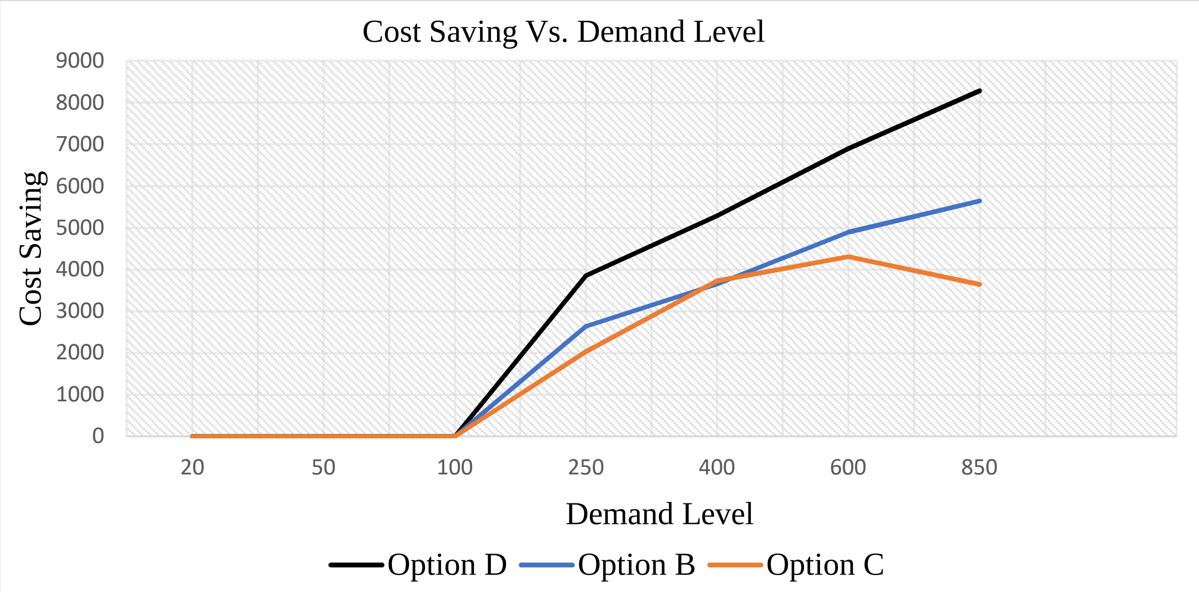


Fig. 2.2 The impact of demand level on the cost saving obtained by different RFID investment Options.

Fig. 2.3 shows the relationship between the demand level and total cost of the objective functions, in which option A (No-RFID) having the highest total cost value and Option D having the least total cost value.

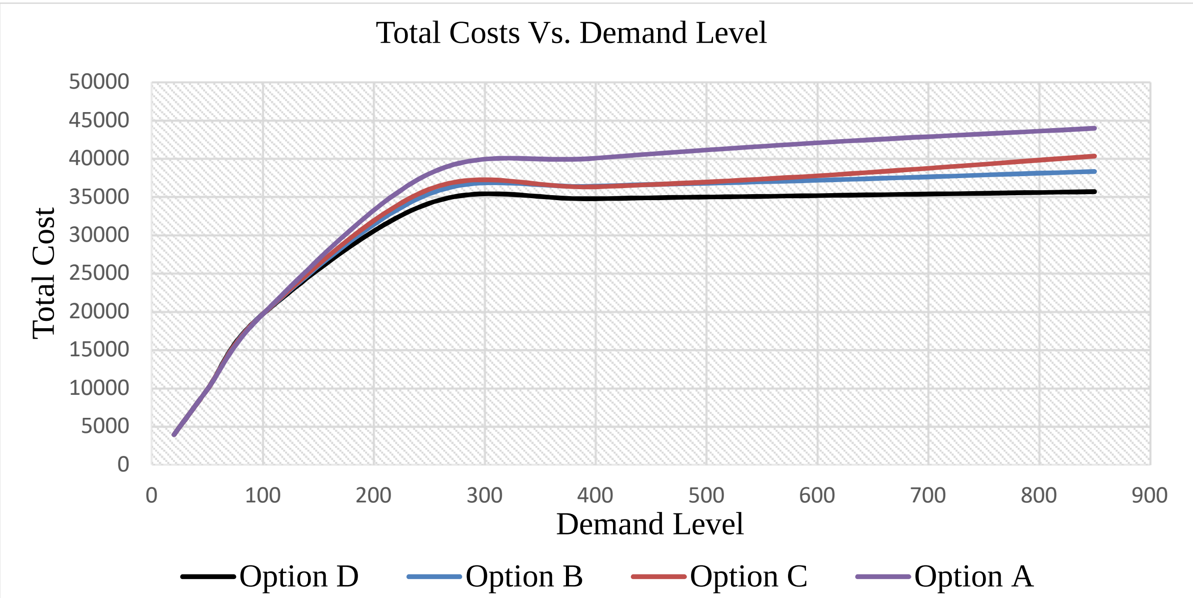


Fig. 2.3 The impact of demand level on the total costs obtained by different RFID options.

Fig. 2.4 presents the response of ordering efficiency (V_i) and holding efficiency (W_i) with the demand level. The figure shows a continuous decrease in the values of V_i and W_i whenever there is a continuous increase in the demand level. Note: Note that a lower value of the ordering V_i and holding W_i efficiencies equate to higher efficiency

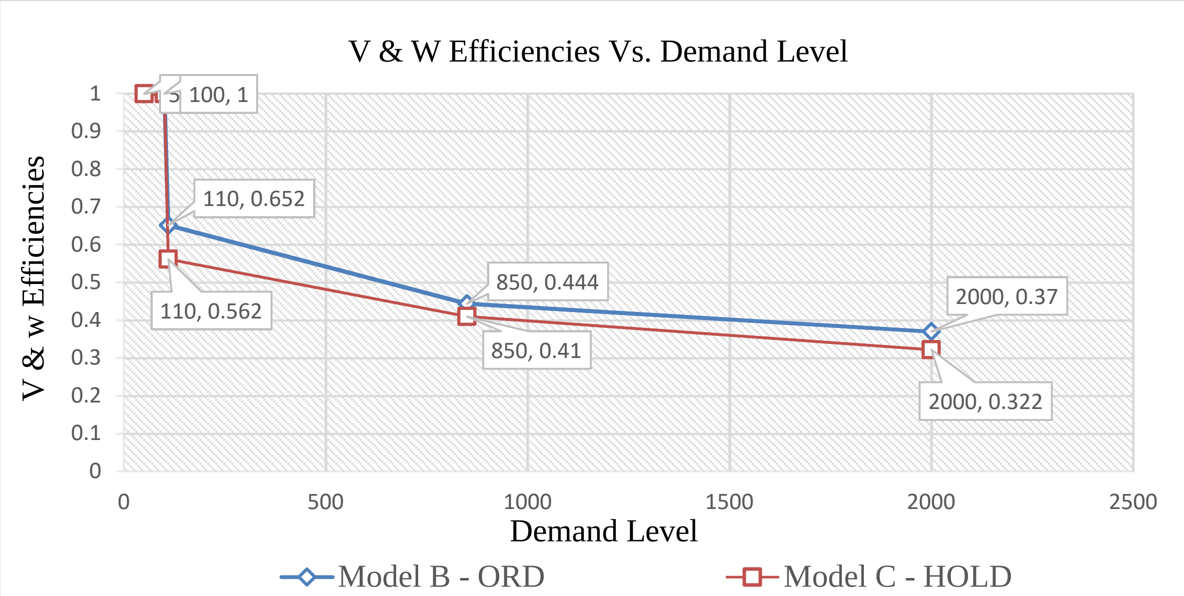


Fig. 2.4 The impact of demand level on holding and ordering efficiencies.

To illustrate the impact of demand level on the total costs of the network and the cost savings obtained by RFID investment, we consider the decision of assigning a warehouse in hospital *i* is an independent decision, in which the location assignment of the storage facility of each hospital does not affect the other location assignment of other hospitals, based on that we will explain the concept of the trend between the cost saving and the demand level through the numerical results obtained by hospital *i*=1 with assigned warehouse..

Fig. 2.3 indicates that the minimum demand level for making the RFID investment viable in ordering and holding efficiencies is given at 110. At the demand level of less than 110, no optimal investment can be found. Also, both no RFID investment (Option A) and optimal RFID investment (Option D) incur the same value of total cost at the demand level of 110. As the demand level increases, the benefits of RFID investing in ordering and holding efficiencies increase. Fig. 2.4 shows that the holding and ordering efficiencies improve significantly near the minimum demand level, and the rate of efficiency keeps improving as the demand level increases. The numerical analysis points out that a large demand level can bring more significant cost savings from RFID technology than a firm with lower demand.

The ordering and holding efficiencies show rapid improvement whenever D_{ij} start to increase more than the breakeven points $D_{ij} \geq 110$. As a result, the demand level plays a major role in RFID investment implementation decision and on the level of this investment in both ordering and holding efficiencies, such findings indicate that the vendor with VMI policy in healthcare network in hospitals with assigned warehouses can achieve higher cost saving by implementing RFID technology in their ordering and holding operations.

2.4.2 Sensitive Analysis

A sensitivity analysis conducted on the model with simultaneous RFID investment (Option D) to study the trend of the holding and ordering efficiency rates against the reduction rate of the total cost of the objective function (cost saving), Fig. 2.5 and Fig. 2.6 shows that the cost-saving improves increase rapidly as the ordering and holding costs improved. As the ordering and holding efficiencies improved rapidly with the increase of the damnd level as we approved it earlier, we can conclude that by implementing RFID technology to improve the ordering and holding efficiencies, the rate of the cost saving is improving rapidly with the increase of the demand level too.

Since the RFID investment decision is based on investment costs-benefits approach and since the cost of an RFID implementation concerns the managers due to the least level of investment cost, a thorough investigation of individual cost components and the cost categories related to supply chain inefficiency activities and RFID outcomes was conducted as elaborated in Table 2.2. Due to the RFID direct and indirect cost categories, we consider having RFID investment lower bound, in which we assigned number of constraints to limit the level of RFID investment to be greater or equal to a specific of investment amount to make the decision of RFID implementation viable and reliable, in our real-world problem we assumed each value of the minimum level of RFID investment (U_{0i} and U_{hi}), which means any RFID investment less than \$ 1000 for ordering operations or holding operations will be unreliable, and the GAMS solver either reject the RFID investment in that operation in the mentioned location or increase the RFID investment to be equal to or greater than \$ 1000.

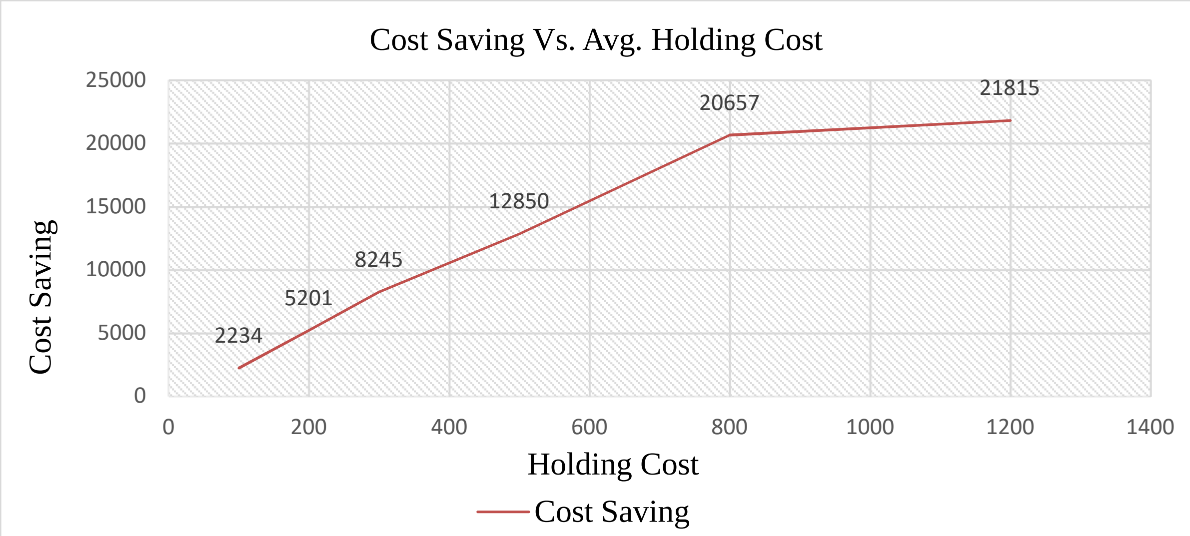


Fig. 2.5 The impact of holding cost on cost saving.

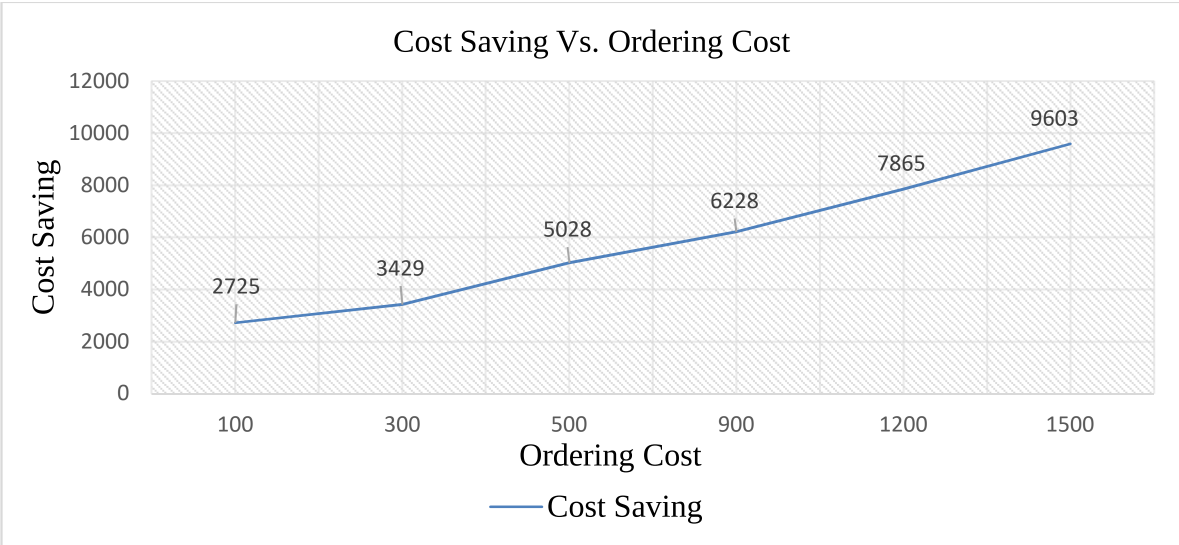


Fig 2.6 The impact of ordering cost on the cost saving.

2.5 Conclusions

In this research, we integrate the location assignment of the storage facility and its replenishment policy with the allocation assignment of RFID technology with its investment level; such integration allows us to have a flexible inventory system by having two types of replenishment policies (VMI and direct delivery policies) in a chain of hospitals subjected to the availability of the warehouse at the hospital. The vendor implements RFID technology at assigned warehouses to enhance his holding and ordering operations to eliminate inventory waste of the expired date, lost, and defected products.

We present in this research the RFID investment evaluation method integrated with the location assignment of the storage facilities at hospitals. This method considers RFID investment level to improve the ordering and holding efficiencies and derives optimal RFID investment levels for the ordering and holding efficiencies. We recommend in this research using the MINLP model with RFID investment evaluation method to solve the location-inventory supply chain network problem; this model gives the vendor a proper understanding to make different strategic and operational decisions.

Considering RFID technology in a vendor managed inventory contract in healthcare network leads to a high impact on the overall cost of the network and generates a significant cost saving by enhancing both ordering and holding efficiencies. This efficiency improvement comes in the form of a reduction in the inventory costs due to the inventory visibility; the reduction in labor costs; the improvement in shortening the administration works regarding the readiness of material orders and purchase orders; and minimizing waste and rejected items. Such RFID cost-saving has a direct impact on the location assignment of warehouse facilities at hospitals, which was discussed in detail in the discussion and analysis section.

To the best of our knowledge, our research is the first effort in integrating VMI and direct delivery policies in a healthcare network based on the location-inventory assignment problem with the allocation assignment of RFID technology and its investment level. Storage facility location assignment and RFID technology allocation assignment under VMI contract are classified as strategic decisions. The vendor, tackling high set up and rental costs, must assign the optimal number of warehouses with implementing RFID technology at hospitals in the most efficient way. Such decisions have a direct impact on cost reduction and maintaining the best possible trade-off between responsiveness and efficiency in healthcare service. In addition, this research is the first study that presents the minimum RFID investment level mathematically, in which we assign constraints to limit the least RFID investment with a specific value to make the decision of RFID implementation viable. Also, this research highlights the impact of cost-saving maintained by implementing RFID technology on the location assignment of the storages at the chain of hospitals.

While our research focuses on integrating the location-inventory assignment with the RFID and its investment level assignment, this research can be extended as future research in developing a model for a non-deterministic condition, such as stochastic or fuzzy demand. In this paper, we consider the demand is deterministic, where stochastic demand has more opportunities in making a significant reduction in overall costs of the network by implementing RFID technology concept through eliminating further costs due to the shortage and overstock incidents. In addition, in this research, we assume the RFID technology as a perfect technology; further research can be done considering RFID as imperfect technology on the objective function and the decision variables of the study.

Also, this research can be extended to bridge the gap of coordination in case of the inventory status between the instant feedback by implementing RFID technology in the hospitals with assigned warehouses and the other warehouses at hospitals with no RFID implementation which use the continuous replenishment policy with a non-instant feedback.

CHAPTER 3: OPTIMAL SUPPLY NETWORK WITH VENDOR MANAGED INVENTORY IN A HEALTHCARE SYSTEM WITH STOCHASTIC DEMAND

3.1 Introduction

Having an effective inventory management system with an optimal supply network is an essential objective for all healthcare industries. This paper presents the optimal location-inventory assignment model applied to a real-world problem arising when a medical vendor supplies a medical implant to a chain of hospitals under Vendor Managed Inventory contract (VMI) in a stochastic environment. The vendor seeks to find the optimal supply chain network that can minimize the system cost by integrating the location assignment of the storage facilities with the allocation assignment of the inventory policies. A Stochastic Mixed-Integer Non-Linear Program (SMINLP) is developed to determine the location of the warehouses, the quantity of products, and the number of orders, the size of the safety stock at the hospitals' warehouses and the vendor's warehouse so that the total cost of transportation, inventory, and other associated operating costs are minimal with a stochastic demand. The input data for the real-world problem is designed based on a practical approach, which represents the actual data for real-world calculations, and a computational result with sensitivity analysis was obtained by using GAMS to illustrate and test the validity of the model's application and behaviour. The study compared the performance of VMI systems under a stochastic environment with the uncertainty of the demand as a random variable following normal and uniform distributions. Total supply chain cost and the network layout are used as the measures of comparison.

3.1.1 Background

Management in the healthcare sector faces several significant challenges, including complexity in healthcare systems, high Supply Chain (SC) and inventory costs, balancing quality and costs, delay in delivery, and unpredictability and uncertainty of the demand (Feibert, 2017). Besides, the increase in the level of competition and the slowdown in the economic growth cycle worldwide are forcing many suppliers and vendors in the healthcare industry to examine their inventory management and their supply network. Vendors are critically reconsidering all areas of their inventory operations, looking for avenues of optimization.

Scholars have indicated that local optimization at any individual part of the value chain network will not guarantee overall system optimization. Therefore, it is logical for vendors to focus on their overall value chain including the flow of material and supply network setup (Kheljani, Ghodsypour, & O'Brien, 2009; Mateen, Chatterjee, & Mitra, 2015). The success of a vendor will depend on its ability to achieve total joint effectiveness across the entire chain. This includes integrating the location assignment of its supply network (storage facilities) with the allocation assignment of the applied inventory policies using VMI.

VMI has gained much attention in recent years. Large firms such as Wal-Mart, Procter & Gamble, HP, and Shell have adopted and tested VMI since the late 1980s. Scholars are actively engaged in studying aspects related to VMI including, but not limited to, replenishment policies and their decisions, contracts, relationships and strategic implications (Marquès, Thierry, Lamothe, & Gourc, 2010; Mateen et al., 2015)

A few researchers have numerically analyzed VMI adoption and tried to mathematically model different aspects of VMI under a stochastic environment. Darwish and Odah (2010), Govindan (2013), and Mateen et al. (2015) have concluded that VMI leads to system significant cost reductions. Kiesmüller and Broekmeulen (2010) researched the benefits and outcomes of VMI in stochastic multi-products systems when dealing with low-demand moving products. Most of these studies only consider the case of a single retailer with no involvement in the location assignment of the storage facilities within the supply network. The high uncertainty of the warehouse setup and rental costs, demands, travel times, and other inputs, directly impact the classical facility location assignment models (Snyder, 2006). This has made the development of the model for the location-inventory assignment problem under uncertainty a high priority for research. This model is unique in its existence, in which optimization under demand uncertainty has been applied to facility location problems, integrating it with the allocation assignment of the replenishment policies under the VMI contract.

3.1.2 Motivation and Application

This research was motivated by a real-world problem arising from one of the world's leading medical implants companies, which manages the supply of medical implants to a chain of hospitals in the province of Ontario. The chain of hospitals under study consists of 147 hospitals located in Ontario, Canada. The vendor is a supplier of three types of medical implants (a heart valve, an artificial knee, and hip). The vendor implements a VMI contract for the whole healthcare network by integrating the location assignment of the storage facility with the allocation assignment of the replenishment policy. The VMI policy is in place for the hospitals with assigned warehouses, and direct delivery policy is in use in the hospitals with no assigned warehouses. Due to the uncertainty in the hospitals' demands, the vendor faces a challenge: if it allocates a storage facility to each hospital, it must assign a suitable replenishment policy based on the availability of the storage facility. The vendor must also extend supply chain activities to comply with all demands regardless of their size or the location of the hospital. Also, the vendor needs to implement an effective inventory safety stock system to cover all expected shortages due to the high uncertainty of demand within the chain of the hospitals' network regardless of the availability of storage facilities at the hospitals.

In this paper, we apply a SMINLP model for coordination in a VMI relationship in a single vendor, multi-commodity, and multi-hospital setting under stochastic demand. In line with the contractual storage agreement and real-world practice, we assume that, based on negotiations between the parties concerned, the vendor has to adhere to a preset upper stock level as safety stock at the vendor's warehouse to cover any expected shortages for the hospitals with no assigned warehouse, in which the penalty cost of any shortage and the extra addition cost on the direct delivery with the same day option, can be utilized efficiently to cover any emergency cases that may occur in case of the hospitals with no assigned warehouses, and use a special type of delivery such as single item delivery with secured and handy transportation method such as using a 3rd party with 24/7 vehicle subject to the hospital request. The rest of the hospitals with assigned warehouses will cover the expected shortages by maintaining the safety stock at their warehouses.

In this research, we integrate two types of replenishment policies based on the location assignment of the storage facilities at the hospitals: VMI policy and direct delivery policy. Each replenishment policy has its type of transportation delivery mode: trucking transportation for all deliveries are directed to the hospitals with assigned warehouses; for the hospitals with no assigned warehouses, the vendor uses a direct delivery on the same day through a courier as a third party.

3.1.3 Research Contribution

The major contribution of our research is designing an integrated location-inventory supply chain network and modelling it mathematically. The research explores integrating the location assignment of the storage facility with the replenishment policy (using either VMI policy or direct delivery policy per hospital). In addition, we present a flexible safety stock system that can respond effectively and efficiently, in which we assigned a local safety stock level at each hospital with an assigned warehouse, and a safety stock level at the vendor's warehouse to cover any expected shortages at the hospitals with no warehouses.

In this research, we present a comparison between the performance of the SMINLP model with the uncertainty of the demand as a random variable following normal and uniform distributions, in which we define the expected shortage as a function of the safety factor in case of demand following the normal distribution. For demand following the uniform distribution, we defined the expected shortage as a function of the reorder point. The total supply chain cost and the layout of the healthcare network are both used as the measure of comparison.

3.1.4 Outline

The paper is organized as follows: a review of the relevant literature is presented in the next section, followed by a presentation of the proposed model in Section 3. Computational results have been carried out to analyze and illustrate the findings and conduct a benefit and sensitivity analysis in Section 4. The last section contains concluding remarks and some avenues for future research.

3.2 Literature Review

Healthcare environments have experienced challenges due to increased healthcare costs, high competition, and sophisticated requirements and regulations. Such challenges have hastened the focus on supply chains in healthcare, which is now more demand driven (Krichanchai & MacCarthy, 2017).

VMI has been defined as a contractual agreement between the vendor and the buyers in which all replenishment decisions and associated costs are covered by the vendor instead of the buyers, and the vendor has the right to decide on when and how much the products will be delivered to the end-users to optimize an inventory with agreed targets of service level (Govindan, 2015).

The VMI in healthcare network covered by the scholars falls into three categories: the first one is literature review papers and focuses on the definition of VMI, classifies the pros and cons of implementing VMI in healthcare networks and its application in the healthcare field; the second one is related to studying real cases in the healthcare industry in which VMI can be cost and quality effective, and in which the VMI boundaries and constraints limitations are considered; the third category is the mathematical modelling and optimizing of VMI in the healthcare network. The third category is the focus of our research with a stochastic demand environment. In our research, we extend the study to integrate the location-inventory assignment problem for a single vendor, multi-commodity and multi hospitals, using two types of replenishment policies under stochastic demand in a chain of hospitals within a healthcare network.

Rad, Razmi, Sangari, and Ebrahimi (2014) studied the stochastic demand using VMI policy for a single vendor, single commodity, and multi-buyer by using weight factor for ordering cost. They formulated a mathematical model for two-echelon supply chain networks and compared the results of using the Vendor Managed Inventory (VMI) policy with the retailer managed inventory (RMI), and the results indicate significant reduction happened by using VMI policy.

Studies conducted by Ben-Daya and Hariga (2004) explored an integrated production for a single vendor and single buyer problem in a stochastic demand environment in which the lead time was responding in linear function with the lot size and assumed to have a fixed delay. A mathematical model was formulated, and a simple algorithm set up to solve this problem.

Razmi, Rad, and Sangari (2010) represent a stochastic demand model for a single supplier and single buyer in which the backorder allows for non-satisfied buyer demand. They present a mathematical model that can enhance the coordination between the vendor and buyer using the VMI model and they make a comparison between the performance of the traditional replenishment system and the VMI system, proving that VMI can bring a cost reduction with high cost effectiveness to the network compared to the traditional system.

Hong, Chunyuan, Xu, and Diabat (2016) formulated a mathematical model for a supply chain network consisting of multi-vendor, multi-buyer and single commodity with stochastic demand with the assumption of having the shortage and unsatisfied demand as a lost sale. VMI and RMI were used separately as inventory replenishment systems, and a comparison was done for the outcomes of both systems and found that using a VMI system in the network has the least total cost.

Mateen et al. (2015) study a supply chain network of one vendor and multi retailer under VMI policy in which all retailers have the same replenishment time of stochastic demand. They consider a shortage at the vendor side and available stock distributed on an equal basis to the retailers.

Rosales, Magazine, and Rao (2014) propose a new hybrid policy as a replenishment policy for medical healthcare supplies under both deterministic and stochastic demands. The concept of hybrid policy is based on merging the low-cost of periodic replenishment and using simulation to optimize the long-run average cost per unit time; this leads to having a significant reduction in cost, inventory, and the number of replenishments. This type of merging avoids having a costly shortage and out-of-stock inventory,

Stochastic demand may occur when the unmet demand is backlogged, which could be costly to the vendor (Corbett, 2001). Stochastic demand is demonstrated in healthcare inventory when the manufacturers and vendors utilize VMI contracts to increase their market share. VMI contracts in stochastic demand become the tools to switch potential lost sales into backorders, thus improving stock-out management (Yao, Dong, & Dresner, 2010). A supply chain incorporates different members whose goal is to deliver products to the end customers (Govindan, 2013). VMI programs have contributed to saving inventory costs while more benefits are accredited to information sharing. VMI can assist healthcare organizations in controlling their ordering, invoice processing, as well as payment, thus avoiding stochastic demand inventory.

We consider using two types of distributions to express the demand uncertainty in order to cover two cases that the vendor may face while seeking accurate demand information from the hospitals. The case of considering the uniform probability distribution for the demand is commonly used in the case of releasing new products, in which sufficient historical data settings are not available to obtain the parameters related to the density function of the demand (Das & Hanaoka, 2014; Wanke, 2008). In the case of having sufficient historical data, the normal probability distribution for the demand can be calculated.

Snyder (2006) reviewed the literature on robust and stochastic facility location models to illustrate approaches or methods for optimization under one category of decision-making environment: uncertainty. According to Snyder (2006), in uncertainty situations, information concerning probabilities is unknown, and parameters are uncertain. The problem under uncertainty situations often seeks to optimize the system's worst-case performance. According to Snyder (2006), robust and stochastic optimization focus on determining a solution that performs well under different combination of random parameters. Snyder (2006) further identified facility location stochastic models, which are aimed at maximizing the system's expected profit or minimizing the expected cost. According to Snyder (2006), other stochastic models take a probabilistic approach.

Lead time in the healthcare inventory management system denotes that inventory is stochastic. Pan and Yang (2002) suggest that lead time can be controlled by creating a procedure that would lead to the optimal order quantity at a time when the lead time demand is considered normal. During the lead time, demand viability may occur owing to the possibility of a new product on the market, which has the same characteristics as the existing product (Govindan, 2015). Demand variability can also happen when there is competition, which leads to the use of different tactics to influence sales. In both instances, the healthcare sector can experience demand uncertainty or stochastic demand. Successful implementation of VMI, even under stochastic demand, is having adequate information exchange between the supplier and the customers (Corbett, 2001; Danese, 2006).

The uniform and normal distributions are both commonly used to represent the uncertainty of the demand. VMI policy is a known industrial practice for facilitating supply chain collaboration and integration. As noted by Zavanella and Zanoni (2009), VMI facilitates supply chain collaboration and integration by integrating practical aspects of the supply chain in transportation planning, inventory management, and pricing policies.

Most VMI models in the healthcare network assume stochastic customer demand under normal probability distribution and uniform probability distribution. For example, Abdel-Malek and Montanari (2005) identified using two constraints, the approach to examining the solution space of a multi-product newsboy problem and suggested a method for obtaining each product's optimum batch size. The method was based on employing Kuhn-Tucker, Leibniz Rule, and Lagrangian Multipliers conditions. The approach could also engage these conditions and the iterative techniques to generate near optimum or optimum solution values. According to Abdel-Malek and Montanari (2005), this approach could be utilized when dealing with probability distribution functions of demands of products, as well as in tightly constrained cases.

Researchers have documented in the existing literature methods of calculating the expected shortage per cycle under normal probability distribution and uniform probability distribution formulated as a function of the reorder point, and safety factor.

Kundu and Chakrabarti (2012) formulated the expected shortage per cycle for a single channel as a function of safety factor with demand following normal probability distribution. Alawneh and Zhang (2018) extended the expected shortage per cycle as a function of a safety factor to consider two echelon dual-channel situations. Moreover, Alawneh and Zhang (2018) relaxed and assumed the expected shortage per cycle as a function of reorder point with demand following the uniform probability distribution.

Gholami-Qadikolaei, Mohammadi, Amanpour-Bonab, and Mirzazadeh (2012) present the lost sales and mixed inventory backorder encompassing four variables: backorder rate, safety factor, lead time, and order quantity. In view of Gholami-Qadikolaei et al. (2012), the order quantity variable could have defective items as random variables. The mixed inventory backorder model suggested by Gholami-Qadikolaei et al. (2012) was assumed to contain controllable negative exponential backorder rate and negative exponential lead time crashing costs. Gholami-Qadikolaei et al. (2012) held that within the context of the real market, unsatisfied demands predict longer lead time, which in turn predict a reduction in the proportion of the rate of the backorder. Gholami-Qadikolaei et al. (2012) further noted that there is a relationship between the backorder rate and the length of lead time mediated by the number of shortages. Again, in the suggested continuous review inventory system, Gholami-Qadikolaei et al. (2012) assumed that the lead time demand takes the form of a normal distribution curve and solves the problem by applying minimax distribution-free procedure.

Yano (1985) developed an algorithm for determining values for the optimal parameter with complete back ordering. The algorithm was designed to serve the purpose of order quantity-reorder point systems. Unlike other algorithms that use an approximation, the suggested algorithm uses an exact cost function in determining the values for the optimal parameter for order quantity-reorder point system. A new heuristic algorithm was also presented, which, according to Yano (1985) could yield excellent results as it was deemed more efficient than the optimal procedure alternative.

We present the solution approach for solving the MINLP model by defining the Expected Shortage per Cycle (ESC) with respect to the Cycle Service Level (CSL). Silver and Peterson (1985) formulated ESC for a single case. In our research, we extend the same concept of ESC method and define the ESC as a function of the safety factor in the case that demand follows a normal distribution and as a function of reorder point in the case that demand follows a uniform distribution. Many researchers solve the expected shortage per cycle using GAMS solver when the demand follows the normal and uniform distributions with deterministic lead time.

After conducting a comprehensive literature review on the healthcare supply network with VMI under stochastic demand, we found that the contribution of this research concerning the demand as a random variable and expected shortage per cycle is categorized into two streams. In the first stream, we consider the demand as an independent random variable for each hospital and the total healthcare network demand is the aggregation of all hospitals within the healthcare network. In the second stream, the expected shortage per cycle and the safety stock level for the hospitals with warehouses are independent variables for each hospital; in contrast, the safety stock level at the vendor's warehouse is the dependent variable and used to cover any unexpected shortage of the demand for the hospitals with no warehouses. In addition, the contribution of this research with regards to the supply network as a location-inventory assignment problem is integrating the location assignment of the warehouses at the hospitals with the allocation assignment of the replenishment policy (VMI) delivery or direct delivery policies.

3.3 Model formulation

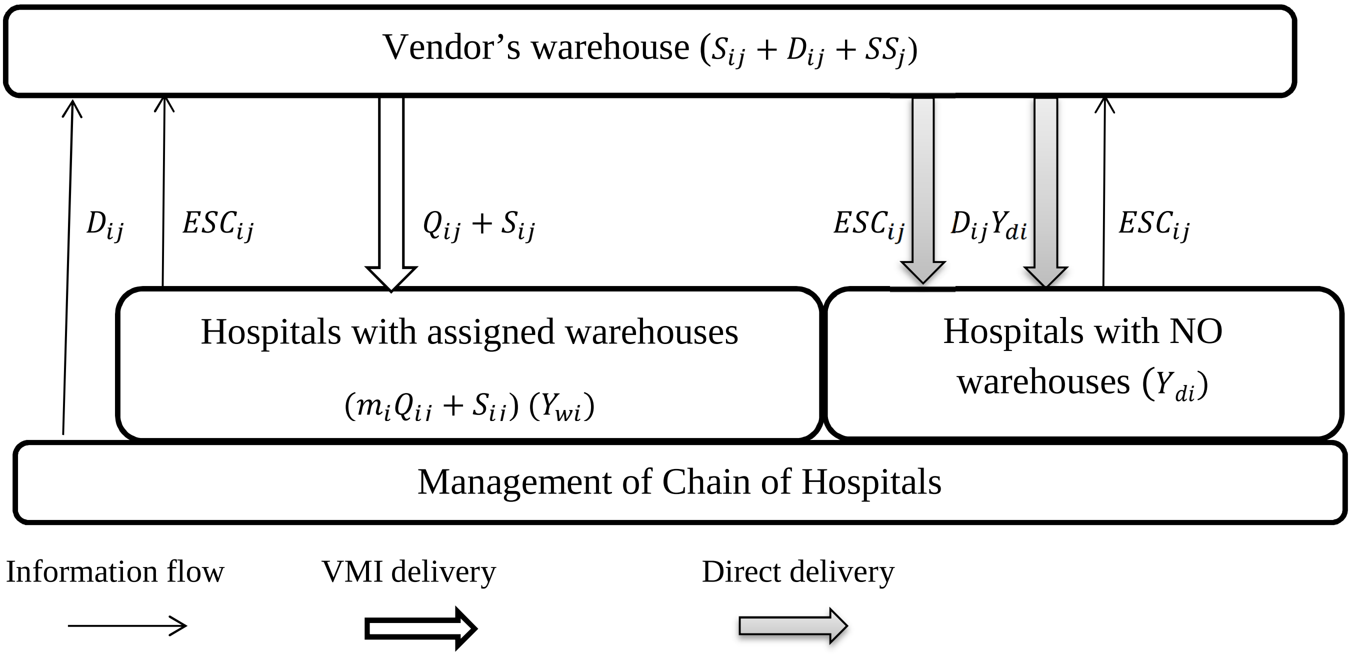
3.3.1 Problem Statement

In this research, we present a VMI model with a single vendor, multi-hospital, and multicommodity using multiple types of replenishment policies integrating into the healthcare supply network located in Ontario-Canada. The vendor supplies three types of medical implants (Heart Valve, artificial hip and artificial knees) to a chain of hospitals located in Ontario-Canada by two type of replenishment policies, VMI policy for the hospitals with assigned warehouses by using trucking transportation delivery and direct delivery to the hospitals with no assigned warehouses subjected their operation's schedule by same day delivery by courier (Purolator). Fig. 3.1 demonstrates the material, delivery, and information's flows of the healthcare supply network.

In case of having a medical implant shortage, the vendor allocates a safety stock level at all hospitals with assigned warehouses. For the rest of hospitals with no assigned warehouses, the vendor assigns safety stock level at his storage facility to cover any expected shortages with same day delivery by a courier.

The vendor seeks to cover all demand of the chain of hospitals by finding the optimal supply chain network that can minimize the system cost. We model the problem as SMINLP to determine the location assignment of the storage facilities at the hospitals and the inventory policy sequentially, so the total expected cost of the objective function is minimized and subject to a number of associated costs and to satisfy all demand regardless of the location of the hospitals and the size of the demand. In this paper we test the demand as a random variable by two types of probability distributions: In the first distribution, we consider the demand as a random variable follows the normal distribution and its expected shortage per cycle (ESC) defined by a safety factor. In the second destruction, we consider the demand as a random variable follows the uniform distribution and its expected shortage per cycle (ESC) defined by reorder point.

Fig. 3.1 Material and an information flow diagram for the chain of hospitals with and without assigned warehouses.



3.3.2 Model Assumptions:

1. There is no capacity constraint at the vendor's warehouse capacity.
2. Hospitals face independent, uniformly, and normally distributed demand. The lead time is deterministic and is different for different hospitals.
3. In case the vendor supplies in shortage status at hospitals, penalty costs will be levied.
4. The demand should be satisfied regardless of the size of the demand or the location of the hospitals.
5. The vendor bears holding costs, order costs, setup costs, delivery costs, warehouse rental costs, penalty costs, and any backorder costs.
6. In case of a shortage, available safety stock is allocated at each hospital with the assigned warehouse to cover such a shortage. Otherwise, safety stock allocated at the vendor's warehouse will cover any shortage that may happen at the hospitals with no assigned warehouses.

3.3.3 Model Notations

3.3.3.1 Indices

We will use the suffixes *i* and *j* for hospitals and products, respectively.

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

j an index for product; *j=1, 2…, n*

3.3.3.2 Notations

h_{ij} Holding cost for Hospital *i* for product *j* (dollar/unit/year)

h_j^v Holding cost at the vendor's warehouse for product *j* (dollar/unit/year)

F_i Total storage space size used at the hospital *i* with assigned warehouse (f^3)

K_i Order and transportation cost per order to hospital *i* (dollars per order)

FC_i Setup cost per for having storage facility at the hospital *i* (dollar per setup)

D_{ij} Mean demand rate (units per year) for hospital *i* for product *j* (units per year)

Vo_j The volume of the product *j* (f^3 per item)

BigM An integer number representing a high value

G_{ij} Order and transportation cost per item to hospital *i* (dollars per item)

μ_{ij} Mean demand during the lead time at the hospital *i* for product *j* (units per lead time)

ρ_j Shortage penalty cost for product *j* at hospital *i* (dollar per unit)

σ_{ij} Standard deviation during the lead time of the demand rate (units per lead time)

x_{ij} Demand during the lead time for product *j* at hospital *i* (random variable)

$f(x_{ij})$ The probability density function of the demand for product *j* ah hospital *i*

Z_j Safety factor for product *j* at the vendor's warehouse.

3.3.3.3 Decisions Variables:

Y_{wi} 1 if the warehouse set at hospital *i*, 0 otherwise

Y_{di} 1 if the direct delivery set at hospital *i*, 0 otherwise

Q_{ij} The quantity of product *j* delivered to hospital *i* with assigned warehouse

SS_j Safety Stock level of product *j* at the vendor's warehouse

S_{ij} Safety Stock level of product *j* at the hospital *i* with assigned warehouse

R_{ij} Reorder point level of product *j* at the hospital *i* with the assigned warehouse.

SF_{ij} Safety Stock factor for product *j* at the hospital *i* with the assigned warehouse.

m_i Number of orders delivered to hospital *i* with the assigned warehouse.

3.3.3.4 Objective Function

$$\text{Min ETC}_{\text{VMI}} = \sum_{i=1}^{r}\sum_{j=1}^{n} G_{ij} D_{ij} Y_{di} + \sum_{i=1}^{r}\sum_{j=1}^{n} h_{ij}\left(\frac{Q_{ij}}{2} + S_{ij}\right) + \sum_{j=1}^{n} h_j^v SS_j + \sum_{i=1}^{r} FC_i Y_{wi}$$
$$+ \sum_{i=1}^{r} K_i m_i + \sum_{i=1}^{r}\sum_{j=1}^{n} \rho_j m_i (ESC_{ij}) \quad (1)$$

The objective function of SMINLP model is to minimize the total annual expected cost, in which optimize the ordering, holding, transportation, setup and shortage costs in order to have an optimal supply network with location assignment decisions for assigning warehouses at the hospitals and integrates with assigning of the relevant replenishment policy. For a given inventory policy (Q_{ij}, R_{ij}) for product j at the hospital i with the assigned warehouse, the average inventory level for the time period can be defined as the summation of the average cycle inventory and the safety stock level, in which it is expressed as $\frac{Q_{ij}}{2} + S_{ij}$, where the safety stock level S_{ij} equals $R_{ij} - \mu_{ij}$. Such relaxation of the average inventory is widely used in real-world cases and sited in academically textbook (De Bodt & Graves, 1985; Fattahi, Hajipour, & Nobari, 2015; Nahmias & Cheng, 2009; Yano, 1985)

The first term of the objective function (1) refers to the transportation and ordering costs for the direct delivery option for the hospitals with no assigned warehouse. The second term refers to the annual approximated holding cost for the hospitals with assigned warehouses. The third term refers to the annual holding costs of the safety inventory at the vendor's warehouse. The fourth term refers to the fixed cost, including the setup and rental costs at the hospitals with assigned warehouses. The fifth term refers to the ordering and transportation cost per order at the hospitals with assigned warehouses. The sixth term refers to the annual shortage cost, and equal to the shortage penalty cost multiplied by the expected number of shortages per cycle and the annual number of orders.

In this research, the expected shortage per replenishment cycle (ESC) can be written as:

$$\mathrm{ESC}\left(\mathrm{R_{ij}}\right) = \int_{\mathrm{R_{ij}}}^{\infty} \mathrm{f}(\mathrm{x_{ij}}) \left(\mathrm{X} - \mathrm{R_{ij}}\right) \mathrm{d}(\mathrm{x_{ij}}) \tag{2}$$

Where, f(x) is the probability density function of the demand, rearranging equation (1), we obtain the final shape of the objective function

$$Min\, ETC_{VMI} = \sum_{i=1}^{r}\sum_{j=1}^{n} G_{ij}\, D_{ij} Y_{di} + \sum_{i=1}^{r}\sum_{j=1}^{n} h_{ij}\left(\frac{Q_{ij}}{2} + \left(R_{ij} - \mu_{ij}\right)\right) + \sum_{j=1}^{n} h_j^v\, SS_j + \sum_{i=1}^{r} FC_i Y_{wi} + \sum_{i=1}^{r} K_i m_i \;+\; \sum_{i=1}^{r}\sum_{j=1}^{n} \rho_j\, m_i \left(\int_{R_{ij}}^{\infty} f(x_{ij}) \left(X - R_{ij}\right) d(x_{ij})\right) \tag{3}$$

S.T.

$$Y_{di} + Y_{wi} = 1 \qquad for\ \forall\ i = 1, \dots, r \tag{4}$$

Network constraint, each hospital *i* either having a warehouse with VMI delivery or having a direct delivery with no assigned warehouse.

$$\sum_{j=1}^{n} \left(Q_{ij} + \left(R_{ij} - \mu_{ij}\right)\right) Vo_j \leq Y_{wi} F_i \qquad for\ \forall\ i = 1, \dots, r \tag{5}$$

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.

$$Q_{ij} \leq Y_{wi} M \qquad for\ \forall\ i = 1, \dots, r\ \ and\ j = 1, \dots, n \tag{6}$$

Upper bound order quantity constraint, the maximum number of each order quantity for each product is equal to or less than the bigM value for the hospital *i* with the assigned warehouse.

$$SS_{ij} \geq m_i \left(\int_{R_{ij}}^{\infty} f(x_{ij}) \left(X - R_{ij}\right) d(x_{ij})\right) \qquad for\ \forall\ i = 1, \dots, r\ \ and\ j = 1, \dots, n \tag{7}$$

Lower bound safety stock level constraint, the lower bound of the safety stock level at the hospital i with the assigned warehouse to be equal to or greater than the expected shortage of all orders.

$$SS_j = Z_j \sigma_j \qquad for\ \ \forall\ j = 1, \dots, n \tag{8}$$

Safety inventory at the vendor's warehouse constraint, the expected shortages at hospitals with no assigned warehouses.

$$\sigma_j = \sqrt{\sum_{i}^{r} (\sigma_{ij})^2 \, Y_{di}} \qquad for \ \ \forall \, j = 1, \dots, n \tag{9}$$

The demand standard deviation constraint, the standard deviation of the demands of all hospitals with no assigned warehouses for each product equal to the square root of the total square of the standard deviations of all hospitals with no assigned warehouses for each product.

$$m_i \leq Y_{wi} M \qquad for \, \forall \, i = 1, \dots, r \tag{10}$$

Upper bound of the number of orders constraint, the maximum number of orders shipped to the hospital *i* with assigned warehouse should be equal to or less than the bigM value.

$$Q_{ij} m_i \geq \; D_{ij} Y_{wi} \qquad for \, \forall \, i = 1, \dots, r \;\; and \, \forall \, j = 1, \dots, n \tag{11}$$

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 product j of hospital *i* with the assigned warehouse.

$$Q_{ij}, m_i,, SS_j, R_{ij} \;\geq 0 \qquad for \, \forall \, i = 1, \dots, r \;\; and \, j = 1, \dots, n \tag{12}$$

Non-negativity constraint, the order quantity, number of orders, the safety stock level for product *j* at the hospital *i* and the reorder point level are all non-negative values.

$$Y_{di}, Y_{wi} \in [0,1] \tag{13}$$

Binary constraint, the location decision variables are binary decisions.

The problem given by (3)-(13) is a stochastic mixed-integer nonlinear program (SMINLP), model. We use GAMS to solve the problem with the real-world case in the next section.

In this research, we will discuss and analyze the solution approaches for both normal and uniform demand distributions by expressing the expected shortage per cycle (ESC) for each demand distribution. in which we will formulate the expected shortage per cycle as a function of a safety factor SF_{ij} in case of normal demand distribution as presented earlier by Alawneh and Zhang (2018); Kundu and Chakrabarti (2012). Also, we will formulate the expected shortage per cycle (ESC) as a function of reorder point R_{ij} in case of uniform demand distribution as presented by Alawneh and Zhang (2018).

3.3.4 Uniform Demand Distribution as a Function of Reorder Point R_{ij}

We consider the demand follows the uniform distribution of (0, D_{ij}), in which the lower limit of the uniform demand distribution is zero, and the upper limit is D_{ij}, based on our assumption, we can formulate the expected shortage per cycle for this case as follows (Alawneh & Zhang, 2018):

$$\int_{R_{ij}}^{\infty} f(x_{ij})\, d(x_{ij}) = \left(1 - \frac{R_{ij}}{D_{ij}}\right) \tag{14}$$

and

$$\int_{R_{ij}}^{\infty} (x_{ij} - R_{ij})\, f(x_{ij})\, d(x_{ij}) = \left(\frac{D_{ij}}{2} - R_{ij} + \frac{{R_{ij}}^2}{2D_{ij}}\right) \tag{15}$$

If (15) substituted into (3) to replace the expected shortage per cycle term in the objective function, then the objective function will be presented as follows:

$$Min\ ETC_{VMI} = \sum_{i=1}^{r}\sum_{j=1}^{n} G_{ij}\, D_{ij} Y_{di} + \sum_{i=1}^{r}\sum_{j=1}^{n} h_{ij}\left(\frac{Q_{ij}}{2} + SS_{ij}\right) + \sum_{j=1}^{n} h_j^v\, SS_j + \sum_{i=1}^{r} FC_i Y_{wi} + \sum_{i=1}^{r} K_i\, m_i + \sum_{i=1}^{r}\sum_{j=1}^{n} \rho_j\, m_i\, \left(\frac{D_{ij}}{2} - R_{ij} + \frac{{R_{ij}}^2}{2D_{ij}}\right) \tag{16}$$

S.T.

All constraints (4-13) will remain the same except constraint (7) will be replaced with constraint (17), and a new constraint (18) will be added to connect the reorder point R_{ij} with safety factor SF_{ij}.

$$SS_{ij} \geq m_i \left(\frac{D_{ij}}{2} - R_{ij} + \frac{{R_{ij}}^2}{2D_{ij}}\right) \qquad for\ \forall\ i = 1, \dots, r \ \ and\ j = 1, \dots, n \tag{17}$$

Lower bound safety stock level constraint, the lower bound of the safety stock level at the hospital *i* with the assigned warehouse to be equal to or greater than the expected shortage of all orders.

$$R_{ij} = \mu_{ij} + SF_{ij}\sigma_{ij} \qquad for\ \forall\ i = 1, \dots, r \ \ and\ j = 1, \dots, n \tag{18}$$

Reorder point level constraint; the reorder point R_{ij} for each product *j* and each hospital *i* with assigned warehouse equal to the summation of the mean demand during the lead time and the multiplication of the safety factor SF_{ij} and the demand standard deviation during the Leadtime for each product *j* and hospital *i* with the assigned warehouse.

3.3.5 Normal Demand Distribution as a Function of a Safety Factor SF_{ij}

In this research, we assumed that the demand is a normally distributed and the lead time is fixed and we defined the $SS_{ij} = SF_{ij}\sigma_{ij}$, in which $R_{ij} = \mu_{ij} + SF_{ij}\sigma_{ij}$. Alawneh and Zhang (2018); Kundu and Chakrabarti (2012) formulated the expected shortage per order as a function of a safety factor SF_{ij} for a single channel as it follows:

$$ESC(SF_{ij}) = \left\{\frac{\sigma_{ij}}{2}\left(\sqrt{1 + SF_{ij}^2} - SF_{iJ}\right)\right\} \quad for \ \forall \ i = 1, \dots, r \ \ and \ j = 1, \dots, n \qquad (19)$$

Based on this formulation, we can formulate the objective function under VMI policy as it follows:

$$Min \ ETC_{VMI} = \sum_{i=1}^{r}\sum_{j=1}^{n} G_{ij} \, D_{ij} \, Y_{di} + \sum_{i=1}^{r} K_i m_i + \sum_{i=1}^{r}\sum_{j=1}^{n} h_{ij}\left(\frac{Q_{ij}}{2} + \left(SF_{ij}\sigma_{ij}\right)\right) + \sum_{j=1}^{n} h_j^v \, SS_j + \sum_{i=1}^{r} FC_i Y_{wi}$$
$$+ \sum_{i=1}^{r}\sum_{j=1}^{n} \rho_{ij} \ m_i \left\{\frac{\sigma_{ij}}{2}\left(\sqrt{1 + SF_{ij}^2} - SF_{iJ}\right)\right\} \qquad (20)$$

S.T.

All constraints (4-13) and constraint (18) will remain the same except constraint (7) will be replaced with constraint (21).

$$SS_{ij} \geq m_i \left\{\frac{\sigma_{ij}}{2}\left(\sqrt{1 + SF_{ij}^2} - SF_{iJ}\right)\right\} \qquad for \ \forall \ i = 1, \dots, r \ \ and \ j = 1, \dots, n \qquad (21)$$

Lower bound safety stock level constraint, the lower bound of the safety stock level at the hospital *i* with the assigned warehouse to be equal to or greater than the expected shortage of all orders

3.4 Analysis and Discussion

3.4.1 Data Settings

In order to illustrate the application of the model developed in the previous section for the real-world problem, we consider using VMI contract at a healthcare network with a single vendor, 147 hospitals located in Ontario-Canada, and three types of medical implants. The input data for the real-world problem designed based on a practical approach which represents the actual data for real-world calculations, Table 3.1 demonstrates the base parameters that we used as input for this problem.

To solve the SMINLP model for the expected total cost of the healthcare network, we used GAMS 25.1- Baron solver software on an Intel(R) Core (TM) i7-4720HQ CPU@ 2.6 GHz with 8 GB RAM.

Table 3.1 The base parameters and scalars values used in the computational results and analysis

Parameter	Value
Z_j	2.00 for the customer service level of 97.72%
h_j^v	10% of the average cost per item at the vendor's warehouse
ρ_{ij}	10% of the average cost per item
FC_i	($3000-$1500) subjected to the location zone of the hospital
D_{ij}	0.0009 city population (Hart et al., 2015; D. S. Lee et al., 2004)
h_{ij}	10% of the average cost per item
K_i	$100 plus transportation cost subjected to hospitals' locations
G_{ij}	$100 plus the courier rates for same day delivery

3.4.2 Sensitivity Analysis

In order to understand the levers affecting the performance of the VMI contract in the healthcare network, we carried out a sensitivity analysis on various parameters. To study the sensitivity analysis, one parameter is being changed at a time, keeping others at their base levels with no changes. For the sake of explanation, we consider hospital i=1 only to analyze the impact of the change in parameters.

In this research, we analyzed the impact of the change in order and transportation cost per order, and per item, the standard deviation of the demand, holding cost, and penalty shortage cost per order on the expected total cost (ETC) of the VMI system at hospital # 1. The results are shown in Tables 3.2a to 3.2d, respectively.

The expected total cost (ETC) of the VMI System increases with an increase in order and transportation cost per order, and per item, holding cost and penalty shortage parameters till certain parameters' values, in which the location assignment decision impact the total cost of the network and switch either from assigning warehouse at the hospital # 1 to having direct delivery policy instead and with no storage facility at the hospital subjected to the total cost optimization concept (e.g., the location assignment switch can be noticed in items # 7 and 8 in Tables 3.2a to 3.2d)

As the order and transportation cost K_i increases, it becomes relatively cheaper to get more units in a single order, thus the value of Q_{ij} increases. On the other hand, as the holding cost increases, it becomes relatively costlier to keep a unit in stock. Thus, it leads to a decrease in the value of m_i (The vendor delivers orders more frequently) as can be seen in Table 3.1 and Fig. 3.2.

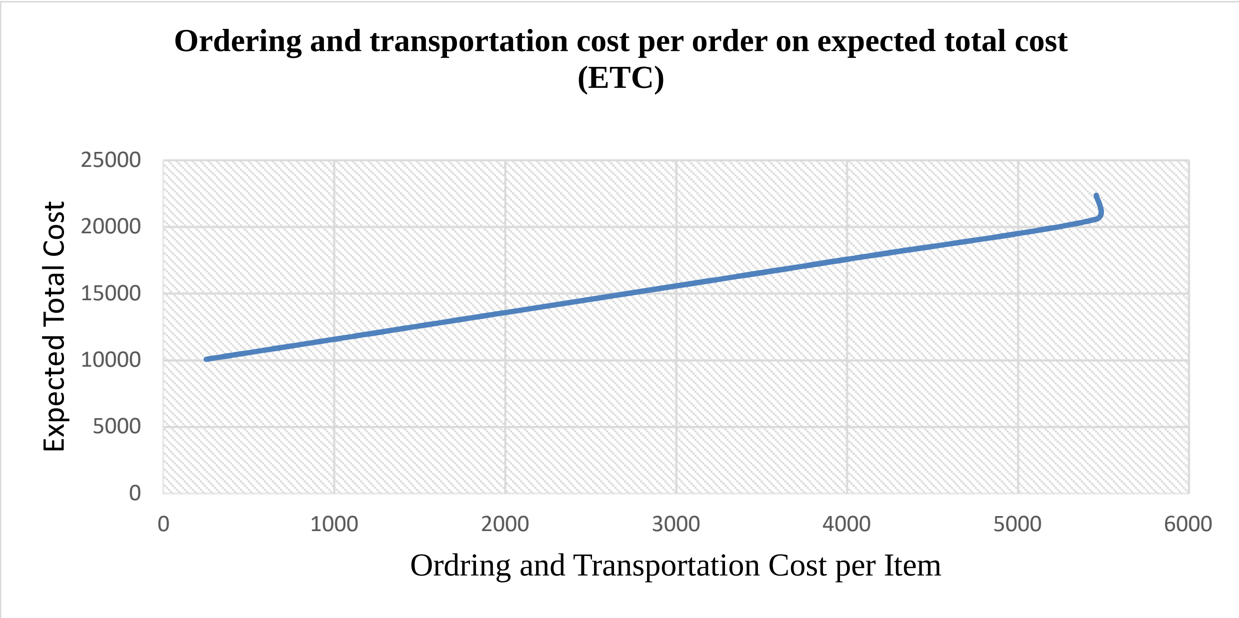


Fig. 3.2. The impact ordering and transportation cost per order on the total expected cost.

Table 3.2a Impact of ordering and transportation cost per order on expected total cost (ETC)

#	K_1	Y_{w1}	Y_{d1}	ETC_1
1	250	1	0	10060.00
2	500	1	0	10560.00
3	1000	1	0	11560.00
4	2000	1	0	13560.00
5	3000	1	0	15560.00
6	4000	1	0	17560.00
7	5459	1	0	20568.00
8	5460	0	1	22362.20

With the same sequence, as the order and transportation cost G_{1j} increases, it becomes relatively cheaper to use the direct delivery shipping per item. Thus the value of expected total cost will be less in case of direct delivery policy without assigned warehouse compares with the VMI policy with the assigned warehouse. The location assignment stays with $Y_{w1} = 0$ and switched to $Y_{w1} = 1$ as soon as the value of ordering and transportation cost per item become more costly compared with ordering and transportation cost per order and as shown in Table 3.2b and Fig. 3.3

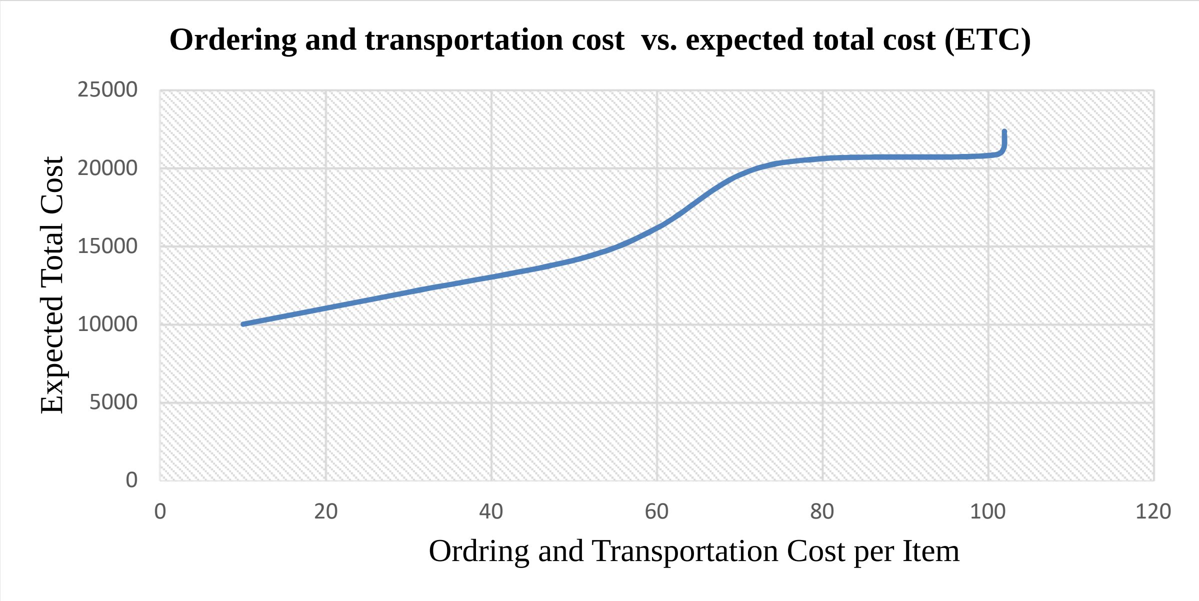


Fig. 3.3 The impact of ordering and transportation cost per item on the total expected cost.

Table 3.2b Impact of order and transportation costs per item on expected total cost (ETC)

#	G_{1j}	Y_{w1}	Y_{d1}	ETC_1
1	10	0	1	10060.00
2	30	0	1	10560.00
3	50	0	1	11560.00
4	60	0	1	13560.00
5	70	0	1	15560.00
6	80	0	1	17560.00
7	101	0	1	20568.00
8	102	1	0	22362.20

On the other hand, as shown in Table 3.2c and Fig. 3.4, as the holding cost increases, it becomes relatively costlier to keep a unit in stock. Thus, it leads to a decrease in the value of m_i (The vendor delivers orders more frequently).

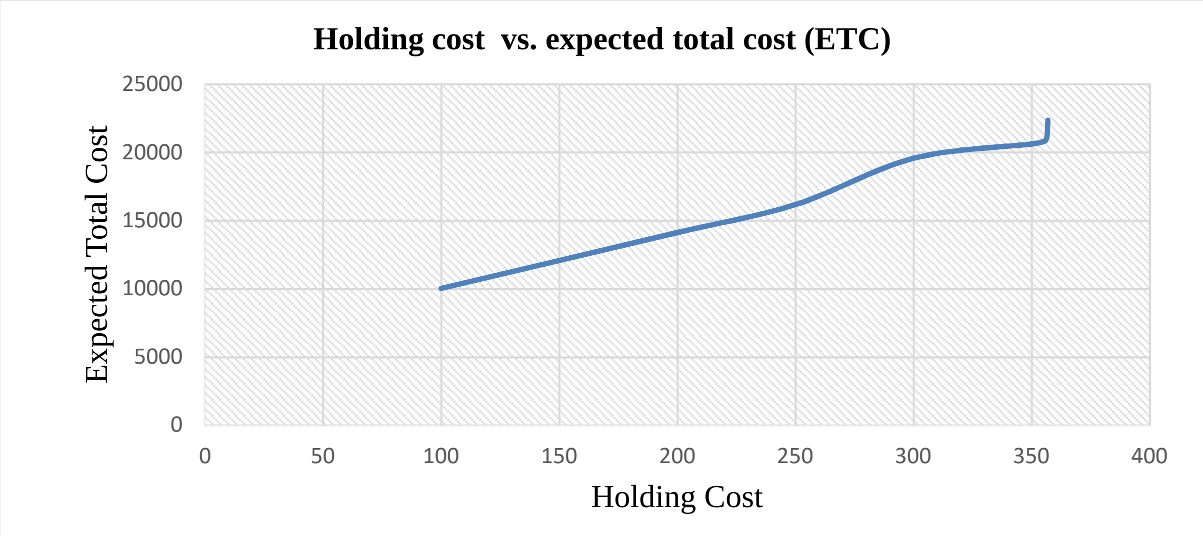


Fig. 3.4 The impact of holding cost on the total expected cost.

Table 3.2c Impact of holding cost on expected total cost (ETC)

#	h_{1j}	Y_{w1}	Y_{d1}	ETC_1
1	100	1	0	10018.00
2	150	1	0	12068.00
3	200	1	0	14118.00
4	250	1	0	16168.00
5	300	1	0	19568.00
6	350	1	0	20618.00
7	356	1	0	20870.00
8	357	0	1	22362.20

As the shortage penalty cost ρ_{ij} increases, it becomes relatively less attractive to keep the safety stock at the hospitals with assigned warehouse till the point where keeping the safety stock at vendor's warehouse and switching to the direct delivery policy without assigned warehouse is cheaper to adopt VMI policy with assigned warehouse as shown in Table 3.2d and Fig. 3.5.

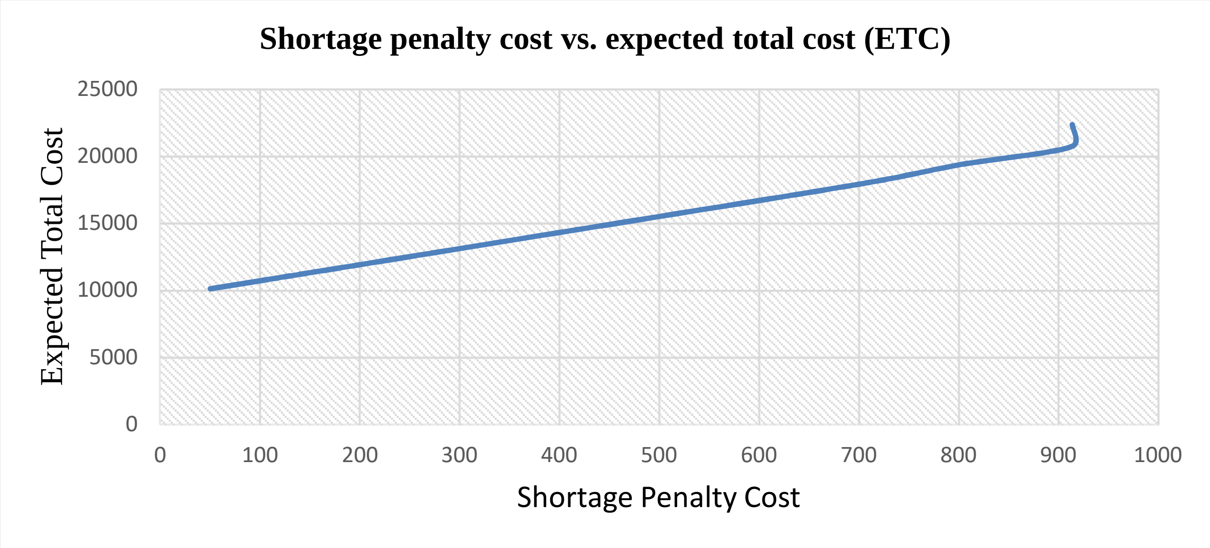


Fig. 3.5 The impact of penalty cost per on the total expected cost.

Table 3.2d Impact of shortage penalty cost on expected total cost (ETC)

#	ρ_{ij}	Y_{w1}	Y_{d1}	ETC_1
1	50	1	0	10118.00
2	100	1	0	10718.00
3	150	1	0	11318.00
4	400	1	0	14318.00
5	700	1	0	17918.00
6	800	1	0	19358.00
7	913	1	0	20714.00
8	914	0	1	22362.20

As expected, the expected total cost (ETC) increases with an increase in demand uncertainty due to the increase in demand standard deviation during lead time σ_{ij}. As a result of the increase in demand uncertainty, the vendor would now have to assign more safety stock at his storage facility to cover any expected shortages at the hospitals with no assigned warehouses or to have more safety stock level to at the hospitals with assigned warehouses to cover their shortages that may occur. Those findings are shown in table 3.3 and Fig. 3.6, when

$\sigma_{ij} \leq 4$ the vendor will respond to the expected shortages by increasing safety stock level at the hospital #1 warehouse, contrary, when $\sigma_{ij} > 4$, the vendor starts to increase the safety stock level at his storage facility to cover any shortages at hospital # 1 as no storage facility assigned anymore in this hospital due to the high uncertainty demand as signified by the increase in σ_{ij}. The system switched to the option of having no warehouse whenever the $\sigma_{ij} > 4$ due to the increase in the safety stock, in which will lead to have more adding cost due to the increase in rental space of the warehouse, holding cost and setup costs, which makes the decision of having no assigned warehouse is more efficient than set up a storage facility at the hospital.

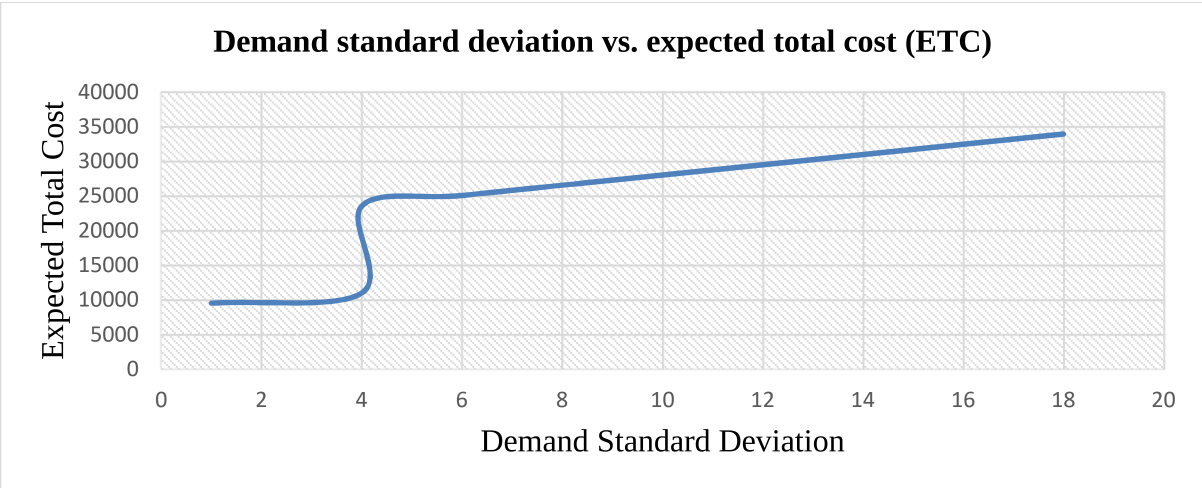


Fig. 3.6 The impact of demand standard deviation on the total expected cost.

Table 3.3 Impact of demand standard deviation during the lead time on ETC.

#	σ_{ij}	Y_{w1}	Y_{d1}	ETC_1
1	1.00	1	0	9518.00
2	4.00	1	0	10998.00
3	4.005	0	1	23611.70
4	6.00	0	1	25088.00
5	9.00	0	1	27308.00
6	12.0	0	1	29528.00
7	15.00	0	1	31748.00
8	18.00	0	1	33968.00

The conclusion derived from the sensitivity analysis remained unchanged for various ranges of parameter values. The trend of the expected total cost (ETC) increases with the increases of the mentioned parameters.

3.4.3 Discussion

Under the VMI contract, the vendor takes responsibility for replenishing the hospital's stock and covering all associated costs. Thus the vendor should gain access to accurate demand data for the chain of hospitals (147 hospitals), the vendor seeks to include the levers of the replenishment time, frequency of replenishments in each order and the expected shortages at various hospitals with no assigned warehouses, also, the vendor should include the following levers of the number of orders, the quantity of each order and the safety stock level to maintain at the hospitals with assigned warehouses to cover their expected shortages.

The vendor may face critical challenges of having a supply of units more than the physical storage space at the hospitals that they could handle in case the vendor did not assign space constraint for the hospitals with assigned warehouses, in our case we assigned Eq. 5 as warehouse space constraint. Also, the vendor may face a challenge of under-supply in the shape of expected shortages; the shortage penalty constraint as shown in Eq. 7 limits the safety stock level at the hospitals with assigned warehouses to be equal to or greater than the expected shortages. By representing the total penalty cost incurred by the vendor, as well as the space constraint at the hospitals, over-supply, or under-supply risk at the hospitals are considered and eliminated.

As a matter of fact, all optimization problems, including our research, relax the constraints and the objective function to improve the processing time of the expected total cost (ETC) solutions. In our research, we adopt using Big M method to relax the SMINLP model in order to mitigate any possible interference between the continuous and integer variables in the same term of the objective function as shown in Eq. 6 and 10.

In this research, we investigate the solution and outcomes of the SMINLP model with demand uncertainty for both normal and uniform distributions with a deterministic lead time. In both cases, we used the same parameters data set in order to conduct a performance comparison based on the expected cost, the network setup (number of storage facilities at hospitals), the level of the safety stock at vendor's warehouse and the CPU time used to solve the SMINLP model for each case.

As shown in Table 3.4, it was observed that the expected total cost (ETC) have the least value in case of considering the normal probability distribution to express the demand uncertainty and with 28.66 % as cost reduction. The cost reduction is obtained by the reduction in the expected shortage cost and facility storages set up cost due to the level of demand uncertainty as signified by the increased value of σ_{ij} during the lead time in case of the uniform distribution and as explained in detail in the data setting section.

The impact of using either normal or uniform probability distributions on the supply network layout is significant. The layout of the healthcare supply network in case of considering the normal probability distribution, 87 hospitals considered for assigning warehouses, in contrary, in case of considering uniform probability distribution, 74 hospitals assigned with warehouses. Such changes in the layout of the healthcare supply network impact the expected total cost (ETC) due to the significant reduction in setup fixed cost for assigning warehouses at the hospitals, in which 13 hospitals became with no assigned warehouse in case of uniform distribution compared with the supply network layout for normal distribution.

In the case of the CPU processing time, GAMS-Baron was faster in solving the model with the normal distribution. 26.7% as time increase obtained by using GAMS to solve the model with uniform distribution.

Furthermore, As shown in Table 4, it was observed that:

1. The total cost expected and incurred by the vendor in case of the demand following the normal probability distribution is the least compared with the ETC of the average uniform probability distribution outcome. This finding is due to the different layout of the supply chain network for each distribution.
2. The high uncertainty of the demand impacts the location-inventory assignment model directly. The expected shortage increased with the variations of the uncertainty as represented by the mean and standard deviation during the lead time (μ_{ij}, σ_{ij}) and characterized by SF_{ij} and R_{ij} as shown in Table 3.4.
3. We analyze two different models using two types of probability distributions on inventory policies. First, we derive the vendor's optimal ETC of the network when the vendor is releasing new products with high uncertainty due to the non-availability of the sufficient historical data settings. Next, we study the ETC, in the case of having sufficient historical data, in which we use the normal probability distribution for the demand with less uncertainty and characterized by SF_{ij}. 1.
4. The optimal ETC would improve when the objective function and its constraints of the optimization problems shown in Equations (16) and (20) are relaxed by using big M approach.

Table 3.4 Healthcare network performance using a VMI contract with demand uncertainty.

#	Activity	Normal Distribution - SF_{ij} Base	Uniform Distribution - R_{ij} Base	Avg. Uniform Distribution - R_{ij} Base
1	Expected Total Cost ($)	1,001,754.52	1,432,916.78	1,643,999.90
2	Cost increase	0.00%	30.09%	39.07%
3	# of hospitals with VMI	87	74	63
4	# of hospitals with DDP	60	73	84
4	Safety stock level at Vendor's warehouse for each product j	60	81	30
		56	74	29
		54	73	27
5	Safety stock level at hospitals' warehouses for product j	329	663	1281
		294	547	1068
		299	587	1151
6	quantity of product *j* delivered to all hospitals with assigned warehouses	2268	2142	2072
		1895	1789	1729
		2030	1920	1862
7	Number of orders delivered to all hospitals with assigned warehouses	156	137	115
8	Avg. Safety Stock factor for product j at the hospitals with warehouses	1.2167	1.0000	1.0058
		1.3570	1.0000	1.0101
		1.2947	1.0000	1.0081
9	Reorder point level of product *j* at the hospitals with warehouses	1787	2068	1961
		1545	1729	1636
		1612	1856	1763
10	The expected shortage for product *j* at all hospitals with warehouses	54	517	503
		43	431	419
		48	464	451
11	GAMS Solver	BARON	BARON	BARON
12	CPU Time used (Sec)	6.95	9.481	11.2
13	CPU Time Increase	0.00%	26.70%	37.95%
14	Absolute gap (optca = 1E-9)	625.4539131	891.7635024	1010.472942
15	Relative gap (optcr = 0.1)	0.089319324	0.089672233	0.087301377

3.5 Conclusions

In this paper we study a single vendor, multi-commodity and multi-hospital VMI system under a contractual inventory supply agreement, in which the vendor has to adhere to having inventory stock to cover the scheduled hospitals' demand and in addition having a safety stock level to cover any expected shortages initiated by the hospitals either by having a storage facility at the hospital and using a VMI policy, or without having a storage facility at the hospitals and instead using the same day direct delivery to cover the regular scheduled demand any expected shortages for the hospitals with no assigned warehouses by using the vendor's inventory stock at his main warehouse.

In order to comply with the demand uncertainty of the chain of hospitals, we used a stochastic mixed integer nonlinear mathematical model (SMINLP), we integrate the location assignment of the storage facility with the allocation assignment of the replenishment policy. Using such integration leads to having a flexible inventory system by having two types of replenishment policies (VMI and direct delivery policies) in a chain of hospitals subjected to the availability of the warehouse at the hospital.

To the best of our knowledge, our research is the first effort in modeling and integrating VMI and direct delivery policies in the healthcare network under stochastic demand environment. In addition, we study the impact of using different probability distributions on the layout of the VMI healthcare network, in which we used two types of probability distributions: normal and uniform distributions with demand uncertainty. Also, we reallocate the safety stock either at the hospitals with assigned warehouses or at the vendor's main warehouse for the hospitals with no assigned warehouses to cover any expected shortage may occur in the healthcare network.

This research can be extended as future research in the following aspects: Implementing the SMINLP model for other probability distributions and analyze the impact of each distribution on the healthcare network layout. In addition, this research was conducted based on the real-world problem for healthcare SC network; the research can be extended by investigating the same research on other industries SC networks.

In addition, this research can be extended to cover the revers SC cycle for the non-used items of the medical implant sets (heart valve set) in which addition cost needs to be assigned for the hygiene process and transportation cost to deliver the items from the hospitals to the manufacturer or a 3rd party's facility to manage treat them and return the suitable ones to the SC cycle again.

CHAPTER 4: VMI AS PREFERABLE TO A TRADITIONAL RMI SYSTEM IN AN OPTIMAL HEALTHCARE SUPPLY NETWORK: A COMPARATIVE STUDY

4.1 Introduction

Vendor Managed Inventory (VMI) system is an emerging replenishment solution in which the vendor monitors and decides the time and the quantity of the inventory replenishment of their customers subject to their demand information exchange. This research studies a chain of hospitals' distribution network composed of a single vendor provides multiple commodities of medical implants to multiple hospitals in a VMI system with deterministic demand. In the VMI system, we integrated the location assignment of the storage facility with the allocation assignment of the replenishment policy. The vendor needs to determine the location of VMI, the number of products, and the number of orders so that the total cost of transportation, inventory, and other associated operating costs is minimal. In this study, we compare the total cost of VMI system with another two situations of traditional RMI system: the first situation deals with the traditional RMI system with a continuous replenishment policy (RMI-CR) for all hospitals. The second situation deals with a traditional RMI system with a direct delivery policy (RMI-DD) for all hospitals without having a storage facility. We consider the total cost for each system as a tool of performance measure between VMI and RMI systems. In each situation, we developed a mathematical model as a mixed integer non-linear programming (MINLP) for the VMI and RMI-CR systems and as mixed integer programming (MIP) for the RMI-DD system. The two types of models were solved using GAMS, and the computational results and sensitivity analysis are provided. The results for this study case show that the application of VMI systems is more justified and works better in terms of lowering cost than traditional RMI systems.

Total global spending on healthcare has increased by an average of four percent per year from 2000 to 2009; out of that increase, hospitals account for 29% (Volland, Fügener, Schoenfelder, & Brunner, 2017). Inventory logistics costs are the second highest-cost segment in hospitals (Ross & Jayaraman, 2009). Researchers have recognized that location-inventory assignment problems in supply chain networks have been recognized in the last twenty years as a significant tool to minimize healthcare expenditures (De Vries, 2011; Tlahig, Jebali, Bouchriha, & Ladet, 2013).

Hong, Chunyuan, Xu, and Diabat (2016) define the VMI system as an integrated practice through which a vendor places orders for the retailers through the retailers' inventory information share, including inventory status and customer demand in a supply chain system.

The vendor and hospitals are motivated to adopt VMI contracts because the vendor can manage its long-term inventory and production plan by having full access to the hospitals' demand information, and the hospitals can eliminate the pressure of managing the inventory to fulfill all of their demand regardless of the size of the demand and the location of the hospital. In practical, many retailers such as Walmart, Kmart, and Proctor & Gamble have adopted VMI contracts in their inventory operations (Hong et al., 2016; Yao, Dong, & Dresner, 2010)

In this paper, we study a real-world problem arising from the world's leading medical implants supply company applied to a chain of hospitals in the province of Ontario. This healthcare network is composed of a single vendor and multiple hospitals (the chain of hospitals under study consists of 147 hospitals located in Ontario, Canada). The vendor supplies three types of medical implants (artificial knee, hip, and heart valve) and ships them to the hospitals based on the hospitals' demand information. First, we formulate a mathematical model for the traditional inventory system (RMI), and then we develop a mathematical model for the VMI system, in which we solve a challenge that the vendor faces whether or not to allocate a storage facility at each hospital and to assign the replenishment system accordingly. Due to a large number of hospitals, the different size of demands and the locations of the hospitals concerning the location of the vendor's main warehouse, the vendor needs to extend supply chain activities to cover all hospitals' demand regardless of the size of the demand or the location of the hospitals. We use the total cost for each system (RMI and VMI systems) as performance measures.

In this paper, we have formulated the problems of the RMI and VMI systems to minimize the total supply network cost for a VMI supply network with a single vendor – multi hospitals and multi-products setting under deterministic demand – and solve the model using GAMS. The contribution of this study is presenting a flexible location-inventory supply chain network by integrating the hospital's storage facility location assignment with the replenishment policy allocation assignment and then modeling it mathematically. The general characteristics of a traditional RMI system and a VMI system, formed by two stages (Vendor and Hospital stages), are presented in Fig. 4.1.

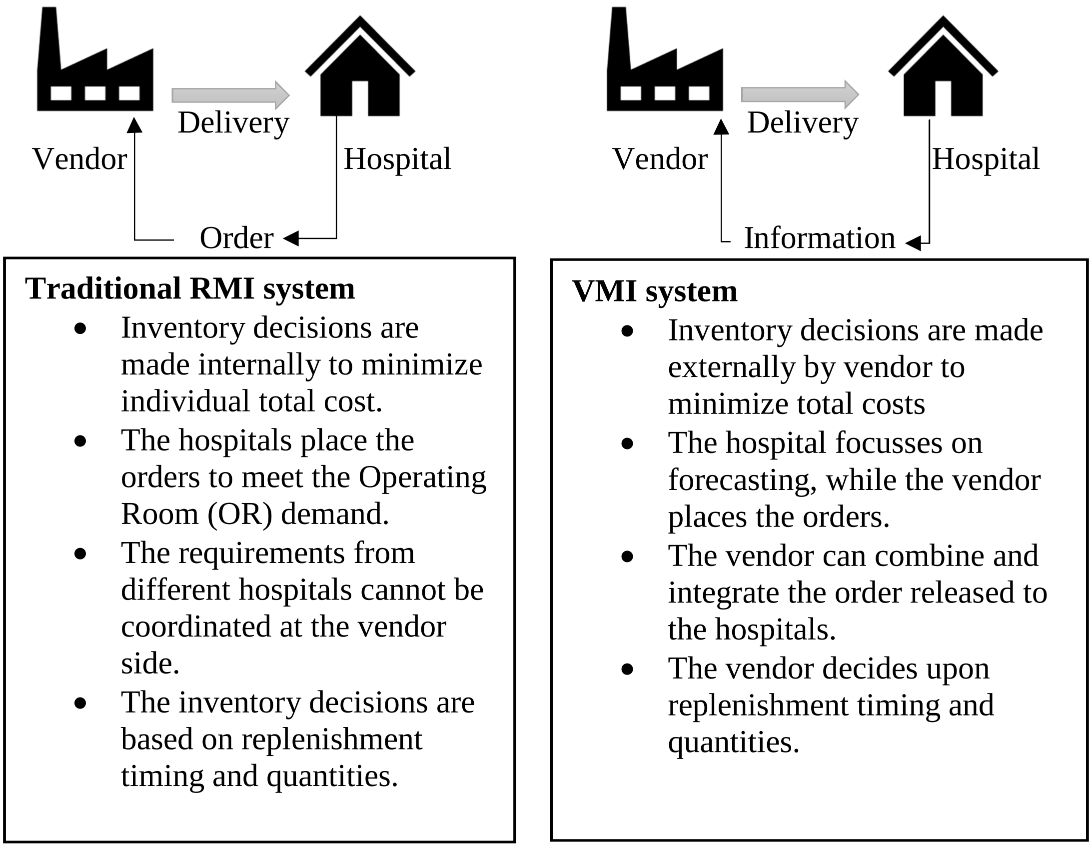


Fig. 4.1 The general characteristics of a traditional RMI system and a VMI system.

Our analytical and numerical results in this case study provide insight into the choice of supply chain arrangements to improve the vendor supply chain performance. More specifically, we find that using our suggested VMI system based on the integration of the location-inventory assignment problem can motivate both the vendor and hospitals to adopt it; in this way, the vendor will gain a significant cost saving, and the hospital will benefit by eliminating the inventory operation stress and having better pricing for the medical implants due to the cost savings obtained by the vendor.

This paper is organized as follows: a review of the relevant literature is presented in the next section, followed by a presentation of the proposed models for both the traditional inventory system represented by RMI and the VMI system in Section 3. Computational results have been carried out to analyze and illustrate the findings, benefits, and sensitivity analysis in Section 4. The last section contains concluding remarks and some avenues for future research.

4.2Literature Review

Researchers have concluded that local optimization at any one party of the value chain will not guarantee the whole supply chain optimization benefit. Thus, it is logical for firms to focus on their whole value chain and attempt to gain a competitive advantage by leveraging it (Kheljani, Ghodsypour, & O'Brien, 2009; Mateen, Chatterjee, & Mitra, 2015). To be successful, any firm needs to have a coordination mechanism to integrate with other parties to achieve total effectiveness across the supply chain network. Vendor managed inventory (VMI) is one such practice which has gained much attention in recent times.

VMI is defined as a replenishment and delivery strategy in which all replenishment decisions and associated costs are covered by the vendors instead of the buyers in the traditional replenishment system. In general, VMI policy can be either a frequent, or it can be an infrequent replenishment system, but the main point is that VMI strategy is a demand-driven supply chain; therefore, the vendors should respond to the buyer demand (hospitals' demands) in a scheduled manner or on immediate delivery subject to the demand feedback secured by the buyers (hospitals) (Haavik, 2000). VMI includes a contractual agreement between vendors and end-users, in which vendors have the right to decide on when and how much product will be delivered to the end-users to optimize an inventory with agreed targets of service level. Also, in VMI agreement, the upstream supply chain party (the vendor) takes responsibility for managing the inventory of the downstream party (the hospital) within specific levels previously agreed upon without the need for orders from the buyer party side to be placed. Therefore, the vendor can focus on optimizing the supply efficiency and capacity planning, while the buyer party has to improve forecast accuracy (Kannan, Grigore, Devika, & Senthilkumar, 2013).

VMI is designed to reduce the total cost and enhance profitability. In this VMI system, the vendor is obligated to cover all activities related to administration and supervision of inventory in addition to making purchase order decisions, rather than allowing the buyer to make the purchases (Danese, 2006; Marquès, Thierry, Lamothe, & Gourc, 2010). VMI has dramatically minimized inventory carrying costs, as well as stock out problems, as it enables vendors to synchronize inventory and transportation decisions (Southard & Swenseth, 2008). VMI fits the health sector because hospitals have complex supply chains that incorporate items required by clinicians; the potential of hospital logistics and network optimization in the healthcare sector is considered significant both by researchers and industry. The most apparent upside from optimizing material logistics is that cost reductions do not directly affect the quality of patient care (Mateen et al., 2015; Rosales, Magazine, & Rao, 2015).

Managing supply chain inventory is a significant challenge for many firms that have simultaneously endeavored to minimize costs and enhance customer service in the current competitive business environment (Daskin, Coullard, & Shen, 2002). To overcome the gap of managing inventory in the healthcare sector, several programs of supply-chain coordination, which include VMI, have recently been implemented to support the supply-chain software (Sui, Gosavi, & Lin, 2010). The challenge of acquiring a long-term competitive advantage through the highly competitive marketplace relies on how organizations succeed in the competitive proportions of cost, flexibility, as well as customer response (Southard & Swenseth, 2008).

Liao, Hsieh, and Lai (2011) studied an integrated location-inventory distribution network problem by integrating the impact of the facility location, distribution, and inventory issues under VMI contract on the inventory decisions; they presented a Multi-Objective Location-Inventory Problem (MOLIP) model. They tested the multi-objective evolutionary algorithm to solve MOLIP, using a multi-objective approach to present the location assignment as a strategic decision and inventory management assignment as operational decisions with VMI policy as a single replenishment policy.

Mathematical modeling is used to identify and compare the benefits of VMI and a traditional inventory system. Hong et al. (2016) studied the two-echelon distribution work composed of multiple vendors and retailers in traditional and vendor-managed inventory systems, and the results illustrate that vendor-managed inventory total system cost is lower than a traditional managed inventory system. Yu, Tang, Xu, and Wang (2015) have presented an Economic Order Quantity (EOQ) based model to analyze how much better VMI is than RMI in a global environment. They concluded that VMI does not perform better than RMI all the time when VMI cannot reduce the ordering, delivery, and holding cost. In our research, we implemented our VMI integrated model based on the location-inventory assignment problem and concluded that the numerical results in our case study show that the new VMI integrated model performs better than traditional RMI systems. It is worthy of applying the VMI strategy due to the high-cost savings obtained, in which such savings will reflect directly on the pricing of the medical implants that the vendor will supply to the hospitals. Such findings are limited to our case study in the healthcare sector, and further research is required to validate such findings in other industries.

The VMI system has been studied by scholars in deterministic demand environments. Kannan et al. (2013) used a real-world case study from the pharmaceutical industry to analyze the outcomes of using VMI; two cases were under study: one using the traditional managed inventory system and the other one using VMI policy. Razmi, Rad, and Sangari (2010) developed a model for a VMI system to analyze the performance of VMI when customer demand is normally distributed. Yao, Evers, and Dresner (2007) developed a mathematical model to investigate the importance of the VMI system on supply chain parameters related to cost savings in a deterministic environment. Darwish and Odah (2010) analyze a VMI case of a single vendor and multiple retailers and formulate a mathematical model to optimize the total cost to be at minimal under a deterministic demand environment. Sadeghi, Mousavi, Niaki, and Sadeghi (2013) extended the problem conducted by Darwish and Odah (2010) to include multiple vendors and multiple retailers with a single and limited space storage facility; they optimize the number of orders between the vendors and retailers using genetic algorithms and particle swarm optimization algorithms. Gümüş, Jewkes, and Bookbinder (2008) developed a mathematical model with deterministic demand to study the benefits of joining VMI and consignment inventory (CI) systems.

Based on the findings in the literature, this paper extends previous research and analyses the possible benefits of the VMI system when integrating the location assignment of the storage facility at hospitals with the allocation assignment of the replenishment policy. We used a single objective optimization instead of using a multi-objective optimization as most publications did, and we develop mathematical models for the VMI system to solve the inventory-location assignment problem and for RMI system to solve the traditional inventory problem with one type of replenishment policy. The mathematical models were developed as a mixed-integer nonlinear programming

(MINLP) for the VMI and RMI-RC systems and as mixed-integer programming (MIP) for RMI-DD system. All the models were solved with GAMS.

4.3Mathematical Model

4.3.1 Problem Statement

The objective of this paper is to develop a mathematical model that integrates the storage facility location assignment with the replenishment policy allocation assignment under a VMI system in the healthcare industry. Also, we aim to project the possible total cost differences between traditional RMI and VMI systems. In this research, we study a real-world case study in a one-level healthcare supply chain, in which the vendor supplies three types of medical implants (artificial knee, hip, and heart valve) to a chain of hospitals located in Ontario, Canada.

The hospital faces external demand from patients, and the inventory ordering process is considered based on the type of the inventory replenishment system used (VMI or Direct Delivery or both integrated systems). Under the traditional RMI system, we will evaluate two types of supply chain networks, first considering that every hospital will have its storage facility so the ordering quantity and its timing for their demand and safety stock of medical implants will be decided by the hospital accordingly. The second network will depend on direct delivery policy without having a dedicated storage facility at the hospital and depending on courier (Post Canada) using same day delivery policy; the safety stock for all hospitals will be stored at the vendor's main warehouse, and all associated cost will be charged to the hospitals. In the traditional RMI system with a storage facility at the hospital, the ordering process is considered as an inventory review system, and the vendor has no control over the ordering policy and observes the ordering process indirectly. The hospital incurs inventory holding costs for this demand and the safety stock stored at the vendor's warehouse, ordering, and delivery costs. The hospital pays the supplier at the time of order receipt.

Under the VMI system, the vendor secures the hospitals' demand information directly from the management of the chain of hospitals. Based on the obtained demand data and other associated costs such as holding, ordering, and delivery costs, the vendor will decide to set up storage facilities at hospitals and apply a VMI policy. The rest of the hospital with no assigned storage facilities will apply a direct delivery policy using a courier (Post Canada) with a same-day delivery option.

We expand VMI research in healthcare networks by presenting a flexible location-inventory management system based on integrating VMI and direct delivery policies subject to the location assignment of the storage facilities at the hospitals simultaneously. Fig. 4.2, and Fig. 4.3 represent the flow diagram of VMI and Direct Delivery Policy (DDP) consecutively; the flow diagrams include the cost and payment, material, information, and delivery mode flow within the vendor supply chain network under VMI contract.

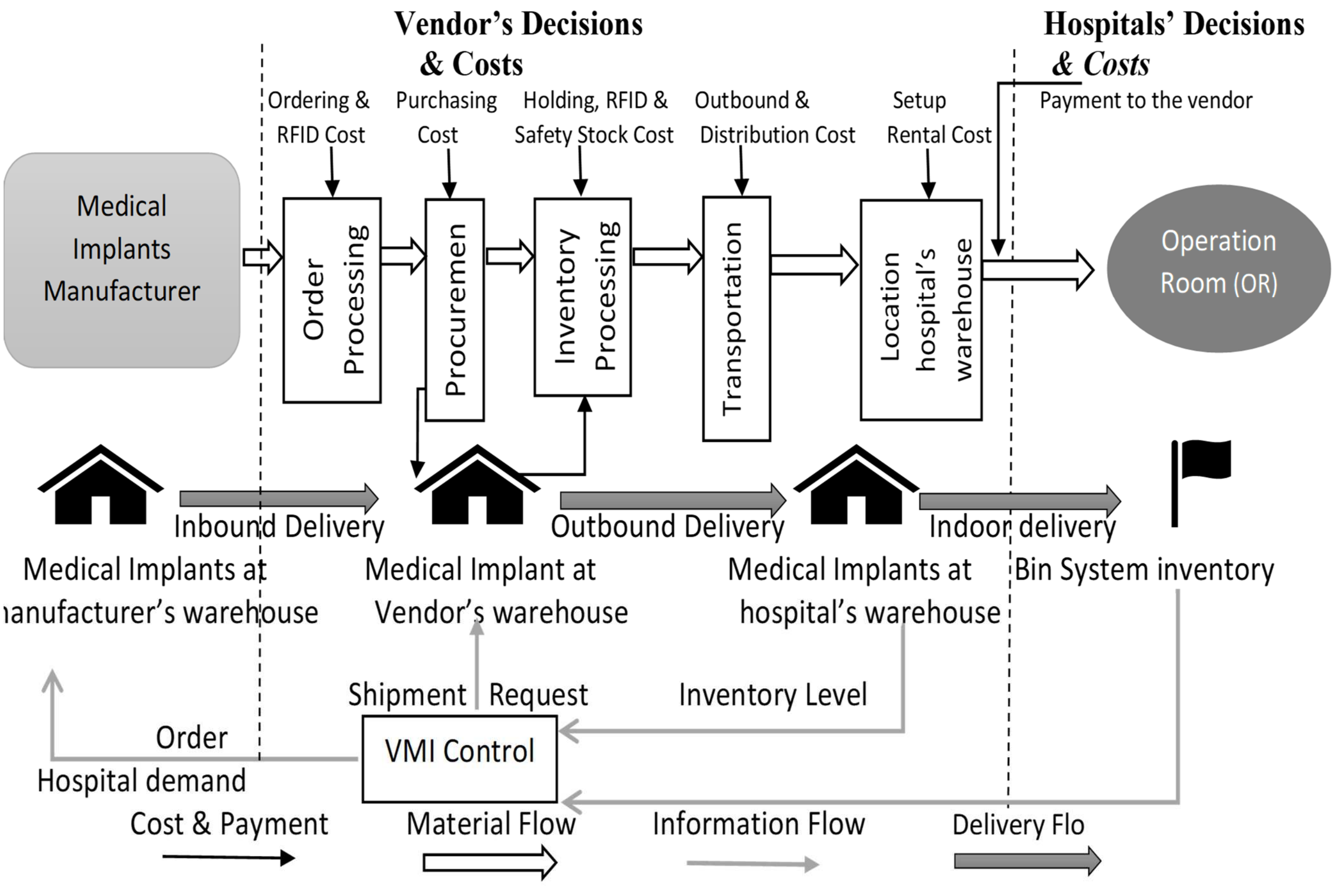


Fig. 4.2 System diagram of VMI policy at the hospital with the assigned warehouse includes cost, information, material, and delivery mode flows.

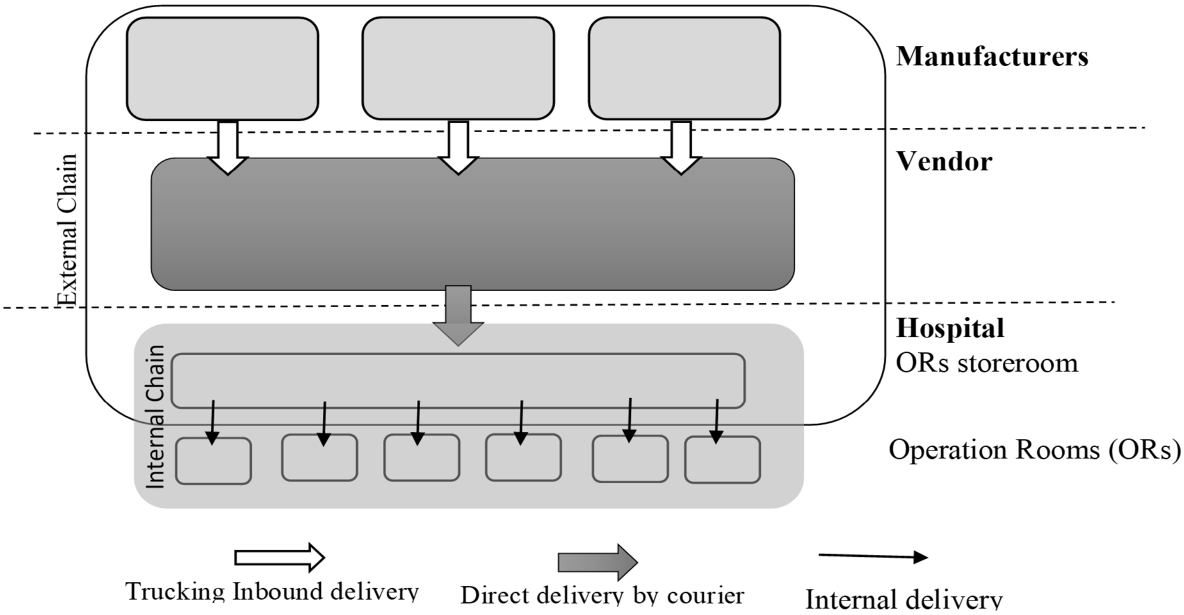


Fig. 4.3 System diagram of direct delivery policy at the hospital with no assigned warehouse.

4.3.2 Model Assumptions:

7. All hospitals' demands for all products are deterministic.
8. The demand should be satisfied regardless of the size of the demand or the location of the hospitals.
9. The cost of ordering per item and per order, holding cost per unit, transportation costs per order and item, the rental rate for the assigned space by hospitals and set up costs for warehouses are all fixed as parameters.
10. Vendor managed inventory is the inventory policy that will be implemented by the vendor at the hospitals with assigned warehouses and direct-delivery policy at hospitals with no assigned warehouses.
11. The transportation cost per item is assumed to be delivered to the hospitals with no assigned warehouses by courier; the rate applied is based on Purolator's rates and service charges for direct same-day delivery due to the specialty of the medical implants that will be delivered.
12. Ordering cost is assumed to have a fixed cost regardless of the type of the product or the quantity shipped per order, as all the administrative costs related to setting up the order inquiry, issuing a local purchase order and the inspection of the order are the same regardless of the quantity and the weight.

13. A continuous review policy is used for VMI.

4.3.3 Mathematical Modelling

3.5.1.1 Indices

i an index for hospital; i = 1; 2…, r

j an index for product; j=1, 2…, n

3.5.1.2 Notations

h_{ij} Holding cost for hospital i for product j

h_j^v Holding cost for product j at the vendor's warehouse

R_i Rental space cost per f^3 per time unit.

F_i (f^3) Total space size of the assigned warehouse at the hospital i per time unit.

FC_i Fixed setup cost for having a warehouse at the hospital i

CAP_{Truck} The capacity of truck used for delivery to hospital i

D_{ij} Demand rate of hospital i of product j per time unit

f_i The volume of one item of the product j (f^3)

M The capability of m_i having a maximum integer number

K_i Unit truck shipment and ordering cost for hospital i

g_{ij} Minimal Safety Stock level for product j at the hospital i with assigned warehouse

A_i Ordering costs for hospital i

c_{ij} Transportation cost per item to hospital i for product j

4.3.4 Traditional RMI System with a Continuous Review Policy (RMI-CR)

4.3.4.1 Decision Variables

Q_{ij} Order size quantity of product j delivered to hospital i with the assigned warehouse.

m_i The number of shipments to hospital i with the assigned warehouse.

SS_{ij} Safety Stock level at the hospital i with assigned warehouse for product j.

4.3.4.2 Objective Function

$$Min\, TC_{VMI} = \sum_{i=1}^{r} K_i m_i + \sum_{i=1}^{r}\sum_{j=1}^{n} h_{ij}\left(\frac{Q_{ij}}{2} + SS_{ij}\right) + \sum_{i=1}^{r}(FC_i + F_i R_i) \qquad (1)$$

The object is to minimize the total cost. The first term represents the cost of the combined ordering and trucking transportation cost for all orders delivered to all hospitals with assigned warehouses. The second term represents the holding cost per item of the summation of average order quantity and the safety stock level for all products at the hospitals with assigned warehouses. The third term represents the sum of the total costs of the fixed cost of setting up the warehouse at hospitals and their rental rate costs.

S.T.

$$\sum_{j=1}^{n} Q_{ij} \leq Cap_{truck} \qquad for\ \forall\ i = 1, \dots, r \qquad (2)$$

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.

$$\sum_{j=1}^{n} (Q_{ij} + SS_{ij}) f_j \leq F_i \qquad for\ \forall\ i = 1, \dots, r \qquad (3)$$

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.

$$SS_{ij} = g_{ij} \qquad for\ \forall\ i = 1, \dots, r\ \ and\ j = 1, \dots, n \qquad (4)$$

Lower bound safety stock level constraint, the lower bound of the safety stock level equal to the minimal value represented by g_{ij} for hospital *i* with the assigned the warehouse.

$$Q_{ij} m_i \geq D_{ij} \qquad for\ \forall\ i = 1, \dots, r\ \ and\ \forall\ j = 1, \dots, n \qquad (5)$$

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 greater or equal to the demand of product *j* of hospital *i* with the assigned warehouse.

$$Q_{ij}, m_i \geq 0 \qquad for \ \forall \ i = 1, \dots, r \quad and \ j = 1, \dots, n \qquad (6)$$

Non-negativity constraint, the order quantity and the number of orders for product j at a hospital i are all non-negative values.

4.3.5 Traditional RMI System with the Direct Delivery Policy (RMI-DD)

4.3.5.1 Decision Variables

$SS_{ij}{}^{v}$ Safety Stock level for hospital *i* for product *j* at the vendor's warehouse.

4.3.5.2 Objective Function

$$Min\ TC_{VMI} = \sum_{i=1}^{r} \sum_{j=1}^{n} (A_i + c_{ij})\, D_{ij} + \sum_{i=1}^{r} \sum_{j=1}^{n} h_j{}^{v}\, SS_{ij}{}^{v} \qquad (7)$$

The object is to minimize the total cost. The first term represents the sum of ordering and courier delivery costs per item for all products' demands and all hospitals with no assigned warehouses. The second term represents the cost of the holding cost per item of the safety stock level for all products at the vendor's warehouse for the hospitals with no assigned warehouses.

S.T.

$$SS_{ij}{}^{v} \geq g_{ij} \qquad for \ \forall \ i = 1, \dots, r \quad and \ j = 1, \dots, n \qquad (8)$$

Lower bound safety stock level constraint, to limit the lower bound of the safety stock level greater or equal to the minimal value represented by g_{ij} for hospital *i* with the assigned the warehouse.

4.3.6 Healthcare Supply Chain with VMI System

4.3.6.1 Decision 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} Order size quantity of product *j* delivered to hospital *i* with the assigned warehouse.

m_i The number of shipments to hospital *i* with the assigned warehouse.

SS_{ij} Safety Stock level at the hospital *i* with assigned warehouse for product *j*.

4.3.6.2 Objective Function

$$Min\, TC_{VMI} = \sum_{i=1}^{r}\sum_{j=1}^{n}(A_i + c_{ij})\, D_{ij}Y_{di}\sum_{i=1}^{r}K_i m_i + \sum_{i=1}^{r}\sum_{j=1}^{n}h_{ij}(\frac{Q_{ij}}{2} + SS_{ij}) + \sum_{i=1}^{r}(FC_i + F_i R_i)Y_{wi} \quad (9)$$

The object is to minimize the total cost. The first term represents the sum of ordering and courier delivery costs per item for all products' demands and all hospitals with no assigned warehouses. The second term represents the cost of the combined ordering and trucking transportation cost for all orders delivered to all hospitals with assigned warehouses. The third term represents the holding cost per item of the summation of average order quantity and the safety stock level for all products at the hospitals with assigned warehouses. The fourth term represents the sum of the totals costs of the fixed cost of setting up the warehouse at hospitals and their rental rate costs.

S.T.

$$Y_{di} + Y_{wi} = 1 \qquad for\ \forall\ i = 1, \dots, r \qquad (10)$$

Network constraint, each hospital *i* either having a warehouse with VMI delivery or having a direct delivery with no assigned warehouse.

$$\sum_{j=1}^{n} Q_{ij} \le Cap_{truck} \qquad for\ \forall\ i = 1, \dots, r \qquad (11)$$

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.

$$\sum_{j=1}^{n}(Q_{ij} + SS_{ij})f_j \le Y_{wi}F_i \qquad for\ \forall\ i = 1, \dots, r \qquad (12)$$

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.

$$SS_{ij} = Y_{wi}\, g_{ij} \qquad for\ \forall\ i = 1, \dots, r \quad and\ j = 1, \dots, n \qquad (13)$$

Lower bound safety stock level constraint, the lower bound of the safety stock level equal to the minimum value represented by g_{ij} for hospital *i* with the assigned the warehouse.

$$m_i \leq Y_{wi} M \qquad for\ \forall\ i = 1, \dots, r \qquad (14)$$

Upper bound of the number of orders constraint, the maximum number of orders shipped to the hospital *i* with assigned warehouse should be equal to or less than the bigM value.

$$Q_{ij} m_i \geq\ D_{ij} Y_{wi} \qquad for\ \forall\ i = 1, \dots, r \quad and\ \forall\ j = 1, \dots, n \qquad (15)$$

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 greater or equal to the demand of product *j* of hospital *i* with the assigned warehouse.

$$Q_{ij}, m_i, SS_{ij} \ \geq 0 \qquad for\ \forall\ i = 1, \dots, r \quad and\ j = 1, \dots, n \qquad (16)$$

Non-negativity constraint, the order quantity, number of orders, and the safety stock level for product *j* at a hospital *i* are all non-negative values.

$$Y_{di}, Y_{wi} \in [0,1] \qquad (17)$$

Binary constraint. The location decision variables are binary decisions.

4.4Analysis and Discussion

4.4.1 Real-World Problem

This section applies the three models developed in the previous section and evaluates the two types of supply chains, the VMI and traditional RMI systems, to evaluate the impact on cost savings based on inventory system used. This evaluation should give an appropriate understanding if VMI system implementation gives higher benefits compared to the traditional RMI system.

In this computational study, we use three types of mathematical models with deterministic demand. First, we formulate the location-inventory problem with the VMI system as a Mixed Integer Non-Linear Programming (MINLP), which is solved using GAMS solver. In the second model, we formulate the traditional RMI system as MINLP in case of having a continuous review system, in which all hospitals have storage facilities, and the problem is solved using GAMS. In the third model, we formulate the traditional RMI system as Mixed Linear Programming (MLP) in case of having a direct delivery policy, in which all hospitals are without storage facilities, and the problem is solved by GAMS.

Our numerical results show that the total cost for the VMI system is always lower than the traditional RMI systems for both policies of continuous review and direct delivery. The total cost of the traditional RMI is always higher than the integrated VMI system where the vendor can benefit by integrating to optimize the order quantity and number of orders so as to reduce the ordering cost and by utilizing the space of the storage facilities at the hospitals. Hence, the vendor would prefer the VMI system to the traditional RMI system. Table 4.1 summarizes the values of the total costs for VMI and traditional RMI systems and the percentage of cost increase for traditional RMI systems compared to the VMI system.

Table 4.1 Computational results of the total costs for VMI and traditional RMI Systems.

Activity	VMI system with CR & DDP	RMI system with CR policy	RMI system with DDP
Total cost ($)	1,054.884	1,243,543	2,504,931
Cost Increase	0 %	15.10%	57.89%
# of hospitals with VMI	77	147	0
# of hospitals with DDP	70	0	147
Absolute gap	0	1.00E-09	0
Relative gap	0.1	0.1	0
GAMS Solver	COUENNE	BARON	COUENNE
CPU Time (Sec)	9513.094	6833.35	0.062

4.4.2 Sensitivity Analysis

Also in this section, we will study the sensitivity of some parameters include the holding, ordering, delivery, trucking transportation, rental, and setup costs and their impact on the total costs of the VMI and traditional RMI systems. To conduct a fair comparison, we change the value of one parameter each time with different values and keep the rest of the parameters with their original values. To reduce our problem space, we fix i=1, 2 so to have a small size sample of network and consider two hospitals to test if the VMI system performs all the time better than the traditional RMI system and to test the role of the VMI system in reducing the holding and ordering costs.

4.4.2.1 Influence of Holding Cost Variation on the Total Cost.

We first investigate the impact of holding cost variation on the optimal total cost of the VMI system numerically. Also, we study the impact of such cost variation in the traditional RMI with continuous review and direct delivery policies. We find that higher cost reduction occurs under the VMI system. We obtain the total cost for VMI and traditional RMI systems by varying the holding cost at hospitals' warehouses in case of the continuous review policies and at the vendor's warehouse in case of the holding cost for the direct delivery policy for the assigned safety stock that belongs to the hospitals with no assigned warehouses. Fig. 4.4 monitors the influence of holding cost variation in the total cost in VMI and traditional RMI systems and shows that regardless of holding cost variation at hospitals and vendor warehouses, the VMI system performs better than the traditional RMI systems.

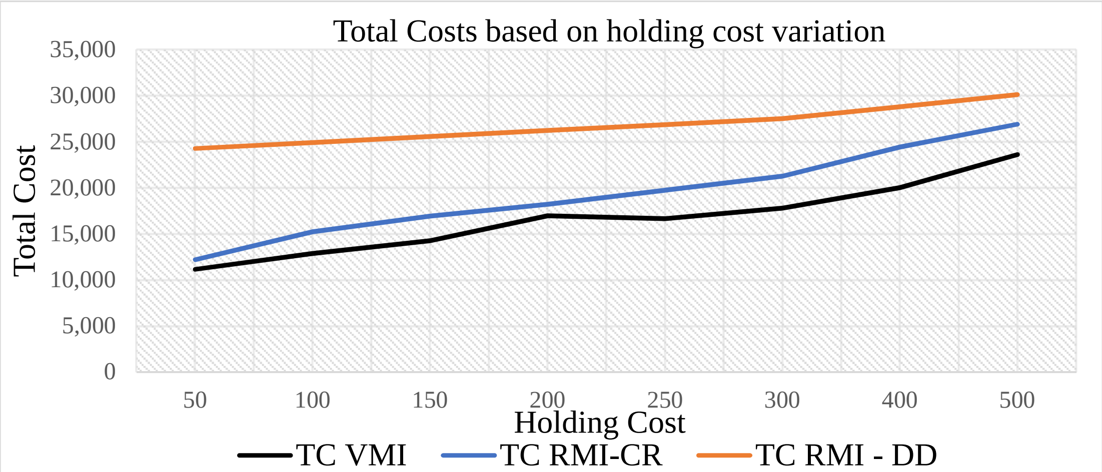


Fig. 4.4 Total costs for VMI and traditional RMI Systems based on holding cost variation.

4.4.2.2 Influence of Ordering Cost Variation on the Total Cost.

We next investigate the impact of ordering cost fluctuation in total costs for VMI and traditional systems. We find that with the ordering cost increase, the total cost of VMI and traditional RMI systems always increases and with different rates: the rate of increase in total cost in the VMI system is the least compared with the other two RMI systems. Hence, the cost savings can be achieved by VMI more than by traditional RMI systems. Fig. 4.5 demonstrates the impact of ordering cost variation in both VMI and traditional RMI systems.

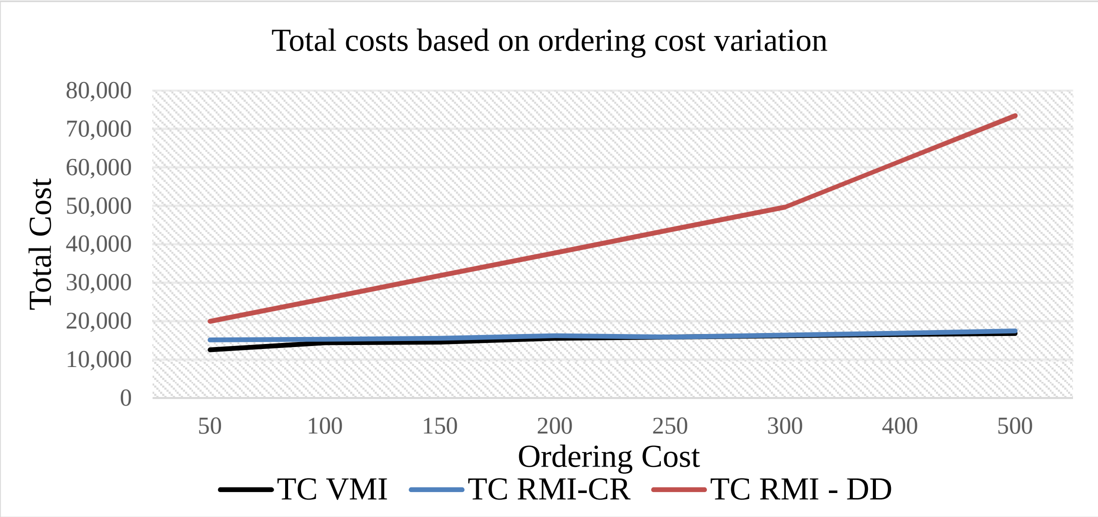


Fig. 4.5 Total costs for VMI and traditional RMI systems based on ordering cost variation.

4.4.2.3 Influence of Courier Delivery Cost Variation on the Total Cost.

Also, we investigate how the third-party delivery cost variation impacts the total costs of VMI and traditional systems. We find that the higher courier delivery cost leads to a higher total cost for the hospitals with no assigned warehouses. However, the increase rate in total cost in traditional RMI systems with the direct delivery policy is higher than the one in the VMI system due to the fact that in the case of the VMI system, the vendor integrates two types of replenishment policies with the location assignment of storage facilities; in this case, such integration minimizes the impact of high courier delivery cost variation by switching to a continuous review policy and setting up warehouses at hospitals instead of having direct delivery policy. Fig. 4.6 demonstrates the impact of delivery cost variation in both VMI and traditional RMI systems.

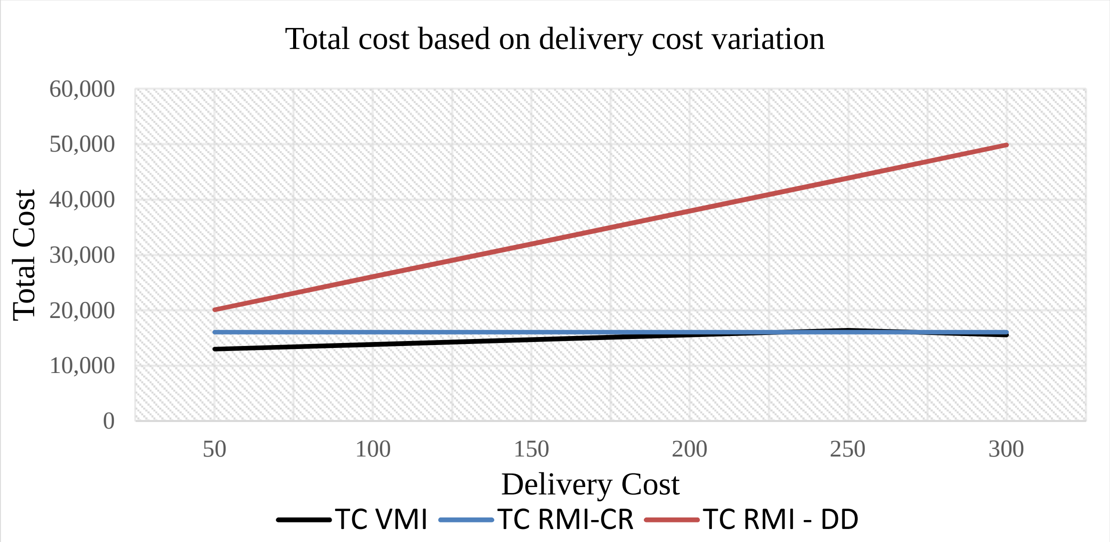


Fig. 4.6 Total costs for VMI and traditional RMI systems based on delivery cost variation.

4.4.2.4 Influence of Trucking Transportation Cost Variation on the Total Cost.

Fig. 4.7 reports the impact of the trucking transportation cost variation in both traditional RMI and VMI systems. The total cost increase rate in the VMI system is less than the increase rate in traditional RMI systems. The vendor optimizes the number of orders to have the optimal total cost whenever having high demand. Otherwise, the vendor will implement a direct delivery policy instead of the continuous review policy in cases of low demand.

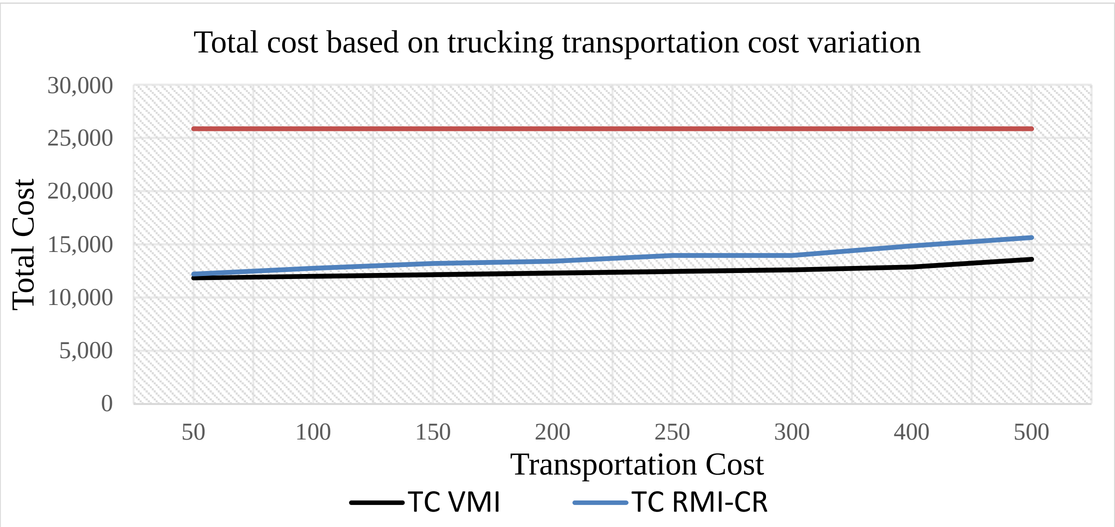


Fig. 4.7 Total costs for VMI and traditional RMI systems based on transportation cost variation.

4.4.2.5 Influence of Storage Space Rental Cost variation on the Total Cost.

To demonstrate the impact of the storage rental cost variation on the total cost of VMI and traditional RMI systems, we varied the storage space rental cost at the hospitals and fixed all other parameters related to holding, ordering, courier delivery transportation and setup costs. The outcomes are shown in Fig. 4.8, which represents the increased rate of total costs for the systems. The results show that the VMI system has the lowest total cost compared with the traditional RMI systems.

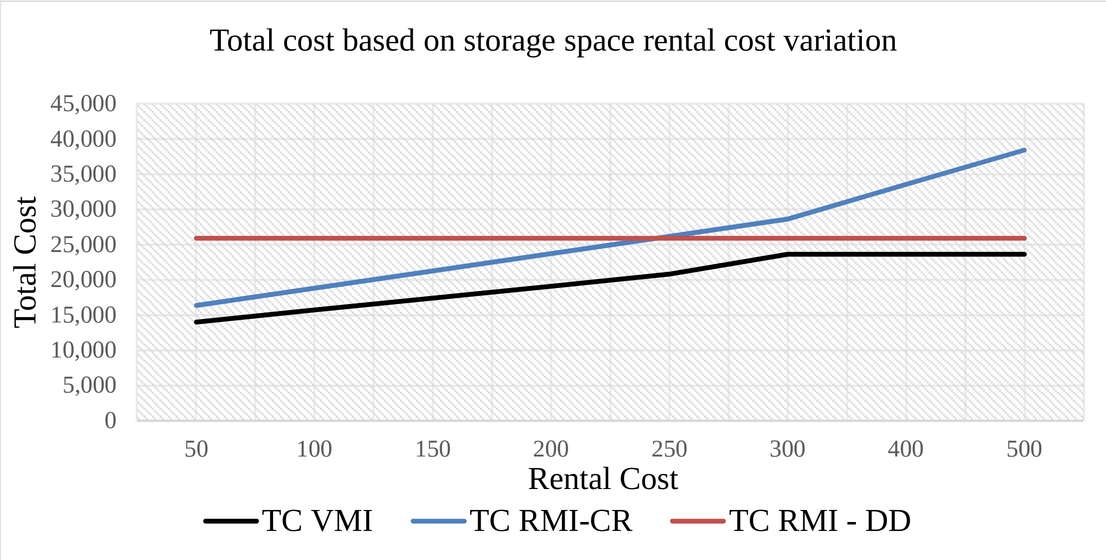


Fig. 4.8 Total costs for VMI and traditional RMI systems based on storage rental cost variation.

4.4.2.6 Influence of Storage Setup Cost Variation on the Total Cost.

Finally, we investigate the influence of storage setup variation on total cost in VMI and traditional RMI systems. Having a VMI system with integrated location-inventory assignment system enhances the performance of the supply chain by using the direct delivery policy at hospitals with no assigned warehouses instead of implementing the continuous review policy with assigned warehouse whenever the setup cost and other associated costs are very high. Such a flexible system enables the vendor to optimize the total cost with such setup cost variation effectively better than the traditional RMI systems. Fig. 4.9 demonstrates the impact of setup cost variation on VMI and traditional RMI systems.

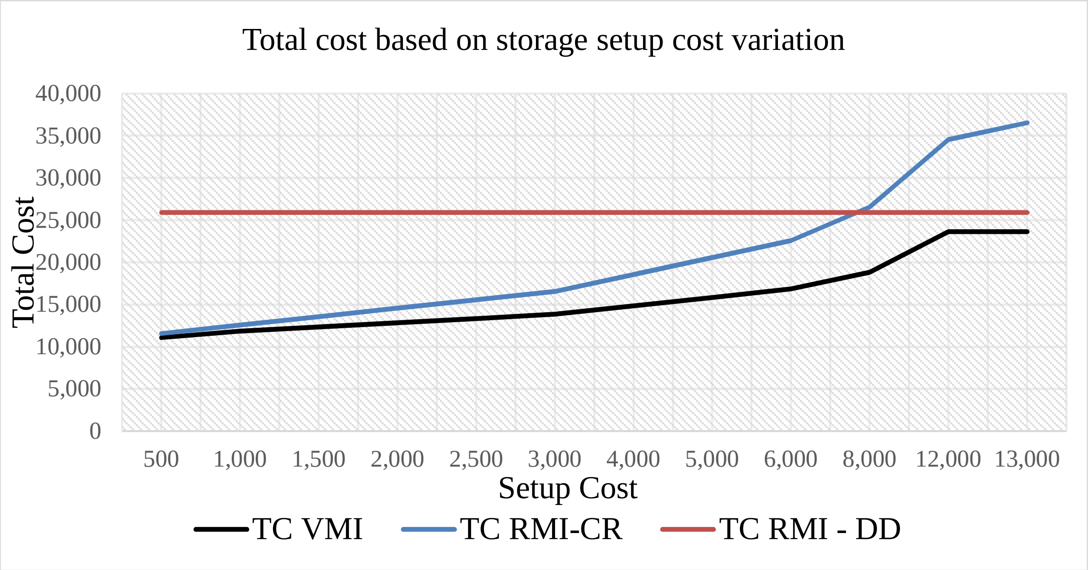


Fig. 4.9 Total costs for VMI and traditional RMI systems based on storage setup cost variation.

4.5Conclusions

In this paper, we investigate three different types of inventory systems in a chain of hospitals: VMI system based on integrating the location assignment of the storage facility with the allocation assignment of inventory replenishment policy, traditional RMI system with continuous review policy (VMI-RC) and storage facilities at all hospitals, and traditional RMI system with direct delivery policy (RMI-DD) and no storage facilities at all hospitals. We also implement a numerical study based on a real-world problem arising from one of the world's leading medical implants supply companies applied to a chain of hospitals in the province of Ontario, Canada. In addition, we examine several cost variations on the total costs of the systems related to holding, ordering, courier delivery, trucking transportation, storage rental, and setup costs.

In our research, we use a mixed integer non-linear mathematical programming (MINLP) to present the VMI system and traditional RMI system with continuous review policy (RMI-RC), and we use a mixed-integer Programming (MIP) to present the traditional RMI system with direct delivery policy (RMI-DD). The aim of modeling those mathematical models in VMI and traditional RMI systems is to present the performance and outcomes of these systems by comparing total costs of the systems and analyze the impact of the cost variations of the parameters on the total cost.

The sensitivity analyses for the vendor and hospitals' holding, ordering, trucking transportation, direct delivery, setup, and storage rental costs are tested to analyze how these parameters impact VMI, RMI-RC, and RMI-DD systems. The results show that in case of ordering, trucking transportation, and direct delivery costs are more important in VMI and RMI-CR systems than in the RMI-DD system, and setup and storage rental costs are more important in the VMI system than in the RMI-RC system. The sensitivity analysis results for this case study particularly show that our new integrated VMI system is more efficient than traditional RMI systems. However, future research is needed to investigate the same outcomes for other industries.

The numerical results in our case study show that the vendor's optimal total cost is obtained in case of implementing the VMI system, and all other traditional RMI systems have a higher total cost than the one of the integrated VMI system. Hence, we could expect that the vendor would prefer the VMI system to the traditional RMI systems due to the high level of cost saving that will reflect on the pricing of the medical implants offered to the hospitals.

While our research focuses on solving the integrated location-inventory assignment problem and explaining the benefits and outcomes of the VMI system over traditional RMI systems, this research can be extended as future research in the following aspects: This research can be extended by implementing the RFID technology concept to eliminating further costs due to its impact on shortage, overstock, and monitoring the inventory waste incidents. This paper studies the optimal supply network in the healthcare sector with deterministic demand, this study can be extended to cover the stochastic demand as a comparative study with other replenishment policies such as RMI policy. Finally, this research can be extended to study other industries such as VMI system for fast-moving items with large demand size such as bearings, lubricants, fittings, and fasteners.

CHAPTER 5: CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

The VMI contract is considered by a large number of firms as a breakthrough in their inventory management as a cost reduction tool throughout the supply chain networks. While the development of the VMI contract depends mainly on the vendor, especially in the healthcare sector, to re-examine their operations, and critically re-evaluate all areas of operations looking for avenues of optimization, it is also important to focus on the RFID technology and its role on the performance of healthcare SC networks in terms of cost reduction and/or improvement of service level.

The starting point or impetus for our research is a real-world problem arising within a medical implant supply company applied to a chain of hospitals in the province of Ontario. The chain of hospitals under study consists of 147 hospitals located in Ontario, Canada. Based on the observations and a thorough literature review of VMI contracts in healthcare networks, we found more and more companies (vendors and hospitals) in the healthcare system are looking for a cost and service effective inventory system with stochastic and deterministic demand environments. Most of the companies are also interested in evaluating the benefits of a VMI contract with advanced identification system such as the RFID technology consideration. In addition, those companies are interested in new functionalities associated with VMI contracts and RFID technology in order to compare it with the performance enabled by the other traditional inventory systems such as RMI systems.

Our aim as a research objective is to quantify the role of the VMI contract in the location-inventory assignment problem under deterministic and stochastic demand environments with the RFID technology consideration. We also provide comparative studies as a decision support tool between the VMI contract with traditional RMI systems. For this purpose, we organize the dissertation in three core chapters:

Chapter 2 introduces the dissertation by presenting the VMI contract in healthcare SC networks with deterministic demand and RFID consideration. We first consider modelling mathematically the role of the VMI contract in the location-inventory assignment problem by integrating the location assignment of the storage facility and its replenishment policy with the allocation assignment of RFID technology and its investment level to determine the location of the warehouses, the inventory policy, and the RFID investment level in the healthcare network so that the total cost of transportation, inventory, and other associated operating costs are minimal. The demand in this proposed model is deterministic, and the computational results and sensitivity analysis have shown the effectiveness of the proposed model with RFID consideration in cost reduction on the overall cost of the healthcare network by enhancing both ordering and holding efficiencies. The numerical example is based on the small size of the real-world problem arising from one of the world's leading medical implants supply companies applied to a chain of hospitals in the province of Ontario, Canada, to demonstrate and examine several cost variations on the total costs of the systems related to holding and ordering costs. We compare the performance of the VMI contract with the the performance of different RFID investment strategies of having objective function with no RFID investment (Option A), with sequential RFID investment only in ordering operations (Option B), with sequential RFID investment only in holding operations (Option C) and with simultaneous RFID investment in holding and ordering operations (Option D). The numerical and computational results for the real-world problem show that a 6.27% cost reduction is obtained by implementing the simultaneous RFID investment in holding and ordering operations strategy (Option D) compared with no RFID investment strategy (Option A).

Our contribution to this research in Chapter 2 is threefold: first, we analyze and provide an optimal healthcare SC network based on integrating the VMI contract in the location-inventory assignment problem with the replenishment policy assignment and model it mathematically. Second, we discuss applying two RFID investment factors in holding and ordering operations and develop an analytical procedure to derive optimal RFID investment levels for these factors. Third, we identify and analyze the impact of the cost saving obtained by RFID investment on the location assignments of the storage facilities at the hospitals.

Motivated by the results and outcomes of the computational results in Chapter 2 dealing with the VMI contract for the optimal healthcare SC network, Chapter 3 of this dissertation considers the VMI contract for the optimal healthcare SC network for the same real-world problem in a stochastic demand environment. We proposed a mathematical model to compare the performance of VMI systems under a stochastic environment with the uncertainty of the demand as a random variable following normal and uniform distributions. The numerical results for the real-world problem have been shown that the total cost expected and incurred by the vendor in case of the demand following the normal probability distribution is the least compared with the ETC of the average uniform probability distribution outcome. This finding is due to the different layout of the SC network for each distribution. In addition, the high uncertainty of the demand impacts the location-inventory assignment layout directly for the proposed model of the VMI contract for the optimal healthcare SC network with stochastic demand.

Motivated by the lack of investigations and comparative studies dealing with the preference of the VMI contract to other traditional RMI systems, Chapter 4 considers comparing the total cost of the VMI system with another two situations of traditional RMI system: the first situation deals with the traditional RMI system with a continuous replenishment policy (RMI-CR) for all hospitals. The second situation deals with a traditional RMI system with a direct delivery policy (VMI-DD) for all hospitals without having a storage facility. The computational results for the real-world problem under study show that the application of VMI systems is more justified and works better in terms of lowering cost than traditional RMI systems. Hence, we could expect that the vendor would prefer the VMI system to the traditional RMI systems due to the high level of cost saving, and the hospital will benefit by eliminating the inventory operation stress.

5.2 Future Research

The computational results obtained in this dissertation provide interesting managerial insights and inspire the development of further research. the following ones are of special interest:

1. While our research in Chapter 3 focuses on integrating and solving the VMI contract in location-inventory assignment with demand uncertainty under normal and uniform probability distributions, this research can be extended as future research in Implementing the proposed model for other probability distributions and analyze the impact of each distribution on the healthcare network layout.
2. Further numerical and comparative studies on the proposed VMI contract in Chapters 2,3 and 4 are important to more understanding the impact of the proposed integrated VMI contract on other industries SC networks such as the industry of fast-moving items with large demand size such as bearings, lubricants, fittings, and fasteners.
3. The research in Chapter 3 can be extended by implementing the RFID technology concept to eliminating further costs in the VMI contract under stochastic demand environment due to its impact on shortage, overstock, and monitoring the inventory waste incidents.
4. Further analysis of the proposed RFID investment in VMI contract in Chapter 2 is necessary to understand more the impact of RFID technology, considering it as imperfect technology on the objective function and the decision variables.
5. The model presented in Chapter 2,3 and 4 considering VMI contract with a single period, this research can be extended to the case of a multi-period case.
6. Research in chapter 2 can be extended to bridge the gap of coordination in case of the inventory status between the instant feedback by implementing RFID technology in the hospitals with assigned warehouses and the other warehouses at the hospitals with no RFID implementation which use the continuous replenishment policy with a non-instant feedback.
7. This real-world problem can be extended to cover all the qualified hospitals which have the facility to manage the medical implants surgeries all over Canada instead of limiting the case study within the province of Ontario.

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APPENDICES

Appendix A. RFID Roots

A.1 RFID technology definition

RFID technology encompasses a radio-frequency identification (RFID) tag (i.e., a tiny chip that holds information used to transmit an RFID reader). Within the hospital setting, RFID tags may be placed on staff budges or in equipment to collect information via its RFID reader. This technology serves the purpose of securing confidential and highly sensitive hospital information. It can uniquely identify persons, animals or objects by incorporating electrostatic or electromagnetic coupling in the electromagnetic spectrum's radio frequency (RF) (Paaske et al., 2017; Gulcharan et al, 2013).

A.2 How RFID technology works

The RFID system is used for asset tracking and providing management solution. This is achieved by fitting the asset to be tracked with an RFID tag, a thin microchip-like structure. The RFID tags and an antenna, an electronic radio transmitter, and a tiny batter. These RFID tags, like barcodes, can be attached to any surface, including farm animals, people, and identity cards (Yazici, 2014). Each RFID tag contains an attached identification number (UIN) for unique identification and for transmitting radio signal containing the UIN. It also contains the RFID scanner/reader that functions as a receiver device. The RFID reader receives UIN from the RFID tags and uses it to update the database (Gulcharan et al., 2013).

A.3 Implementation of RFID In the Hospital Supply Chain

Decision makers in hospitals are confronted with the challenge of selecting from a range of medical equipment and technologies that challenge capital allocation processes. One of these medical technology options is RFID. RFID technology is increasingly being implemented in the healthcare sector at an unprecedented rate. Research indicates that RFID technology will exponentially grow in the healthcare industry by 2021. Yao et al. (2012) identify a large number of applications associated with RFID technology as one of the key reasons for the increasing use of RFID technology in hospitals' surgical department. According to Yao et al. (2012), RFID exists in multiple forms including tracking staff and patients; tracking of surgical tools;

medicine and pharmaceuticals; surgical tools; single-use items; large equipment; security; and laundry.

A.3.1 Medicine and Pharmaceuticals

Within the surgical department, RFID technology is used for inventory authentication/tracking. As suggested by Krohn (2008), RFID tags have increasingly become readily available in the surgical hospital units for tracking the ever-changing and growing supply of medicine. Krohn (2008), further noted that typical inventory tracking solutions involve barcodes and manual counts, which takes time to complete. According to Page (2007), hospital staff uses RFID to reduce the amount of time on manually counting of pharmaceuticals. This helps hospitals to obtain accurate data as well as obtain correct amounts and types of drugs. Supporting this view, Page (2007) hinted that during the inventory process, handheld readers can read with ease the RFID tags on each box and that the tags can also be inventoried via shelf antennas and fixed readers. Page (2007) further observed that some hospital management use RFID tags as an anti-counterfeiting or authentication resource. This is achieved using encrypted tamper-proof RFID labels within medicine box or bottles.

A.3.2 Staff and Patient Tracking

As revealed by Yazici (2014), hospitals are using active and passive RFID technology in surgical units to track staff and patients. According to Kamel, Boulos, and Berry (2012), hospitals outfit staff, and patients for three primary reasons: locate patients; reduce bottlenecks and wait times, and verify patient information. In another study, Kamel, Boulos, and Berry (2012) opined that active RFID is used by hospitals in Real-Time Location Systems for identification of problems in the workflow and that passive RFID systems (i.e., RFID wristbands) are used to maintain and verify patient records wristbands. The wristbands are useful identification tools in emergencies as they ensure patients do not receive wrong medication or files switched.

A.3.3 Surgical Tools

Surgical tools, including retractors, clamps, scissors, and scalpels, needs to be always clean, disinfected, on hand, and ready to use for surgical purposes. Unfortunately, studies have shown that these surgical instruments transfer bacteria from previous surgical use either as a result of not being sterilized (Fisher & Monahan, 2008). In view of Kamel, Boulos, and Berry (2012), RFID tags ensure that these surgical tools are properly sterilized prior to use. According to Fisher and Monahan (2008), on-metal

RFID tags applied or embedded on a surgical tool ensures they undergo the autoclave disinfecting process and tracked for inventory purposes.

A.3.4 Single-use items

Items such as plastic vials, boxes of gloves, and disposable exam paper are all useful single-use inventory items. These items are relatively low cost and are single-use, and this makes in not feasible for hospitals to track them using high-cost RFID. However, RFID inlays can offer cost-effective inventory solutions to hospitals to store these single-use items in inventory rooms, in RFID outfitted vending machines or shelving units (Bunduchi et al., 2011). According to Chao et al. (2007), RFID-enabled vending machine can be configured to make it a requirement for an RFID-enabled badge to be identified and read before the inventory is released.

A.3.5 Large equipment

Miscellaneous portable testing machines and hospital beds are high-value items that can get misplaced or go missing. In addition, the replacement costs for these items is high, yet these items are not readily available. For this reason, the hospital is using RFID Real-Time Location System (RTLS) systems to keep track of these items within the building (Ngaia et al., 2008).

A.3.6 Security

Hospitals are using RFID-enabled badges for people tracking and access control purposes. This is achieved by hospitals requiring staff members to wave their RFID-enabled badges at the door readers to be allowed to gain access. This process provides medical equipment, medicine, and patients with security that prevents damage and theft (Page, 2007).

A.3.7 Laundry tracking

Sheets, blankets, and towels and other textiles and lines that reside in hospital surgical rooms need to be disinfected and washed for use before the admission of the next patient. RFID laundry tags are efficient ways to track these assets and ensure they are sterile (Perez et al., 2012).

Appendix B. RFID Shortcomings

B.1 Cons of implementing RFID at hospitals

RFID technology can potentially save hospitals money and time by providing location data for resources and people, and real-time traceability, communication, temperature, and identification. For the emergency room (ER), RFID has the potential of helping hospitals track nurses, patients, or doctors to render health services effectively. However, there are barriers to the implementation of these RFID systems that must be overcome to allow hospitals to utilize these systems in their surgical units effectively.

Studies have highlighted common barriers to the implementation of RFID systems in the hospitals' major surgery rooms as security, privacy, organizational, technical, legal, and economic challenges As highlighted (Paaske et al., 2017; Gulcharanet al., 2013).

According to Gulcharan et al. (2013), the key setbacks of RFID technologies lies in their ability to obtain accurately and efficiently data transfer, monitoring and tracking limitations associated with human error, privacy concerns, and patient safety, and restrains in terms of cost.

B.2 Cost/Return On Investment (ROI) Shortcomings

As noted by Paaske et al. (2017), one of the shortcomings of implementing RFID systems in the hospital surgical unit lies in their return on investment (ROI) and cost. This view is supported by figures reported by Yazici (2014) that the cost of each RFID tag may range between $0.40 and $50 depending on the capabilities with each passive tag costing between $0.10 and $0.50 and active tag costing between $0.50 and $50. Other researchers have reported high cost of implementing RFID infrastructure in the hospital setting; increased networking costs; unclear ROI and inadequate information to assess the implementation cost of RFID (Perez et al., 2012; Page, 2007; Ngaia et al., 2008; Bunduchi et al., 2011; Chao et al., 2007; Fisher & Monahan, 2008; Yao et al., 2012). Yazici (2014) also noted that RFID tags can be disposable or reusable and have associated costs. Yazici (2014) further clarified that reusable RFID tags require a standard cleaning method before they can be safely reentered in circulation and that they tend to be higher in price. Moreover, Most RFID tags tend to be light weight and small in size. However, these tags can easily be moved away from the hospital facility, thus leading to tag inventory, and unexpected cost (Okoniewska et al., 2012). Estimates by Yazici (2014) suggests that the cost of RFID tag readers may range between $1,000 and $3,000 per reader. This suggests that a fully functional RFID system can cost millions of dollars to an organization as it requires infrastructure, printers, middleware, readers, tags, and so on (Yazici, 2014). Supporting this view, Okoniewska et al. (2012) estimated the 2018 RFID technology cost in healthcare as surpassing 2 billion dollars.

B.3 Interoperability shortcomings

Technical limitations known to impede the adoption of an RFID system in surgical rooms in hospitals include interference with medical equipment, interoperability with other health information technology (HIT), RFID tag readability, and system errors (Coustasse et al., 2015). According to Coustasse et al. (2015), the evolution of HIT has presented interoperability challenges to healthcare organizations as a result of non-standardization of RFID software and hardware across providers. Other researchers also reported interoperability challenges between RFID systems and existing hospital systems noting that there were no international standards between the United States and Europe (Sarac et al., 2010; Fisher & Monahan, 2012).

Since the RFID investment decision is based on investment costs-benefits approach and since the cost of an RFID implementation concerns the managers due to the least level of investment cost, a thorough investigation of individual cost components was conducted as elaborated in Table A.1 which presents the list of costs relevant to RFID investment, the RFID investment cost is classified into two major cost categories: direct cost includes the hardware and software costs, and indirect costs include development training and services. (Lee & Lee, 2010)

B.4 Location accuracy, signal problems, and Interference shortcomings

Researchers highlight location accuracy and system errors as shortcomings of implementing RFID systems in hospital surgical rooms (Okoniewska et al., 2012; van der Togt et al., 2011).

As indicated by Kamel, Boulos, and Berry (2012), liquids and metals may cause problems during the reading of RFID tags. This shortcoming limits the application of RFID tags to paper, plastic packaging, and cardboard. Kamel, Boulos, and Berry (2012) also noted that the accuracy of RFID read depends on multiple factors, namely tag placement, read distance, and angle of rotation.

Interference can be observed if walkie-talkies, forklifts, and other devices are placed at the distribution centers. Furthermore, studies have shown that the presence of electronic devices towers such as mobile phones towers tends to interfere with radio waves associated with RFID. In the same vein, RFID signals may interfere with medical devices within the hospital environments. The reliability of RFID tags may also be impacted by metal surfaces, humidity, and more. This complicates the use of RFID systems for surgical instruments.

Reyes, Li, and Visich (2012) indicated that system errors might occur for various reasons. First, RFID readers may yield false reads as a result of the interference in the electromagnetic field occurring in moist environments, glass, liquid, metallic objects, and other medical equipment. Secondly, these environments and objects may also affect read accuracy and read rates. Worth noting is that the reporting of the systems and loss of accuracy tend to occur in situations where RFID tags are damaged or lost, thus making them unreadable. Moreover, the RFID system may not function to full capacity without properly functioning equipment (Reyes, Li, & Visich, 2012). Ohashi et al. (2010) found evidence of RFID technical issues, including lack of staff knowledge to detect areas during the administering medications, the radio frequency waves' inability to reach the tags on the medication card and nurses, and wireless network connectivity.

Similarly, Okoniewska et al. (2012) assessed the ability of the RFID system to track equipment location and track staff in a hospital's acute care setting. In this study, Okoniewska et al. (2012) reported that the system's asset tracking capability, which helps users identify tagged equipment had modest accuracy in locating the asset. Okoniewska et, al. (2012) further highlighted the importance of frequently calibrating the locating system equipment and noted that this might be constrained by cost and time primarily when the RFID system is implemented on a large scale. In addition to organizational concerns and challenges, security and privacy concerns have been highlighted during the implementation of RFID. For example, Yao, Chao-Hsien, and Li (2012) highlighted concerns for intentional and inappropriate misuse of RFID systems and the unauthorized disclosure of healthcare information by people contributed by deliberate or inadvertent interception of RFID tag information. These security and privacy concerns have been raised due to the sensitivity of the information contained in RFID which could be accessed by unauthorized readers as well as the surveillance of the technology (Yao, Chao-Hsien & Li, 2012).

Other disadvantages of implementing RFID systems reported in the extant literature include large active RFID tags that require more maintenance; active tags requiring installation of antennas and readers throughout the hospital; active tags only functioning over WiFi and infrastructure of receivers; and the inability of passive tags to track in real-time.

B.5 Preventive actions to eliminate RFID shortcomings

While there are shortcomings of implementing RFID technology within hospital surgical units, the data related to their implementation is promising. The following strategies can be used by hospitals to aid them to overcome such shortcomings when adopting RFID systems.

As suggested by Modrak and Moskvich (2012), hospitals should analyze the economic effects of implementing RFID technology in order to overcome cost-related concerns of implementation. On the overall, the cost of implementing and maintaining RFID technology may deter hospitals from implementing and using it. For this reason, hospitals should conduct a cost-benefit analysis prior to their adoption and implementation of RFID technology.

Healthcare organizations should also consider assessing the success of RFID systems in supply chain management based on the documented evidence. As demonstrated by Kumar, Kadow, and Lamkin (2011), companies such as Wal-Mart have adopted the RFID technology, thus recognizing and demonstrating its benefits.

Some RFID systems have been found to have technical limitations. On this account, it would be beneficial for hospitals to test these RFID systems prior to widespread adoption and implementation. As suggested by Togt, Bakker, and Jaspers (2010), undertaking early performance testing prior to the implementation of the RFID system can allow organizations to address unforeseen technical issues. This may reveal hazardous interference and unexpected cost in the early stages of implementation of RFID.

Organizations should also test the RFID system in a real-life healthcare setting to determine whether it can fulfill its anticipated purpose. This view is reflected in Ting et al. (2012) that the capabilities of RFID vary from product to product and that hospital should assess the desired product to ensure it meets the intended goal. Ting et al. (2011) further suggested that the hospital should address the limitations of RFID technology during the preparation stage of implementation. In addition, acknowledgment of the shortcomings of the product may help define its capabilities to its users and avoid over-expectations.

Trained personnel can help minimize signal problems. Training of the healthcare providers prior to the implementation of RFID technology is thought to promote awareness among the staff as it ensures they recognize its value in practice and thus utilize it as anticipated. In a study evaluating the utilization of RFID system in hospital settings to track assets, Okoniewaska et al. (2012) sought suggestions from nurses regarding the utility of the RFID technology. Result revealed that nurses have limited knowledge regarding the RFID technology and how it functions and that staff should be trained about the use of RFID prior to its implementation. In a similar study, Ku et al. (2011) reported that persistent computer training and education and communication prior to the implementation of RFID technology could help address staff concerns regarding additional workload. Reinforcing this view, Rosenbaum (2014) noted that it is imperative that organizations demonstrate the value of RFID technology to employees, which can be achieved through training. According to Rosenbaum (2014), the value of RFID technology can be revealed in the captured data. In this way, educating healthcare providers on the ability of RFID technology to increase workplace efficiency through the captured data can help reduce negative perceptions held by the staff. The organizations should also maintain written guideline to help ensure equal distribution of information.

To address the security and privacy concerns regarded to RFID devices, the organization should create awareness among the staff regarding the potential security and privacy risks of the technology prior to its adoption (Rosenbaum, 2013). According to Rosenbaum (2013), organizations should weigh the risks and benefits of RFID technology before investment. Appropriate security measures should also be implemented should also be considered to reduce these risks. According to Rosenbaum (2013), ongoing assessment and monitoring of the RFID may help confirm the functionality of the system.

Table A.1 RFID investment cost types

#	Type of costs	RFID investment Set up costs (Overhead costs)	RFID Running costs
1	RFID direct costs (hardware and software investments)	Labeling machines, active and passive tags, stationary and mobile readers, antenna modules, transponder chips, range sensors, printers, network infrastructure, RFID host system	Updating and upgrading, preventive and corrective maintenance, cost of the move if it is stationary or changing the location.
		Software sets related to data collection and management, middleware, encoder management, and event sensor software sets, RFID application for tracking and condition monitoring applications	Updating and upgrading, preventive and corrective maintenance, cost of the move if it is stationary or changing the location, Integration costs with other resource planning systems such as ERP system.
2	RFID indirect costs (training, development and other services)	Any indirect costs as part of the vendor obligations such as making the existing infrastructure consistent RFID application, testing and quality control activity, all installation costs, and documentation.	Internal technical staff, corporate overhead cost, collaboration with external partners, tagging labor costs, communication costs
		Training and certifying the staff	Continuous training and certification process
		Consulting services and maintaining services.	Having continuous support from the vendor of a certified third party to maintain the flow of the service.

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