A STUDY OF HEALTHCARE APPAREL SUPPLY CHAIN MANAGEMENT WITH RADIO FREQUENCY IDENTIFICATION (RFID) SYSTEM

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A Study of Healthcare Apparel Supply Chain Management with Radio Frequency IDentification (RFID) System

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CERTIFICATE OF ORIGINALITY

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Abstract

Since a wide variety of healthcare apparel products need to be managed in a healthcare organization, traditionally, an information system such as bar-coding system is an important tool which not only mitigates the workload of the employees but also improves the product availability service level being provided to the patients. Apart from the bar-coding system, in recent years, an Radio Frequency IDentification (RFID) system has been a popular topic in the inventory management in which the operation is more automatic, yet, its application feasibility and adoption impacts in the healthcare industry have not been well explored.

This dissertation aims at exploring the business value of the RFID system for apparel product management in the healthcare industry through a multi-methodological approach. To be specific, it consists of case studies and mathematical modeling studies. The case studies firstly help to reveal the existing industrial practice of the apparel products management. It also provides motivation to further examine the use of the RFID system with respect to the current practice in the healthcare industry in the later mathematical modeling studies.

In the case studies, one Hong Kong public hospital and one Hong Kong private hospital were chosen as the study targets. After conducting the interviews with the staff members of these two hospitals, it was observed that the bar-coding system had been adopted to manage the apparel products to enhance the operation efficiency. On the other hand, however, they suffered inaccurate inventory planning due to a lack of the scientific inventory determination mechanism. Their supply chains were also not coordinated. As

supported by recent industrial reports that the RFID system was a promising tool that can be employed to better manage the apparel products in the healthcare organizations, two analytical studies were conducted to investigate the impact of the RFID adoption for inventory management of healthcare apparel.

In the first analytical study, it was motivated by the fact that the successful read rate of the RFID system was only between 60-70%, it addressed the issue on the fact that the accuracy of both bar-coding and RFID scanning systems were imperfect, and explored when the RFID system should be adopted under the existing real industrial practice (of the public hospital) that inventory level was periodically reviewed. To be specific, it was found that the ratios between the RFID and bar-coding systems' stock-taking costs and error variations will determine whether one system outperformed the other one. The impact of optimally changing the scanning system toward the upstream apparel-product supplier and the downstream healthcare organization in a supply chain context was then examined. The analytical result showed that the supplier would always suffer a loss and would be discouraged to work faithfully with the healthcare organization when a new system was in place. Therefore, a surplus sharing contract was proposed to create a win-win situation under which both the supplier and the healthcare organization would have improvement with the change of the scanning system from the bar-coding to the RFID. Numerical analyses were also conducted to better visualize the impact of the RFID system under the proposed contract.

In the second analytical study, as reflected by our real world observations in a local private hospital, it studied an inventory planning decision of a hospital which was using a bar-coding system and considering switching to a

RFID system. With the use of the RFID system, the hospital could effectively capture the demand of the correlated products to improve its inventory planning under a quick response system (QRS). QRS is a kind of postponement strategy which enables the hospital to delay the ordering decision to a time point that is closer to the selling season, and the inventory planning (after observing the demand information of the correlated products to update the initial forecast) will become more accurate and precise with respect to the real need of patients (i.e. "customer demand"). This information updating process was modeled by a formal analytical Bayesian approach and the value the RFID system was investigated. By considering the expected value of information acquisition cost of each system, it was found that the hospital should switch from the bar-coding system to the RFID system when the operational cost factor (associated with the RFID system) is smaller than the cost threshold. Later on, the impacts of the QRS on the expected profit and level of risk of (i) the hospital, (ii) the supplier, and (iii) the whole supply chain system were evaluated via the Mean-Variance (MV) framework. Specifically, with the RFID system, the analytical results illustrated that the MV win-win situation in the supply chain cannot be achieved under the QRS alone. Thus, two policies, namely the (hospital-side-driven) service-level commitment policy and the (supplier-side-driven) minimum quantity with price-commitment policy, were introduced to achieve the MV win-win coordination in the RFID-mediated QRS supply chain. Numerical analyses were reported and important managerial insights on the value of the RFID and the respective coordination issues were derived.

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1. Introduction

1.1. Background of Study

Due to the wide variety of healthcare apparel products available in a healthcare organization, adopting an information system to manage the respective inventory is crucial. In Hong Kong, it is observed that healthcare organizations are employing a bar-coding system for managing the healthcare apparel products such as surgical tape, wound dressing, and support wrap. Apart from the bar-coding system, recently, Radio Frequency IDentification (RFID) technology has been proposed in the existing literature for inventory management in both fashion and healthcare industries. With the successful cases of implementing the RFID for tracking and controlling clothing in apparel retailing such as Marks and Spencer (M&S) (Collins, 2006) and Gap Inc. (Abell, 2003), its application has spread over to the healthcare industry such as handling pharmaceutical inventory (Thompson, 2004), planning and controlling blood products (Hohberger et al., 2012), managing bottle gas delivery (Meiller et al., 2011), and tracking the medical assets (Oztekin et al., 2010; Buyurgan and Hardgrave, 2011). Industrials reports, such as AMR Report, have estimated the value of the RFID with which it can reduce supply chain cost by 3 to 5% and increase revenue by 2 to 7% (Abell and Quirk, 2003; Lee and Özer, 2007). However, existing literature have also commented that the RFID technology is far from perfect when the read rate inaccuracy issue is considered (White et al., 2007; Tu and Piramuthu, 2008; Tu et al., 2009). In fact, it is reported that the successful read rate in real world RFID application is just in between 60-70% (Floerkemeier and Lampe, 2004; Jeffery et al., 2006; Derakhshan et al., 2007). The stability of the RFID on reading a tag depends on various factors such as nature of the tagged object, tag placement, angle or rotation, as well as read distance (Ohashi et al., 2008; Yao et al., 2010). Therefore, relatively limited healthcare organizations have employed the RFID technology for inventory management. Questions on whether and when they should deploy the RFID system in inventory management are still under explored.

In addition to implementing an appropriate information system to enhance the operations efficiency, proper inventory planning and controlling for the healthcare apparel products itself is also an important but challenging topic. In 2003, many Hong Kong hospitals suffered a severe shortage of masks during the outbreak of Severe Acute Respiratory Syndrome (SARS) disease. However, in 2012, more than a million surgical masks found in the public hospital's warehouse were expired and had to be disposed. Indeed, some healthcare apparel products, such as surgical masks, disposable gowns and disposable gloves, possess similar characteristics of the fashionable products of having a volatile demand and a short shelf life. It is well agreed that the healthcare organization should provide a high (inventory) service level to the patients, yet, having an enormous inventory leftover will incur a significant inventory cost and the expired leftover items have to be disposed due to the hygienic reason. On the other hand, if the healthcare organization keeps insufficient inventory to satisfy the demand and stock-out occurs, both patients and physicians could not be well protected from germ and might result in serious adverse outcome. Therefore, the hospitals have to carefully make a trade-off on the inventory decision to prevent shortage from happening while not keeping unnecessarily excessive stock. It is believed that the Quick Response System (QRS) is a possible way for planning the healthcare apparel products. QRS is a kind of postponement strategy which helps the organization to respond to the market changes quickly with respect to its inventory decision. With the help of the information system, like RFID, it potentially supports and enhances the implementation of the QRS. Since the healthcare apparel products play a vital role in providing high quality of care to the patients, the healthcare organization should maintain a good and long term relationship with the suppliers (for the sake of getting the right amount of products in good quality without delay) and hence, it is worthy to examine the impact on the suppliers and the supply chain efficiency when the healthcare organization facilitates the QRS.

Motivated by the observed industrial practices and the significance of the healthcare apparel products, this dissertation explores (i) the appropriate time to employ the RFID system, (ii) the value of the RFID deployment for healthcare apparel inventory management, (iii) the ways to achieve healthcare supply chain coordination with the help of the RFID system for facilitating the QRS.

1.2. Research Objectives

This dissertation focuses on studying the value of the RFID deployment for healthcare apparel inventory management in the context of supply chain operations management. It is a pioneer study which contributes to the literature and advancement of practices by analytically exploring when the healthcare organization should adopt the RFID technology in managing its apparel products and how supply chain coordination (i.e. systems optimality) can be achieved with the existing industrial inventory management practice. The specific four research objectives are listed as follows:

(i) To explore the real world inventory management decision and practice in the Hong Kong healthcare organizations especially concerning the apparel related healthcare products.

(ii) To investigate the feasibility of adopting the RFID technology for managing both reusable and perishable healthcare apparel products.

(iii) To analytically evaluate the appropriate time and business value to adopt the RFID technology with the consideration of system inaccuracy and examine the impacts on the supply chain channel.

(iv) To address the risk issues from each supply chain member's perspective and propose the incentive alignment schemes which can coordinate the healthcare apparel supply chain.

1.3. Outline of Methodology

This dissertation adopts a multi-methodological approach which is recently advocated in operations management (such as Cheng et al., 2012, Singhal and Singhal, 2012) and dissertations (as in Liu, 2012; Shen, 2013). Specifically, three methods are used:

(i) An in-depth personal interview with staff members of Hong Kong hospitals;

(ii) Reviews of the industrial reports of the RFID adoption for managing the healthcare apparel products;

(iii) Mathematical modeling analysis with optimization and game-theoretical models, supplemented by numerical analyses.

The rationale of adopting these approaches is as follows. Firstly, the interview can give a clear picture about the current practices of handling the healthcare apparel products in the Hong Kong healthcare industry. Secondly, the industrial reports show the successful stories and potential benefits of the RFID deployment for healthcare apparel products management. With the illustration of the personal interview and the successful case studies as the foundation and motivation, analytical modeling studies are then conducted to explore the RFID adoption principle, its underlying value as well as the feasible incentive alignment schemes to achieve the optimal supply chain. It is believed that the analytical modeling study could generate significant managerial insights on the healthcare supply chain when the RFID technology is considered to be adopted and help to reveal how the healthcare organization can improve the supply chain efficiency in such ways.

1.4. Significance of this Research

In the existing literature, the inventory management optimization problems in the healthcare industry were not well discussed. Moreover, the reported studies only considered the case that the healthcare products were manually handled. Regarding the studies with the application of information technology such as RFID system, they focused mainly on asset management; inventory management (of medicine), identity management, authenticity management, as well as process management (Buyurgan and Hardgrave, 2011) and with the perfect system assumption. In fact, only limited healthcare inventory related analytical literature addressed the imperfect information system and evaluated the supply chain coordination issue. Hence, the significance and originality of this research are specific as follows: This dissertation focuses on studying the healthcare supply chain with the RFID implementation for apparel products management. Besides, the multi-methodological approach firstly reveals how the RFID system supports apparel inventory management and then analytically explores the respective impacts on supply chain members. The analytical findings from this dissertation research can help the healthcare organizations to better understand the value of the RFID technology adoption as well as making an “optimal” decision from the scientific aspect. Overall, it contributes to the literature and helps to advance the industrial practices by achieving the objectives as defined in Section 1.2.

1.5. Organization of this Dissertation

This dissertation consists of seven chapters and is organized as follows: A comprehensive literature review on the RFID application in the healthcare industry, inventory management problems and the adoption of the QRS is conducted in Chapter 2. Next, Chapter 3 introduces the methodology for conducting this dissertation and Chapter 4 presents the case studies on the RFID application and the real industrial practice for apparel inventory management in healthcare sector. Based on the industrial observation, two chapters on analytical analysis are developed. To be specific, in Chapter 5, an analytical model is developed to show the performance of the RFID system in terms of the safety stock requirement, to discuss the impact brought by the RFID system, and to propose the possible contract to achieve win-win situation in a supply chain context. In Chapter 6, an analytical background is developed to study the value of the RFID technology which helps to facilitate the QRS. The impact brought by having the QRS in terms of the expected profit and level of risk towards the supply chain members and the entire supply chain system, and the respective supply chain coordination mechanism, are investigated. Finally, this dissertation is concluded in Chapter 7 with a discussion on future research directions.

2. Literature Review

According to the research objectives indicated in Section 1.2, the purpose of this dissertation is to evaluate the business value of the RFID deployment for apparel management as well as the corresponding impact on the supply chain channel in the healthcare industry when the RFID system is adopted. Hence, in the following, literature related to “information systems application in healthcare industry”, “inventory management related problems and the use of the RFID system”, “inventory management policy in healthcare industry”, and “Quick Response System (QRS)” is reviewed one by one.

2.1. Information Systems Applications in Healthcare Industry

Due to the existence of a substantial amount of healthcare apparel products along with continuous inflow and outflow of the patients in each healthcare organization, the information technology system for managing the healthcare products and patients plays a significant role in daily inventory management and operations. In particular, two systems, namely the bar-coding system and the RFID system, are important in terms of getting inputs (in a digital format) and supporting the operations. They are reviewed as follows.

2.1.1. Bar-coding System

Bar-coding was a well-established and versatile system which could be launched in the healthcare industry. There were two kinds of the barcodes commonly found in the market: linear (or called 1D) and 2D systems. Linear barcode refered to the case when data were stored in the lines and the space among the parallel lines, while the bars were replaced by symbols in the 2D barcode (P.S.: refer to Gao et al. (2007) for details). A bar-coding system consisted of a barcode reader and a barcode printer. Because of its low cost and low error rate, this system not only was applied in general retail industry but also in healthcare sector. For example, it was used to identify the patients (Chan et al., 2004; Koppel et al., 2008), manage the inventories such as pharmaceutical products (Çakici et al., 2011; Bhakoo and Singh, 2012), and verify the drugs to reduce medication errors (Poon et al., 2006). However, the bar-coding system required the user to scan the object one by one manually which was known to be time-consuming, and the physical scanning meant the items must be found on hand before they could be scanned.

2.1.2. RFID System

Apart from the bar-coding system, recently, an Radio Frequency IDentification (RFID) was another promising system that could be applied in the healthcare organizations. The RFID was a set of information technologies that information was transmitted in real-time through radio frequency. This system was composed of a tag, a reader and a middleware. The RFID tag consisted of an integrated circuit to store the tag's unique information as well as an antenna to transmit and receive the radio signal. There were two kinds of the RFID tags, namely the active tag and the passive tag. An active tag had its own internal power supply (e.g., battery) while passive one did not have. The RFID reader (also contained the antenna) emited radio waves and formed an electromagnetic field; at the same time, a passive RFID tag would be powered from the electromagnetic energy and sent the radio waves back to the reader. The reader decoded the data and transmited it to the middleware for formatting. Finally, the proceeded data were provided to the backend application system. For more details of the RFID system operations, refer to Zhu et al. (2012) and Wong and Guo (2014). When the RFID system was applied to various domains, different types of tag and frequencies were required (Buyurgan and Hardgrave, 2011). For instance, the passive RFID tag with Ultra High Frequency (UHF) was suitable for inventory management while active RFID tag with microwave was appropriate for asset management (Chawla and Ha, 2007; Buyurgan and Hardgrave, 2011). Nowadays, the RFID system could also be functioned under wireless technologies; therefore, users could easily keep track of the RFID tag without physical contact. Because of the improved product traceability and visibility along the supply chain, the RFID system helped to reduce the inventory level for about 10% (Glabman, 2004). For example, the RFID system was able to tackle the problem of counterfeit pharmaceutical products (Greengard, 2003; Koh et al., 2003; Booth et al., 2006; Potdar et al., 2006; Fosso Wamba and Ngai, 2011). Business Wire Market Research (2008) estimated the market of the RFID systems deployment in healthcare industry would increase by about 12% to 2.05 billion dollars in 2017. With the unit tag price kept dropping as indicated in Table 2.1, the RFID system adoption would become prevailing. Because both the bar-coding and the RFID systems possessed similar functionality, prior studies such as Aguilar et al. (2006), Wyld (2006) and White et al. (2007) compared their pros and cons. Specifically, the RFID system had advantages over the bar-coding system. For example, many RFID tags could be read and written while the bar-coding system was read only. Besides, the RFID system could actively identify the item (by writing the information into the tag) but the bar-coding could only passively identify the item. A summary of the comparison is shown in Table 2.2.

Table 2.1 Passive RFID unit tag price

Type	Frequency	Unit tag price in 2006 (Weis, 2007)	Approximate unit tag price in 2014
Low frequency	< 135KHz	USD 1.0	USD 0.35
High frequency	13.56 MHz	USD 0.5	USD 0.25
Ultra-high frequency	860-960 MHz	USD 0.15	USD 0.1

Table 2.2 Summary of the comparison of the bar-coding and the RFID systems (adopted by Aguilar et al. (2006), Wyld (2006) and White et al. (2007))

	Bar-coding system	RFID system
Operation	Manual	Automatic
No. of items can be scanned each time	One item at a time	Multiple RFID tags can be scanned simultaneously by an RFID reader
Can the stored information in the bar-coding label/RFID tag be updated?	No	Yes. Passive RFID tags allow information to be updated
Requirement of line-of-sight	Yes	No
Privacy and security of the system	There is no protection to avoid being decrypted	Data protection is higher than that of the bar-coding system
Durable	It is unreadable when the label is covered by dirt	It can function well under excessive dirt, dust, moisture and extreme temperature
Cost	Cheaper	More expensive

Since the RFID system was a very timely application, over the past few years, a number of reviews were published (see Table 2.3). In the following, some review papers on the RFID deployment in the healthcare industry are examined. First, Wicks et al. (2006) presented a short review on the RFID system in hospitals and illustrated the potential benefits, possible application, implementation difficulties, and then suggested solutions to tackle them accordingly. Regarding the innovative RFID system development, Nahas and Deogun (2007) and Lahtela (2009) gave a brief review in the works published in between 2003 and 2006 in the healthcare industry. Besides, Nahas and Deogun (2007) also discussed the problems, such as security and privacy, reliability, safety, cost, extensibility, and false alarms that might appear when developing the RFID system. Based on the work of Nahas and Deogun (2007), Lahtela (2009) further analyzed each study into different fields and argued that data security was the main challenging. Different from Lahtela (2009), Coustasse et al. (2013) concluded that high implementation cost and a lack of the RFID standard were the major barriers for the hospitals to fully apply the RFID system. Later on, a comprehensive survey paper that identified the RFID applications and barriers in healthcare industry was presented by Buyuran and Hardgrave (2011) and Yao et al (2012). The former categorized the empirical studies and developed a framework of the industrial RFID implementations and suggested the future applications. This framework included five main application areas, namely the asset management, inventory management, authenticity management, identity management and process management. The authors commented that employing the RFID system to manage inventory could provide enormous opportunities for improvement. Furthermore, they summarized that technical issues, privacy and legal concern, and high capital investment were the major obstacles of the RFID deployment. On the other hand, the later one constructed a critical success factor framework for the RFID implementation in the healthcare industry. Yet, further in-deep study would still be required for testing its validation. Recently, Fosso Wamba (2012) reviewed the paper related to the RFID studies published in the Journal of Medical Systems (JMS) and classified them as applications, issues and benefits. Based on the number of papers found, they proposed that more contributions should be made on the asset management, organizational and financing issues, as well as management gains. The limitation of this paper was that it reviewed the studies in the JMS only but other journals should be treated as equally important. Therefore, Fosso Wamba et al. (2013) resolve this limitation and classified the

RFID-enable applications into patient management, staff management, and asset management, and illustrated that most of the literature studies explored the RFID system on the asset management. After checking the above review papers, undoubtedly, the RFID applications were explored according to various functionalities such as tracking, identification and verification, sensing, intervention, and alerts and triggers (Yao et al., 2012) or asset, patient and staff management (Fosso Wamba et al., 2013). Tu et al. (2009) commented that asset management, patient care, and inventory management were the three main fields benefited from the RFID technology in the healthcare industry while Buyurgan and Hardgrave (2011) believed that inventory management provided substantial opportunities for improvement with the RFID deployment. Table 2.4 summarizes the above literature review papers on the RFID implementation in healthcare industry while Table 2.5 summarizes the applications and the benefits of the RFID system in the healthcare industry specially.

Table 2.3 Summary of the literature review on the RFID application

Paper	Title	Year of Publications
Li et al. (2006)	Radio frequency identification technology: applications, technical challenges and strategies	2002-2006
Chao (2007)	Determining technology trends and forecasts of RFID by a historical review and bibliometric analysis from 1991 to 2005	1991-2005
Koh (2007)	RFID in supply chain management: A review of applications	2002-2010
Sahin and Dallery (2007)	A literature review on the impact of inventory data record inaccuracies on inventory management and the potential of the RFID technology to tackle this issue	2003-2006
Lehtonen et al. (2008)	From identification to authentication – a review of RFID product authentication techniques	2003-2006
Ngai et al. (2008)	RFID research: An academic literature review (1995-2005) and future research directions	1995-2005
Mehrjerdi (2008)	RFID-enabled systems: a brief review	2005-2007
Nambiar (2009)	RFID technology: A review of its applications	2008-2009

Sarac et al. (2010)	A literature review on the impact of RFID technologies on supply chain management	1958-2009
Zhu et al. (2012)	A review of RFID technology and its managerial applications in different industries	2003-2010
Mehrjerdi (2014)	RFID: a bibliographical literature review with future research directions	1985-2012

Table 2.4 Summary of the literature review on the RFID adoption in the healthcare industry

Paper	Title	Year of Publications	Domains
Wicks et al. (2006)	Radio frequency identification applications in hospital environments	2004	- Applications - Benefits - Implementation difficulties and solutions
Nahas and Deogun (2007)	Radio frequency identification applications in smart hospitals	2003-2006	- Applications - Barriers
Lahtela (2009)	A short overview of the RFID technology in healthcare	2003-2006	- Applications - Benefits - Barriers
Buyurgan and Hardgrave (2011)	RFID in the healthcare industry	2004-2010	- Applications - Benefits - Opportunities - Challenges
Fosso Wamba (2012)	RFID enabled healthcare applications, issues and benefits: an archival analysis (1997 – 2011)	1997-2011	- Applications, - Benefits - Issues
Yao et al. (2012)	The adoption and implementation of RFID technologies in healthcare: a literature review	2004-2010	- Applications, - Benefits - Barriers - Successful factors
Coustasse et al. (2013)	Impact of radio-frequency identification (RFID) technologies on the hospital	2004-2012	- Benefits - Barriers
Fosso Wamba et al. (2013)	A literature review of RFID-enabled healthcare applications and issues	2000-2011	- Application - Benefits

Table 2.5 Summary of the RFID system applications in the healthcare industry

Applications	Functions (findings from the published existing case studies)	Corresponding Benefits
Asset management	Tracking medical equipments such as patient beds, IV pumps, wheelchairs, blood bags (Tzeng et al., 2008, p. 606)	To enhance the staff productivity, reduce the searching time and improve the equipment utilization rate
	Tracking critical items e.g., blood bags (Tzeng et al., 2008, p. 606)	To enhance the real time assessment of the critical items
Inventory management	To trace the high value and consignment items (e.g., heart valves, breast implants) or drugs for triggering replenishment automatically (Bendavid et al., 2012, p. 3483)	To generate cost saving by reducing inventory shrinkage and improve the service level
	To perfectly match the blood to the patient (Tzeng et al., 2008, p. 606)	To reduce the medication errors
Authenticity management	To monitor the flow of the high risk drugs to reduce drug-counterfeiting (Koroneos, 2004, p. 17)	To improve patient safety
Identify management	To identify the newborn (Tzeng et al., 2008, p. 607)	To improve patient's satisfaction
	To track the locations and paths of the severe acute respiratory syndrome (SARS) patients and the person whom they had contacted (Tzeng et al., 2008, p.606-607)	To prevent the spread of SARS
	To monitor the movement of the bed ridden or handicapped patients (Tzeng et al., 2008, p. 607)	To maintain better quality of care when there is a lack of manpower
Process management	To access the medical record of a patient (Tzeng et al., 2008, p. 606)	To improve treatment quality and patient satisfaction
	To identify the patients and verify the correct drugs are dispensed (Tzeng et al., 2008, p. 607)	To reduce the medication errors
Information management	To exchange the related medical information of patients with other hospitals effectively (Tzeng, et al., 2008, p.606)	To enhance the operations efficiency and provides the appropriate treatment to the patient in a timely manner

2.2. Inventory Management Related Problems and Use of the RFID System

In retail industry, inventory inaccuracy problem was commonly observed (Dehoratius and Raman, 2008). Inventory inaccuracy was defined as the inventory level in an information system did not match the real physical levels (Kang and Gershwin, 2005). In the existing literature, inventory inaccuracy was classified into four different categories, they were: transaction errors, misplacement, shrinkage, and supply errors (Sheppard and Brown, 1993, Raman and Ton, 2003; Rekik et al., 2007a).

i. Transaction errors were contributed by the scanning errors (i.e., the inventory record cannot perfectly reflect the actual amount of inventory), wrong delivery, or inaccurate product identification (Sarac et al., 2010). The physical inventory level was unchanged but would lead to inaccurate inventory record (Atali et al., 2006). The actual physical inventory level could be larger or smaller than the recorded data.
ii. Misplacement, or inaccessible inventory, was occurred when the product was misplaced to the shelves. It diminished the amount of products that could be sold to the customers and this problem could not be discovered unless there was an inventory audit (Atali et al., 2006). Raman et al. (2001) estimated that it could reduce the company profit by 25%.
iii. Shrinkage, also known as stock loss, was caused by theft, spoil or damage (Lee and Özer, 2007). It reduced the physical inventory level but did not affect the inventory record (Atali et al., 2006).
iv. Supply errors, or random yield was caused by the unreliable supply or the product's quality was unsatisfactory (Rekik et al., 2007a).

In the literature, Iglehart and Morey (1972) was the pioneer study which considered the inventory record inaccuracy caused by the transaction error. They studied a periodic review system and aimed at determining the optimal safety stock level and optimal frequency of the stock checking to mitigate the effect brought by stochastic demand and inventory record inaccuracy. They considered a single item and modeled the errors of the inventory record inaccuracy in successive periods as an independent, identically random variables with a mean 0 and a variance σ^2. Assuming that the probability of errors not deplete the safety stock level between stock checking was larger than $1-\alpha$, the required safety stock level with n stock checking was developed as $B(n) = \sigma n^{1/2}\Phi^{-1}\left(1-\frac{\alpha}{2}\right)$, where $\Phi^{-1}(x) = \frac{1}{(2\pi)^{1/2}}\int_{-\infty}^{x} e^{-\frac{u^2}{2}}du$. It was then used to derive the optimal number of stock checking to minimize the total expected cost per period with the following expression: $n^* = \left[\frac{2Kh}{\sigma}\Phi^{-1}\left(1-\frac{\alpha}{2}\right)\right]^{2/3}$, where K was the inventory counting cost, and h was the inventory holding cost per item per period. With the inventory record inaccuracy, Kang and Gershwin, (2005) believed that safety stock could be used to protect against uncertainties, such as demand, lead time, and even inventory record. Kang and Gershwin (2005) considered information inaccuracy was occurred due to shrinkage and employed both analytical and simulation approach to evaluate the inventory management decision. They examined a continuous review system with (Q,R) policy and the event sequence were as follows: Firstly, the on-hand inventory level record was reviewed and a replenishment order was placed if it fell below the reorder point R. Next, the order was received and sales together with shrinkage would occur. Through the simulation analysis, it was found that only small amount of shrinkage could result in stock-out and the cost of losing the customer was even higher than losing the inventory. As such, they proposed various compensation methods, for instance, setting a higher safety stock level, conducting stock checking, manually reset the inventory record, decrementing the inventory record, as well as using the RFID system. The study of Iglehart and Morey (1972) was further extended to finite horizon. Kök and Shang (2007) proposed to employ the cycle counting policy for correct the data inaccuracy through counting the inventory regularly. Their analytical derivations showed that whether an inspection (i.e., inventory counting) should be conducted depended on the value of the expected inspection costs and the recorded inventory level, and these factors would eventually influence the decision on the optimal base-stock level. This Inspection Adjusted Base-Stock (IABS) policy was then proved to be optimal for the single period. They further proposed a heuristic policy, cycle-count policy with state-dependent base-stock levels (CCABS), that the base-stock level would be revised base on the number of periods from the last inventory taking, to deal with the inventory inaccuracy problem. Results revealed that the CCABS was preferred over the IABS policy under a situation with standard cycle-counting heuristic (i.e., inventory inaccuracy problem was not considered between cycle-count). Rekik et al. (2007a) conducted a comprehensive investigation of the newsvendor model for unreliable supply problem. They considered a random error which would affect the accepted product quantity of the retailer and this error was modeled as either addictive (i.e., the variance of the received quantity did not depend on the order quantity) or multiplicative (i.e., the variance of the received quantity was proportional to the order quantity). Their analysis helped to decide the optimal stocking quantity in the existence of the errors. Furthermore, Rekik et al. (2008)

addressed the misplacement problem and evaluate the impact toward each channel member when the manufacturer was the Stackelberg leader in a two-stage supply chain system. They considered that the optimal stocking level of the retailer and the optimal wholesale price of the manufacturer were affected by the level of awareness of both the channel members towards the misplacement errors. Numerical findings revealed that retailer was better off while manufacture was worse off when both parties take the errors into the consideration for formulating the expected profit model. This study was then extended to investigate how supply chain coordination could be achieved by a modified buy-back contract such that both parties were better off. DeHoratius et al. (2008) constructed an intelligent inventory management tool using the Bayesian approach for updating the error distribution. They considered a single item with periodic review inventory management policy, and modeled the inventory record error by "invisible" demand process which influenced the physical inventory level but was unobserved until there was stock checking. Through estimating the required parameters from the existing database, the simulation results showed that the Bayesian inventory record was an efficient method for placing replenishment orders and planning for the inventory audit, while the required parameters could be estimated from the existing real data. Mersereau (2012) extended the model developed by DeHoratius et al. (2008) with unobserved lost sales to study the replenishment optimization problem under the periodic review system. They adopted the Markov decision process with the Bayesian approach to update the physical inventory level and incorporated the inventory position uncertainty and unobserved lost sales (i.e., shrinkage problem) into the model in both single-period and two-period system. In addition, they indicated the optimal replenishment was affected by four effects: inventory level uncertainty effect would lead to a higher optimal replenishment level while the direct loss effect, inventory carryover effect, and information effect would lower the stocking quantity. On the other hand, the analytical models illustrated that a higher cost would be resulted in the naive policy (i.e., no inventory record errors were considered) than the policy with the record errors consideration. Even though the forward-looking replenishment policy, namely A-POMDP policy, was an approximate algorithm, it reduced the stocking quantity and helped to lower the average cost when compared with the naive policy, basic myopic policy and full myopic policy. Besides, the simulation result demonstrated the cost differences between these policies were insignificant. Hence, the simple and intelligent myopic policy under the situation with record errors and high service level requirement was appropriate to achieve the nearly optimal approximation.

Because the RFID system can enhance the product traceability and real-time visibility, smoothen the product movement, as well as generate more accurate information (Chow et al., 2006; Sarac et al., 2010), and hence, numerous analytical studies employed this system to correct the inventory discrepancy. Heese (2007) studied a simple supply chain with a Stackelberg manufacturer and a retailer whose inventory record was uncertain. By comparing with the classical Newsvendor model, it was found that the retailer should order more (fewer) for the product with high (low) critical fractile. Besides, the analytical expression demonstrated that the high critical fractile product would further intensify the double marginalization effect in a decentralized supply chain. Interestingly, the analytical findings illustrated that it was more profitable to use the RFID system in a decentralized supply chain even the system execution cost was higher when there was inventory inaccurate record. Later on, Gaukler et al. (2007) considered the deployment of the RFID system to reduce the shrinkage and item misplacement problem, and hence, analytically examined the benefits of item-level RFID to both the manufacturer and the retailer. By modeling it as a newsvendor problem, whether the manufacturer or the retailer was the Stackelberg leader will affect the result: If manufacturer was the Stackelberg leader, the RFID tag cost-sharing parameter was independent of the supply chain profit and the profits allocation. On the other hand, if the retailer was the Stackelberg leader, there was a maximum fraction of the tag cost that the manufacturer was willing to share, and worse still; it might come to a situation that the retailer had to bear all the costs. The inventory inaccuracy problem of the newsvendor product was also explored by Rekik et al. (2007b). Rekik et al. (2007b) analyzed the case with product misplacement problem in a retail store and examined how the retailer's attitude towards the error existence influenced the optimal expected profit. Besides, they developed an analytical condition on the RFID tag cost in which it was beneficial to implement the RFID technology to reduce the inventory inaccuracy problem. Sahin and Dallery (2009) investigated the economic impact of having inaccurate inventory data due to the recording errors from the supplier's perspective using the newsvendor model. It was assumed that the physical inventory level was recorded by a bar-coding system and errors arose in the data collection process. This situation was analytically compared with error-free scenario and the impact was evaluated based on the extra associated overage or underage costs. The authors also proposed to implement the RFID system to eliminate the inventory data inaccuracies which could help to visualize the inventory and generate significant cost saving. Xu et al. (2012) focused on the inventory shrinkage problem and developed the model base on the newsvendor framework. They studied a two-stage supply chain in which the manufacturer was Stakelberg leader and considered four different practices to deal with the inventory errors: (i) neglecting the inventory errors, (ii) roughly guessing the error, (iii) sharing information between the retailer and the manufacturer, as well as (iv) using the RFID system. They concluded that the RFID system was not always the best decision in which the tag cost should be seriously considered because it could affect the supply chain performance.

By analytically comparing the cost and benefit of the RFID deployment, a clear picture on the value of the RFID system could be found. Thus, Atali et al. (2006) studied an inventory management problem for a single item in which the inventory record inaccuracies were caused by shrinkage, misplacement as well as transaction error. First, through modeling these error sources, an optimal replenishment policy for the periodic review system with finite horizon in the presence of unobserved inventory discrepancies in real time basis was developed. Besides, the total cost saving under the system with informed policy (i.e., consider the unobserved error statistics to facilitate replenishment) was compared with information recovery policy (i.e., employed the RFID system to achieve inventory visibility and accurate inventory data) to determine the value of inventory visibility under which there was an elimination or reduction on the causes of inventory discrepancy. The RFID-enable system was able to reduce some of the inventory inaccurate errors as well as the inventory costs. Lee and Özer (2007) realized that the benefits of the RFID system had not yet been explicitly quantified before 2007; therefore, they had extensively reviewed the literature on the impact of the RFID supply chain especially on the analytical models for evaluating the true value of the RFID system. Hereafter, De Kok et al. (2008) developed an analytical model to evaluate the impact of the RFID to avoid the occurrence of shrinkage problem. They compared the benefits and the addition cost brought by the RFID system and found that the length of the inventory inspection cycle was dependent of the value of the items and the theft rate. Besides, the break-even price was composed of the value of the lost items, the theft rate and the remaining shrinkage after implementing the RFID system. In case the read rate of the RFID system was not perfect, the break-even price for the low value product was even stricter. However, this study did not consider the operational cost and the fixed cost of the RFID system. In order to analytically investigate the suitable time point for the RFID investment, Uçkun et al. (2008) explored a two echelons supply chain that the retailer ordered the products from the supplier which would be distributed to several warehouses for temporary storage. They mainly focused on the shrinkage and misplacement factors attributed to the inventory error, and hence, the inventory record might be higher or lower than the actual physical inventory level. They modeled the inventory record error as a random variable, and evaluated how the fixed and variable costs of the RFID system would affect the system investor's (i.e., either the supplier or the retailer) expected profit under the decentralized supply chain. They further determined the optimal order decision and optimal investment level with respect to the cases when inventory sharing among the warehouses was and was not permitted. By comparing the investment threshold of the centralized system and the retailer under the decentralized system, it was found that supply chain was inefficient and hence a revenue-sharing contract was proposed to achieve supply chain coordination. Numerical results illustrated that the retailer would invest on the RFID system to reduce the demand variance if and only if she had a high profit margin which was beneficial to herself. Besides, it was more worthy to invest on the RFID system when there was no information sharing among warehouses. This study also discussed the investment decision under asymmetric parameters; correlated demand relationship among the warehouses, as well as imperfect RFID system. Recently, Camdereli and Swaminathan (2010) studied the benefits of the RFID system to deal with the inventory misplacement and considered the supply chain coordination issue. Assuming that the fixed cost of the RFID system was shared between the retailer and manufacturer while the variable cost was carried by either party, Camdereli and Swaminathan analytically illustrated the impact on the wholesale price under the decentralized supply chain when the manufacturer was the Stackelberg leader. Besides, it was proven that no one would benefit from the RFID deployment except the case when the fixed cost of the RFID system was extremely low. To be specific, both parties would benefit from the RFID adoption if and only if the tag price was within the threshold value. Apart from the wholesale pricing contract, the closed-form expressions of the corresponding wholesale prices were also developed under the revenue sharing contract and the buyback contract to achieve supply chain coordination. Dai and Tseng (2012) evaluated a supply chain with a retailer, a wholesaler, a distributor and suppliers with (s,S) replenishment policy. They firstly quantified the benefits of visibility and prevention with the use of the RFID and revealed that the RFID system should be adopted by an industry in which the inventory inaccurate uncertainty was significantly high, or the product has a high value. Besides, they also measured the value of collecting the demand information, regarding the inventory error. Finally, they calculated the saving from mitigating the bullwhip effect. Different from the above studies which assumed the retailer was risk-neutral; Zhu et al. (2013) examined a risk-averse retailer who had a permanent shrinkage and a temporary shrinkage problem. They adopted the Conditional-Value-at-Risk (CVaR) to measure the risk level of the retailer. Since there was inventory inaccuracy, either manual or automatic (e.g. RFID) inventory checking was required; hence, they developed the conditions in which it was more cost-effective to implement the RFID system. Results demonstrated that the risk-neutral retailer was more willing to adopt the RFID system and it should be used to manage the high value products. Kök and Shang (2014) investigated a multi-stage supply chain in which inventory loss would be accumulated and realized when a cycle count was conducted. They assumed to adopt a base-stock policy in the supply chain. In other words, the retailer had to order inventory to reach the target base-stock level when the nominal inventory position at a stage was less than the target level. A heuristic was then developed to formulate the base-stock level and extensive sensitivity analysis was conducted to generate the managerial insights. Numerical results showed that the retailer should conduct more frequent cycle counts when the inventory error distributions and inventory counting costs were the same at both stages in a two-stage supply chain. Specifically, whether the manufacturer or the retailer should conduct more cycle counts depended on the value of two parameters: the ratio of individual lead time to the supply chain lead time, and the ratio of individual holding cost to the supply chain holding cost. In general, retailers had to conduct more cycle counts for a supply chain with more stages. Through logically comparing the RFID investment cost at each stage, Kök and Shang suggested that the channel member who incurred a relatively lower counting cost should conduct more frequent cycle counts. For example, it should be performed at the downstream side as the retailers could make use of a much cheaper hand-held RFID readers to conduct the cycle-count than the manufacturer.

Similar to the retail companies of carrying a huge amount of products, it is believed that inventory inaccuracy is also found in the healthcare industry. In the existing literature, it was found that only limited analytical studies had addressed the inventory management issue with the use of RFID system in the healthcare environment (which was also illustrated in Fosso Wamba et al., 2013). Çakici et al. (2011) examined the benefit of the RFID system over the bar-coding system for managing pharmaceutical. According to a case study conducted in the US hospital, the authors highlighted that the RFID system facilitated automatic inventory counting and reordering which could enhance the accuracy of inventory record and provide the information in a real time base. In addition, the RFID system was also able to keep monitoring the expiration date of the pharmacy to avoid shrinkage. The authors developed a model to analyze the difference between periodic and continuous review policies for monitoring single item. It was assumed that inventory manager was risk neutral and aimed at minimizing the long-run average inventory cost. Under the periodic review policy, shrinkage demand was deterministic and proportional to the average inventory on hand. With the same fixed ordering cost, continuous review policy could achieve a lower inventory level, fewer backorder, and lower inventory cost than that of the periodic review policy when the shrinkage problem was eliminated under optimal decision. Besides, the authors also conducted a sensitivity analysis to examine the impact on inventory cost at the radiology practice when the measurement parameters (i.e. backorder cost, lead time, fixed ordering cost, demand rate, demand variability and shrinkage rate) were varied in three different scenarios, they were: using the bar-coding system alone, using the RFID system alone, or using the RFID system together with business process reengineering (which means that the ordering cost was reduced, shrinkage problem was eliminated while optimal continuous review order point-order quantity (s,Q) policy was adopted). Results showed that the RFID system with business process reengineering was the best policy in terms of the cost saving (i.e., all measurement parameters increased with the cost saving) while simply using the RFID system alone could also obtain same benefits except the cost per order. Therefore, continuous review policy was superior to periodic review system when no extra cost was incurred in the system. The analytical studies regarding the inventory inaccuracy issue are summarized in Table 2.6.

Table 2.6 Summary of the analytical studies on the inventory inaccuracy issue

Paper	Cause of inventory inaccuracy	Periodic or continuous review system?	Single item or multiple items?	Inventory replenishment policy	Single period or multiple periods?	What kind of information system is considered in the model to correct the discrepancy?
Iglehart and Morey (1972)	Transaction error	Periodic	Single	(s,S)	Multiple	No
Kang and Gershwin (2005)	Shrinkage	Continuous	Single	(Q,R)	Single	RFID
Atali et al. (2006)	Misplacement, Transaction error, Shrinkage	Periodic	Single	(s,S)	Multiple	RFID
Gaukler et al. (2007)	Misplacement, Shrinkage	Not Applicable	Single	Newsvendor	Single	RFID
Heese (2007)	Misplacement, Transaction error, Shrinkage	Not Applicable	Single	Newsvendor	Single	RFID
Kök and Shang (2007)	Transaction error	Periodic	Single	Not mention	Single, Multiple	No
Rekik et al. (2007a)	Supply yield	Periodic	Single	Newsvendor	Single	No
Rekik et al. (2007b)	Misplacement	Periodic	Single	Newsvendor	Single	RFID
DeHoratius et al. (2008)	Misplacement, Transaction error	Periodic	Single	(s,S)	Multiple	No
Rekik et al. (2008)	Misplacement	Not Applicable	Single	Newsvendor	Single	No
Uçkun et al. (2008)	Misplacement, Shrinkage	Not Applicable	Single	Newsvendor	Single	RFID
De Kok et al. (2008)	Transaction error, Shrinkage	Periodic	Single	(R,S)	Multiple	RFID
Sahin and Dallery (2009)	Transaction error	Not Applicable	Single	Newsvendor	Single	RFID, bar-coding
Camdereli and Swaminathan (2010)	Misplacement	Not Applicable	Single	Newsvendor	Single	RFID
Çakici et al (2011)	Shrinkage	Both	Single	(R,S), (s,Q)	Multiple	RFID, bar-coding
Dai and Tseng (2012)	Shrinkage	Periodic	Single	(s,S)	Multiple	RFID
Mersereau (2012)	Shrinkage	Periodic	Single	Order-up-to Newsvendor quantity	Single, Multiple	No
Xu et al. (2012)	Shrinkage	Not Applicable	Single	Newsvendor	Single	RFID
Zhu et al. (2013)	Shrinkage	Not Applicable	Single	Newsvendor	Single	RFID
Kök and Shang (2014)	Shrinkage	Periodic	Single	(s,S)	Single, Multiple	RFID

2.3. Inventory Management Policy in Healthcare Industry

In the existing literature, two major inventory replenishment policies were well explored, they were: periodic review policy and continuous review policy. When quantifying the benefit of a particular inventory management policy, it was found that the proposed model in the literature considered the hospital setting with periodic review inventory system (Bijvank and Vis, 2012). Under the periodic review system, (*R*,*S*), (*R*,*s*,*Q*) and (*R*,*s*,*S*) were commonly adopted. Regarding the (*R*,*S*) policy, inventory position (i.e., on hand inventory level plus outstanding order minus backorders) was reviewed regularly at the time intervals of length *R* and an order of up-to level *S* was placed (Lewis, 1981; Hax and Candea, 1984; McClain and Thomas, 1985). A simple heuristic approximation could be used to determine the review period *R*, and the order-up-to level S when demand and lead time were random variables. Their expressions were shown as follows:

$$R = \frac{Q}{D},$$

$$S = \overline{D}(L + R) + k\sqrt{(L + R)\sigma_D^2 + \overline{D}^2 \sigma_L^2},$$

where *Q* was the economic order quantity with an expression $Q = \sqrt{\frac{2AD}{H}}$, *A* was the ordering cost per order, *H* was the holding cost, *D* was the annual demand, $\overline{D}$ was the average demand, *L* was the average lead time, and *k* was the service level factor. The expression S showed that it covered two types of inventories, i.e., cycle stock and safety stock. The first term $\overline{D}(L + R)$ was the cycle stock quantity for satisfying the average demand, while the second term $k\sqrt{(L + R)\sigma_D^2 + \overline{D}^2 \sigma_L^2}$ was the safety stock quantity for dealing with the demand and lead time uncertainty to protect against stock-out. As for the (*R,s,S*) policy, inventory level was reviewed every *R* period and a replenishment order of up-to level *S* was triggered when it fell to or below the re-order level *s* (Tijms and Groenevelt, 1984; Porteus, 1985); otherwise, replenishment order would not be triggered. The approximation for R, s, as well as S, were shown as follows:

$$R = \frac{Q}{D},$$

$$s = \overline{D}(L + R) + k\sqrt{(L + R)\sigma_D^2 + \overline{D}^2 \sigma_L^2},$$

$$S = s + Q.$$

Finally, (*R,s,Q*) policy was used to illustrate the fact that inventory position was reviewed every *R* period and a replenishment order of fixed quantity *Q* was placed when it fell to or below the re-order level *s* (Hax and Candea, 1984; Silver et al., 1998). The following expressions showed the approximated expressions for *R*, *s*, as well as *Q*:

$$R = \frac{Q}{D},$$

$$s = \overline{D}L + k\sqrt{L\sigma_D^2 + \overline{D}^2 \sigma_L^2},$$

$$Q = \sqrt{\frac{2AD}{H}}.$$

Table 2.7 summarizes the scope of each study with respective to the inventory management in the healthcare industry. Cost minimization and service level maximization are two major objectives for inventory management in the healthcare industry. For the cost minimization model, Dellaert and van de Poel (1996) developed a simple inventory control model for a single item, namely (*R,s,c,S*) model, based on the Economic Order Quantity (EOQ) model with stochastic demand and applied it in an academic hospital in Netherlands. This model considered the situation that a supplier supplied various medical items to the hospital and the replenishment order could be placed to that particular supplier simultaneously (i.e. joint replenishments). Initially, the parameters such as order level *s*, can-order level *c*, and order-up-to level *S* were determined in an intuitive way while the procedures of finding the order level were also proposed. The order level was assumed to be s with the chance of P_s or uniform distribution on the interval $(s, s+X]$ with the chance of $1-P_s$. Besides, demand during review period x_{R+L} and demand during delivery period σ_{R+L} were assumed normally distributed and the service level P_2 could be determined when the order level $s = x_{R+L} + k\sigma_{R+L} + P_s \cdot undershoot$ was picked, where k was determined by the following expression: $G_k = \int_k^{\infty} (u-k)\exp(-u^2/2)/\sqrt{2\pi}du = \left(\frac{3}{1+2P_s}\right)\left(\frac{Q(1-P_2)}{\sigma_{R+L}}\right)$. The expression of $\int_k^{\infty} (u-k)\exp(-u^2/2)/\sqrt{2\pi}du$ was a function of normal distribution and $(m_2/2m_1)-0.5$ was the mean of undershoot. Here m_i was the *i*th moment of the transaction size distribution (please refer to Silver and Peterson (1985) for details). The performance of the developed model was compared with the one developed by Federgruen et al. (1984) through simulating Poisson arrivals. Results showed that the model proposed by Dellaert and van de Poel (1996) with a simple rule generated more orders and a lower average inventory level than the sophisticated rule model such as Federgruen et al. (1984). However, both models behaved similarly in terms of the annual total costs. Another simulation was constructed to examine the performance of the developed model and the existing system used in the hospital with a Poisson arrival times and normally distributed demand. A sustainable cost saving and improved service level could be achieved with the developed model. Except from placing the purchasing order directly from the healthcare organizations to the suppliers, Nicholson et al. (2004) explored the case with outsourcing. They constructed two inventory models which focused on single item, single-review period for non-critical items in healthcare industry to numerically analyze the impact of outsourcing. In their study, non-critical item was defined as the one with a relative long shelf-life and low purchasing cost such as tubing, suture sets, latex examination gloves, and plastic/disposable sheeting. Both models incorporated the inventory related cost (i.e. inventory holding cost and backorder penalty costs) at each echelon and pre-specified minimum service level that should be maintained by each hospital department, however, the service center would charge the hospital department an additional cost if the backorder was larger than the pre-assign thresholds in the outsourced network. The first model was a three-echelon in-house distribution network which comprised of central warehouse, hospital warehouse, and departments within each hospital. It aimed at minimizing the total expected cost for each department, each hospital and the central warehouse. For the second model, it was an outsourced two-echelon distribution network with service center (operated by the distributor) and departments within each hospital. The service center charged a unit penalty cost of P_i^B if the total emergency delivery to a hospital was less than α_i units but would charge a higher unit penalty cost of P^B if it was exceeded α_i units. The objective was to minimize the total expected cost for each department, each hospital and the service center. These problems were solved by LINGO and heuristics that the service level of the hospital department could be determined as the maximum of the ratio of penalty cost to holding cost to obtain the feasible solutions. In addition, data on the demand during the review period was collected to analyze the service level and total inventory cost in each model. The authors concluded that outsourced network always dominated in-house network in terms of the total costs while the service level of both network was comparable. Lapierre and Ruiz (2007) studied a multi-item inventory replenishment problem from the supply chain perspective instead of the traditional multi-echelon inventory management system that decision was made de-centrally, and hence, the logistics activity of each echelon was coordinated. The problem was formulated into two different non-linear models as inventory cost oriented model and balanced schedule model with human resources and storage capacities constraints, and solved by Tabu, a meta-heuristic method. The authors gathered the supply data of the generic products (i.e. products that were commonly required by at least one-third of the care unit) from a Canadian hospital to illustrate how the developed models could be applied to a real case. Outputs of the models generated insights for balancing the workload of the medical staff on the time allocation between purchasing and inventory control in the care unit and central warehouse. In addition, a what-if analysis was suggested to compare different strategies through changing the parameters to improve the supply system. This paper was a pioneer study that incorporated scheduling decisions with supply chain modeling; however, further research was needed as the proposed models were more complex than the traditional inventory models such that the optimal solution or tight bounds could not be found.

Regarding the service level maximization, Little and Coughlan (2008) developed an optimization model based on a constraint programming for multiple products associated with space, frequency of delivery and service level restrictions. Their model was evaluated in an intensive care unit of an Irish Hospital on the sterile and bulk items. By varying the restrictions with respect to different objective functions (such as maximize the minimum service level or maximize the average service levels for all products), an optimal inventory policy could be identified. The proposed system was constructed for the products with a constant demand. According to the above literature, it is observed that most of the studies related to the inventory management considered product substitution or performed an emergency delivery when the actual demand exceeded the available stock level, yet, Bijvank and Vis (2012) excluded these in the stock-out situation but incorporated lost sales into their model as the original demand that could not be satisfied. They studied the inventory management of disposable items at Point-Of-Use (POU) location in a hospital and developed a service model and a capacity model for a single-item with lost sales, fractional lead times and service level restrictions based on the Markov decision model (Kapalka et al, 1999). The authors defined the term "risk period" as the period of time that the inventory level reached the reorder point until the replenish order arrived. During this period of time, the fulfilled demand could be evaluated by undershoot (which was the difference between reorder position and the inventory position at the order placement). Following the study by Tijms (1994) and Bagabha et al. (1996), the average and variance of undershoot were calculated as $\mu_{\mu} = \frac{E[D_R^2]}{2E[D_R]} - \frac{1}{2}$ and $\sigma_{\mu}^2 = \frac{E[D_R^3]}{3E[D_R]} - \left(\frac{E[D_R^2]}{2E[D_R]}\right)^2 - \frac{1}{12}$, respectively. The expected lost sale ELS was modeled as $ELS = \sigma\left\{\frac{\mu - s}{\sigma}\left[1 - \Phi\left(\frac{s-\mu}{\sigma}\right) + \phi\left(\frac{s-\mu}{\sigma}\right)\right]\right\}$, where $\phi(\cdot)$ and $\Phi(\cdot)$ represented the probability density function and cumulative distribution function of the standard normal distribution, respectively. The fill rate β was the ratio of satisfied demand over the total demand in a replenishment cycle. For the (*R,s,Q*) policy, the fill rate was estimated by $\hat{\beta} = \frac{Q}{Q + ELS}$ while for the (*R,s,S*) policy, it was determined by $\hat{\beta} = \frac{S - s + \mu_\mu - ELS_u}{S - s + \mu_\mu - ELS_u + ELS}$, where ELS_u was the expected lost sales during the waiting time for a new order placement after the inventory position had reached the reorder level s. With these expressions, the inventory rule for finding the optimal reorder level s and order quantity Q was developed as follows: (i) Set $s = (C + \mu_L)/2$ for $C \geq 2\mu_R + \mu_L - 1$, otherwise, performed step (ii); (ii) set $s = C + \mu_R$ for $C \geq 2\mu_R + \sqrt{\mu_{R=L}}(2 - \sqrt{\mu_{R=L}})$, otherwise, performed step (iii); (iii) set $s = 0.5(C - \mu_{R-L} + 2\sqrt{\mu_{R=L}})$. In these three situations, $Q = C - s$, where *C* was the storage capacity. The developed models were firstly tested at the University Medical Centre and a hospital in Netherlands for examining the service level of infusion liquids at three POU locations (i.e. paediatrics, intensive care and obstetrics) with (*R,s,Q*) replenishment policy. Results demonstrated that the capacity of the POU locations was insufficient such that stock-out possibly occurred. Three possible solutions to minimize the chance of stock-out were proposed, they were: using *(R,s,S)* replenishment policy, shortening the length of review period, and increasing the available capacity. More importantly, the authors derived the closed-form expressions to approximate the performance measures (e.g., fill rate, total cost) for any lost sales inventory systems with

(*R,s,Q)* and (*R,s,S*) policy. Furthermore, a heuristic inventory rule for the capacity model was developed for finding the optimal reorder level and order quantities with (*R,s,Q*) policy. The author concluded that if the inventory was managed automatically such as using the RFID system, both replenishment policies were recommended and their performance were comparable good when the service level was rather high. Besides, the proposed approximation procedure facilitated calculating the near-optimal solution; therefore, it was also possible to extend to retailing industry.

Table 2.7 Summary of the studies for managing healthcare products

Paper	Policy	Demand	Item	Objective	Constraints	Types of Product
Dellaert and van de Poel (1996)	(R,s,c,S)	Stochastic	Multi	Min. Cost	Not applicable	Disposables sterile items (e.g. gauze, cottonwool, catheters) and general operation items (e.g. printing, stationery)
Nicholson et al (2004)	(R,S)	Stochastic	Single	Min. Cost	Manpower, Space	Non-critical items (e.g. tubing, suture, disposable sheeting)
Lapierre and Ruiz (2007)	(R,s,Q)	Deter-ministic	Multi	Min. Cost	Manpower, Space	General products commonly required among care units
Little and Coughlan (2008)	(R,S)	Stochastic	Multi	Max. Service	Delivery frequency, Space, Service level	Not specified
Bijvank and Vis (2012)	(R,s,Q) & (R,s,S)	Stochastic	Multi	Max. Service	Space, Service level, Fractional lead time	Disposables items (e.g. gloves, needles, sutures)

As a remark, in addition to modeling the non-critical items in the healthcare industry, numerous prior studies also examined the optimization of pharmaceutical supply chains (such as Papageorgiou et al., 2001; Shah, 2004; Sundaramoorthy and Karimi, 2004; Stefansson et al., 2006; Colvin and Maravelias, 2010; Costantion et al., 2010; Baboli et al., 2011; Sousa et al., 2011). However, note that the pharmaceutical products and vaccination are not the main focus of this dissertation. A recent comprehensive discussion on this area was conducted by Narayana et al. (2014).

2.4. Quick Response System (QRS)

Similar to the fashionable products, healthcare apparel products were also characterized by volatile demand and short shelf-life. The inventory management approach adopted in the fashion and textile supply chain to better matching demand and supply could also be facilitated in the healthcare system. Quick Response System (QRS) was a well-known strategy that was well-studied in the literature. It aimed at facilitating a quicker response to the market changes and shortening the ordering lead time (Hammond, 1990). For example, retailers could postpone the ordering decision from the first-stage (i.e., the time point that was far away from selling season started) to the second-stage (i.e., the time point that was closer to the selling season started). In such way, the retailers could update their forecasting demand and modified the initial order decision with the used of more precise market demand information (Iyer and Bergen, 1997). This information, indeed, could be collected and analyzed through the information technology such as the bar-coding system, the RFID system or the mobile computing devices, and thus, the “forecasted” demand of the products could be kept updating and become more accurate. When this strategy was applied in the healthcare industry for inventory planning, it helped the healthcare organizations to reduce the forecast error with respect to the real patient's need and hence, they can provide better service and treatment to the patients.

2.4.1. Single-period Problems

Under the QRS, market information was kept updating to improve initial forecasting and resulted in a better inventory planning. Its value contributed to the supplier and the entire supply chain was also worth studying. In the existing supply chain management literature, the impact of the QRS was extensively discussed. The basic formulation of a single-ordering with two-stage setting in a single period was developed by Iyer and Bergen (1997) who studied the impact of the QRS in a simple single-supplier single-retailer supply chain with single-order two-stage setting. They assumed the retailer had only one ordering opportunity before the selling season started and the products could be sold in a single-period. Besides, the retailer kept collecting and observing the demand information to revise the initial forecast estimation through the Bayesian approach. Under this approach, they assumed the demand during the season at the first-stage x was normally distributed with a mean θ and a variance σ^2, where the demand mean was uncertain but also following the normal distribution with a mean μ and a variance τ^2. After collecting the demand information of the correlated product d_1, the conditional distribution of the demand during the season was modelled as the normal distribution with a mean $\mu(d_1)$ and a variance $\frac{1}{\rho}$, where $\mu(d_1) = \frac{\sigma^2 \mu}{\sigma^2 + \tau^2} + \frac{\tau^2 d_1}{\sigma^2 + \tau^2}$ and $\rho = \frac{1}{\sigma^2} + \frac{1}{\tau^2}$. Demand during the season at the second-stage was modeled as

$m(x|d_1) \sim N(\mu(d_1), \sigma^2 + (1/\rho))$. Under the QRS, the expected profit of the retailer was derived as $EP_{QR} = (r-c)\mu - \sqrt{\sigma^2 + \frac{1}{\rho}}\{(c+h)Z(s) + (r+h+\pi)b_r(Z(s))\}$, where r was the revenue generated per unit, c was the wholesale price per unit, h was the holding cost per unit, π was the loss of goodwill cost, $Z(s)$ represented the standard normal distribution with a cumulative probability of service level s, and $b_r(Z(s))$ was the right linear loss function of $Z(s)$. Regarding the manufacturer, its expected profit becomes $EP_{QR-mfr} = (c-w)\left[\mu + Z(s)\sqrt{\sigma^2 + \frac{1}{\rho}}\right]$. Through comparing the expected profit of each member with and without the QRS, their study generated an important insight that the QRS was benefited to the retailer and the whole supply chain but not the manufacturer if the retailer was responsible for setting a service level threshold larger than 0.5. Therefore, three practical policies, namely, wholesale pricing commitment, volume commitment, and service level commitment, were proposed to achieve the Pareto Improvement. Pareto improvement was defined as the situation that at least one channel member was better off and no one was worse off. Hereafter, numerous studies extended the work by Iyer and Bergen (1997) to explore the impact brought by the QRS under different scenarios. For instance, Chen and Xu (2001) compared the single-ordering and dual-ordering with information updating setting in a two-echelon supply chain. Consistent with the findings of Iyer and Bergen (1997) that the supplier was worse-off under the QRS, two measures, namely, price strategy and goodwill cost adjustment were discussed to achieve Pareto improvement. Choi et al. (2006) further evaluated two information revision models: Model I revised both the unknown demand mean and demand variance, while Model II updated the unknown demand only. They analytically compared the values of the QRS under these two models and generated the following findings: (i) the QRS was always beneficial to the retailer and entire supply chain under Model II; (ii) whether the QRS benefited retailers and entire supply chain depended on a parameter which was related to the ratio between the expected posterior coefficient of variance and the prior coefficient of variance; (iii) supplier could be worse-off under the QRS especially when the service level of the retailer was larger than 0.5. The authors also concluded that the effectiveness of the QRS was dependent of the accuracy of the information updating model and the choice of the right pre-seasonal products as the observation object to predict the demand of the seasonal product. Similar to the case underlying by Choi et al. (2006), Choi (2006) studied the two-stage supply chain with dual information updating that both unknown demand mean and demand variance of the seasonal product were revised after observing the market signal. Besides, it was assumed that the ordering cost and the production cost at the second-stage was unknown to the retailer at the initial stage (i.e., first-stage). Under this setting, the QRS was always beneficial to the retailer; yet, both manufacturer and the entire supply chain had to satisfy some conditions to acquire the benefits. Since the manufacturer might suffer under the QRS, feasible measures such as cost adjustment method, revenue sharing policy, and buyback policy were discussed to achieve Pareto-improvement. Based on the above literature, it was observed that the Bayesian approach was one of the popular methods used to model the information revision. We refer interested readers to Berger (1985) for the details of this approach.

In addition to single-order supply chain setting, existing studies also investigated two-stage dual-order setting in which the retailer could request an additional order at the second-stage. Gurnani and Tang (1999) assumed that information was jointly distributed while demand was bi-variate normally distributed. They studied the information updating policy with an unknown future wholesale price and developed the conditions that the retailer should postpone the ordering decision to the second-stage. Lau and Lau (1997) addressed a problem that a retailer could reorder a newsvendor product during the mid-season after the demand of the early-season was observed. In their models, they compared the cases with normal and beta demand distribution. Numerical analysis showed that placing a reorder in the mid-season would help earn more profit if the profit margin of that item was not significantly high. Sethi et al. (2005) extended the work with the consideration of service level constraint which was imposed at each ordering stage and evaluated the effect of the market signal quality. Liu et al. (2006) addressed the inventory planning decision of a short-life-cycle product with two selling periods. They firstly developed a dynamic programming model to compare the performance between the QRS and two-stage decision policy under the Bayesian information update and then extended to evaluate the situation with three ordering opportunities. By considering the variable ordering cost and information quality, it was found that two-stage decision policy performed better than that of the QRS in most cases. Tiwari et al. (2011) considered a retailer could trigger two orders before the selling season but the product supplied at the second-stage was unreliable. Supplier guaranteed on the minimum order quantity and the maximum yields. The optimal order quantity at each stage was firstly investigated and the impact of the minimum guarantee under uniformly distributed demand was also discussed. They concluded that a unit improvement in the minimum order guarantee at the first-stage resulted in a lower cost than that of the unit improvement in the maximum yield. Therefore, supplier should increase the minimum order guarantee at the first-stage in order to reduce the supply variability.

Existing literature was not limited to single or two-stage setting, specifically, multiple-delivery under the QRS was also examined. For example, Choi et al. (2004) extended the information updating process to N periods and the retailer could place an order at Stage N (which was before the selling season launched). Under this setting, the retailer had a trade-off on the product cost payment and the demand forecast accuracy. A dynamic programming supplemented by simulation experiments was triggered to discuss the optimal order time period. Later on, Choi (2007) studied both inventory ordering decision and selling pricing of the retailers with multiple information updating. It was assumed that two orders of a seasonal product were placed before the selling season startd. Meanwhile, demand of the pre-seasonal product was observed which helped to revise the demand forecast of the seasonal product at the forthcoming stage. This issue was modeled as a dynamic optimization problem to generate the optimal stocking level and optimal retail pricing with respect to maximize the expected profit with risk consideration, respectively. Because of the problem complexity, it was found that analytically deriving the optimal solution was challenging, hence, dynamic programming should be adopted for solving the inventory problem under the QRS with multiple-stage.

2.4.2. Supply Chain Coordination

Because of the disparate incentives of each channel member in the supply chain, for instance, the healthcare organization would consider its expected cost or profit only but not the supplier's when making the inventory decision, it would lead to a double marginalization effect and resulted in an inefficient supply chain (Spengler, 1950). This phenomenon was extensively explored. In fact, it was a well-known fact that the inventory decision in a decentralized supply chain setting under the pure wholesale price contract would not be coordinated. Thus, coordinating the incentives of all channel members was the key to achieve an optimal supply chain performance (Cachon, 2003) and extensive literatures proposed various contracts such as buyback contract (Pasternack, 1985; Xiao et al., 2010; Wu, 2013), revenue-sharing contract (Cachon and Larivier, 2005; Xu et al., 2014), markdown money contract/return contract (Tsay, 2001; Wang and Webster, 2009; Chen and Grewal, 2013; Shen et al., 2013), option contract (Barnes-Schuster et al., 2002; Xu, 2010; Zhao et al., 2013), and quantity discount (Dada and Srikanth, 1987; Weng, 1995; Chen, 2012) to achieve the supply chain coordination. The measures to mitigate the double marginalization effect were also widely discussed with respect to the QRS.

Eppen and Iyer (1997) analyzed a "backup agreement" in the apparel industry which specified the amount of products that the manufacturer would commit for the whole selling season. Under this contract, the retailer could place an order at the beginning. After updating the market information, a second order up to the backup quantity could be triggered. However, the retailer had to pay for a penalty cost to the manufacturer if any of the backup quantity was not purchased. This problem was formulated as a stochastic dynamic programming to derive the optimal stocking policy. Besides, it concluded that the backup agreement was beneficial to both channel members in terms of the expected profit. Donohue (2000) studied a scenario that the manufacturer had a lower production cost if there was a longer production lead-time but this cost was higher if the lead-time was short. Supplier allowed the retailer to place two orders: one was at the initial phase while another was at the second phase after the demand information was collected. Under this situation, decentralized system was not coordinated and hence, an appropriate price setting and a buy-back policy were designed to better allocate the supply chain profit. Barnes-Schuster et al. (2002) investigated a single product with correlated demands between two periods of time. Initially, buyer not only placed an order to the supplier but also purchased an option at the first-stage. Buyer updated the demand information and might execute part of the option to satisfy the demand at the second-stage. Numerical findings showed that supply chain was coordinated if and only if the price of the options was a linear function. The author concluded that options purchase was an effective measure to increase the operation flexibility and improved the supply chain performance. In contrast, Wu (2005) developed a risk-sharing contract and studied a situation that the retailer could quote the initial order quantity at the first-stage as a production reference point to the manufacturer. Then, the retailer adopted the Bayesian approach to update the demand information and decided the ultimate order quantity. They assumed the demand was uniformly distributed and distribution of the demand variance is Pareto. In their proposed contract, the final committed order quantity of the retailer was constrained by a flexibility factor towards the initial forecast quantity and the production quantity of the manufacturer (which was determined at the first-stage). By conducting the numerical analysis, it demonstrated that the retailer attained more benefits than that of the manufacturer with a higher flexibility level. Chen et al. (2006) proposed a bi-directional return policy contract to facilitate supply chain coordination. They studied a two-channel supply chain that the supplier had to commit a production quantity at the first-stage. After updating the demand distribution at the second-stage, the retailer would adjust the initial ordering decision. Through adopting the proposed risk sharing contract, retailer, on one hand, had to share and compensate a portion of supplier's overproduction cost if the final ordering decision was less than that of the quantity determined at the first-stage; while the supplier, on the other hand, provided partial subsidy to the retailer by buy-back the overstock products. Sethi et al. (2007) extended the work by Sethi et al. (2005) in which retailer had to fulfill the service target at each ordering stage and then examined the situation with order cancelation at the second-stage after observing the market information. In this case, they proposed to implement a buyback contract to coordinate the supply chain when there was a service level constraint. The impact of the order cancelation was also explored by Yang et al. (2011). Yang et al. (2011) investigated a scenario that a retailer purchased components for assembly from two suppliers with different delivery lead times. At the first-stage, the retailer placed an order to the long lead-time supplier and kept updating the demand forecast until the second-stage. At the second-stage, retailer could partially cancel the order placed at the first-stage if the initial ordering quantity was too excessive or triggered another order to the short lead-time supplier if shortage might result. The authors firstly developed the condition to achieve supply chain coordination when there was no information updating between the two stages, i.e., the retailer was willing to compensate the long lead-time supplier for the order cancelation and both suppliers bought the leftover products back from the retailer. This finding was further extended to the situation with information updating. A generalized revenue-sharing contract, which incorporated the loss of order cancellation and the shortage penalty cost, was developed to coordinate the supply chain with endogenous price setting. Chen et al. (2010) examined a fashion supply chain in which demand was stochastic and price-dependent. It considered the supplier had limited capacity for supplying the product within a short period of time and assumed that supplier reserved production capacity at the initial stage while retailer could not order more than the reserved capacity at the second-stage after the marketing signal was observed. This problem was modeled as an optimization problem to determine the optimal capacity reservation of the supplier and the optimal order quantity together with the retail price of the retailer. A three-parameter risk and profit sharing contract was designed in which the retailer would share the supplier's risk of over-reservation to overcome the double marginalization problem. In contrary to placing orders before the selling season with information updating in between, retailer might make an ordering decision during the sales period. Zhou and Wang (2012) considered a scenario in which the retailer had two ordering opportunities: one was placed at the beginning of the selling period while another order was triggered during the selling period. The selling period was separated into two sub-periods by the second ordering. They assumed that the demands in the two sub-periods were stochastic and auto-correlated. Bayesian approach was adopted to update the demand during the pre-season as well as the demand distribution in the second sub-period before placing the second order. It was assumed that if excessive demand was found at the first sub-period, it would be partially backordered; if it was realized at the second sub-period, it would be perceived as lost. They concluded that supply chain coordination was achieved with the help of an improved revenue sharing contract in which the manufacturer offered a wholesale price which was lower than the unit production cost so as to get a subsidy from both the production setup cost at the second-stage and partial generalized revenue from the retailer.

2.4.3. Risk Consideration

From the above review, it showed that inventory decision of the retailer and the expected profit of retailer, supplier, and entire supply chain would vary under the QRS in different scenarios. Indeed, implementing the QRS would also affect the variance of profit of each channel member. Mean-Variance (MV) approach was one of the well-known approaches to conduct the risk analysis. It was firstly developed by Markowitz (Markowitz, 1959). Details of this approach could be found in Choi and Chiu (2012). With the help of the MV approach, the payoff and risk level of the channel members under the QRS could be quantified and compared.

To be specific, Choi et al. (2003) studied a two-stage ordering policy with a known ordering cost at the first-stage while that of the second-stage was unknown. They compared the service level and variance of profit level when the order could be placed at the first-stage, and at both stages. The analytical findings demonstrated that the service level under the two-stage optimal policy was higher than or equal to that of the ordering policy placed at the first-stage only. However, the variance of profit was smaller when the retailers placed the order at the first-stage than that of the two-stage optimal policy which meant that the QRS reduced the risk level of the retailers. Özer et al. (2007) studied a dual purchase contract that the retailer could enjoy a lower product price for the advance order (i.e., before the time point with forecast update). Through offering this contract, it not only helped manufacturer to hedge against the profit variability (which was especially useful for the one with risk averse attitude) but also achieved the Pareto improvement. Choi and Chow (2008) considered the single-ordering setting in which the retailers could suspend the ordering decision to the time point that was closer to the selling season. By using the MV approach, they found that the QRS was beneficial to the retailer only but not the manufacturer and hence, they proposed three different policies, namely, price-commitment policy, service-level commitment policy, and buy-back policy, to achieve an MV win-win situation that both parties were better off in terms of the expected profit and variance of profit. The proper setting of each parameter under each policy was also discussed. With the analytical finding that the manufacturer would be worse-off under the QRS, Chow et al. (2012) considered a real life situation in which there was a minimum order quantity (MOQ) requirement imposed on the retailer for postponing the ordering decision closer to the selling season launched. By addressing the retailers' reservation expected profit (i.e., the minimum expected profit) for ordering up to the MOQ requirement, the appropriate range of the MOQ was suggested so that the retailer would not reject the contract. Besides, it analytically showed that the expected profit of the retailer with the MOQ constraint was non-increasing which reflected the retailer would earn less when the MOQ is large. Furthermore, the authors simulated 1000 pairs of posterior demand mean and realized demand to measure the risk level of each channel member towards the imposition of the MOQ under the QRS. Even though the MOQ implementation would increase the expected profit of the manufactures, they also had to bear a higher risk level. This analytical finding was also supplemented by the numerical analysis which revealed that the MOQ would lead to supply chain inefficiency or enhance supply chain performance depending on how the MOQ was set. Ma et al. (2012) studied ordering flexibility issue under the QRS. Retailer could either place an additional order or partially cancel the order quantity at the second-stage according to the updated information. They assumed that the retailer was risk-averse who had to commit a penalty cost if a target profit was not met and examined the total profit once the demand was realized based on a loss-averse utility function. Their analytical result showed that the optimal total order quantity at the second-stage was non-increasing in the penalty coefficient while that of the order quantity at the first-stage was decided by the degree of worthiness of the information and the level of demand uncertainty. They also extended the analysis to evaluate the situation when the retailer was allowed to cancel all or part of its first-stage order quantity at the second stage and found that it would increase the retailer's optimal order quantity at the first-stage. Recently, Choi (2013) incorporated a timely issue, environmental sustainability, into the QRS. It illustrated how to impose a carbon footprint taxation scheme in the QRS and analytically proved the optimal decision on the sourcing strategy (i.e., local sourcing or offshore sourcing) when there was or was not a carbon footprint tax in both single-ordering and dual-ordering setting. Through conducting the risk analysis on the retailer associated with the scouring decision, the analytical findings contributed to the literature that the carbon footprint taxation scheme could motivate the fashion retailers to seek for a local manufacturer but it also benefited them with a lower risk level. Yan and Wang (2014) examined a case that there were two instant ordering opportunities with demand information updating in between but was constrained by a limited capability. Despite assuming the retailer was risk-neural, they also considered the retailer was risk-averse and modeled it by adopting a loss aversion with exponential utility. Their findings showed that the target safety capital played a crucial role in the capital allocation between the two orders; for instance, retailers would consume all the capital to place the order at the first-stage if the initial capital was smaller than the target safety capital. In contrary, some capital would be saved and spent at the second-stage when the initial capital was greater than the target safety capital; and fewer optimal order quantities were ordered at the first-stage when the retailer possessed a higher initial capability. Also, the retailer should retain more capital for the second-stage when there was a high correlation between the market information and the demand, or the retailer was more risk-averse. The above analytical studies on the QRS are summarized in Table 2.8.

Table 2.8 Summary of the analytical studies on the QRS

Paper	Single, dual or multiple ordering?	Two or multiple stage(s)?	RFID related?	Bayesian approach?	Model with multiple demand observations?	Risk analysis?	Proposed Contract for coordination/ Pareto improvement
Iyer and Bergen (1997)	Single	Two	No	Yes	No	No	Wholesales pricing, volume commitment, service-level commitment
Lau and Lau (1997)	Dual	Two	No	No	No	No	Not applicable
Eppen and Iyer (1997)	Dual	Two	No	Yes	No	No	Backup agreement contract
Gurnani and Tang (1999)	Dual	Two	No	No	No	No	Not applicable
Donohue (2000)	Dual	Two	No	No	No	No	Buy-back policy
Chen and Xu (2001)	Dual	Two	No	Yes	No	No	Price strategy, goodwill cost adjustment
Barnes-Schuster et al. (2002)	Dual	Two	No	No	No	No	Return policy
Choi et al. (2003)	Dual	Two	No	Yes	No	Yes	Not applicable
Choi et al. (2004)	Single	Multiple	No	Yes	No	Yes	Not applicable
Sethi et al. (2005)	Dual	Two	No	No	No	No	Not applicable
Wu (2005)	Single	Two	No	Yes	Yes	No	Quantity flexibility contract
Chen et al. (2006)	Single	Two	No	No	No	No	Bi-directional return contract
Choi (2006)	Single	Two	No	Yes	No	No	Revenue-sharing policy, buy-back policy, cost adjustment policy
Choi et al. (2006)	Single	Two	No	Yes	No	No	Not applicable
Liu et al. (2006)	Dual	Two	No	Yes	Yes	Yes	Not Applicable
Choi (2007)	Multiple	Multiple	No	Yes	No	Yes	Not applicable
Özer et al. (2007)	Dual	Two	No	No	No	Yes	Dual purchase contract

Sethi et al. (2007)	Dual	Two	No	No	No	No	Buy-back contract
Choi and Chow (2008)	Single	Two	No	Yes	No	Yes	Price commitment policy, service-level commitment policy, buy-back policy
Chen et al. (2010)	Single	Two	No	No	No	Yes	Risk and profit sharing contract
Tiwari et al. (2011)	Dual	Two	No	No	No	No	Not applicable
Yang et al. (2011)	Dual	Two	No	Yes	No	No	Return policy
Chow et al. (2012)	Dual	Two	No	Yes	No	No	Dynamic MOQ policy
Ma et al. (2012)	Dual	Two	No	No	No	Yes	Not applicable
Zhou and Wang (2012)	Dual	Two	No	Yes	No	No	Not applicable
Choi (2013)	Dual	Two	No	Yes	No	Yes	Not applicable
Yan and Wang (2014)	Dual	Two	No	No	No	Yes	Not applicable

2.5. Summary

From the above reviewed literature, it was observed that most of the studies applied the RFID system to managing the assets, tacking the patients, and monitoring the inventories of pharmaceutical products. However, very few of them focused on the healthcare apparel products. Similar to pharmaceutical products, various disposable healthcare apparel products such as surgical masks, gloves and gowns also had expiration restriction and other inventory management challenges. Therefore, motivated by the facts that (i) RFID system was very versatile for enhancing inventory management, and (ii) RFID system was used in some hospitals, it was believed that the RFID was a promising tool which could be used to manage the healthcare apparel products efficiently. Hence, this dissertation explored the optimal inventory planning of the healthcare apparel products with the use of the RFID system.

As a remark, in the healthcare industry, Rigby and Anand (2000) classified the apparel products into the following four categories: (i) healthcare hygiene products, e.g., mattress covers, face masks, surgical gowns; (ii) extracorporeal devices, e.g., artificial kidney; (iii) implantable materials, e.g., sutures, artificial ligaments and joints; and (iv) non-implantable materials, e.g., wound dressing, gauzes, bandages. Majority of these healthcare apparel products were perishable that were for single-use and had to be disposed after consumption; while minority of them were reusable which could be cleaned and sterilized for repeated usage. No matter which types of the healthcare apparel products, according to Ng et al. (2011), these healthcare apparel products were playing critical roles in serving the following main purposes: (i) protecting the patients from bacteria, pollutants, or harmful substances, for example, face masks and surgical gowns were important apparel products for both the patients and the medical personnel to prevent from infection; (ii) providing treatment, for instance, pressure garment was used for treating hypertrophic scars to accurate the maturation rate after burnt (van den Kerckhove et al., 2005); and (iii) providing caring for the patients with different physical and psychological requirements. Among all these functions, it was believed that the most significant one was to protect the users (i.e., patients and medical personnel). Since the healthcare apparel products were critical items that should be available in the healthcare organization when needed, therefore, they should be very well monitored and planned. The use of the RFID system hence provided a means to enhance inventory management of these important items in the hospitals.

3. Methodology

Case study has been well presented in the academic research related to the healthcare industry. It emphasizes on the exploration on the contemporary situation in real-life, together with the data collection and context analysis; therefore, it is suitable to use it as a tool to study the real world phenomenon in which the context is not clearly evident (Yin, 2009). A case study helps to analyze the core problems that exist in a supply chain and possible solutions can be suggested to tackle them accordingly (Mustaffa and Potter, 2009). Because the application of the RFID in healthcare industry is still at an emerging phase and many issues are under explored, it is appropriate to adopt case study approach (Yin, 2009).

In the field of the operations management, the illustration of the quantitative findings and the theory development are usually achieved based on the qualitative understandings (Meredith, 1998). Besides, the case study is an appropriate method for operations management because it helps to gather the facts on a particular situation (Sodhi and Tang, 2014) and define the conditions and constraints in a real-world practice (McCutcheon and Meredith, 1993; Voss et al., 2002). The purpose of presenting the case studies in this dissertation is to generate managerial insights from collecting contextual information on the existing inventory practice and the information system adopted in Hong Kong healthcare industry. The reported case studies in Chapter 4 were developed from individual in-depth interviews, supplemented by simple data analysis, as well as the secondary information collected from the industrial reports. Through this methodology, it helped to give a clear picture in the industrial practice, generate crucial insights and guide future research directions on the analytical models development in the subsequent chapters. Figure 3.1 summarizes the outline of the study methodology of this dissertation and illustrates how the research objectives can be achieved.

3.1. Interview with Medical Personnel in Hong Kong Hospitals

Conducting interviews with the relevant medical personnel generates important insights on the first-hand and relevant information related to the study topic. To better understand the real-world practice, two hospitals with different funding nature were selected: the first one was a Hong Kong public hospital and the second one was a Hong Kong private hospital. The purpose of conducting the case study for these two types of hospital was to evaluate the similarities and differences on inventory decision with respect to different objectives. To be specific, the interviews were conducted with a manager and a senior registered nurse of a Hong Kong public hospital and a Hong Kong private hospital, respectively, and they were responsible for managing and making decision toward the healthcare apparel products. The interview questions are shown in Appendix (A). Hence, through conducting interview with the medical personnel, research objective 1 (as indicated in Chapter 1), which aimed "*To explore the real world inventory management decision and practice in the Hong Kong healthcare organizations especially concerning the apparel related healthcare products*", was achieved.

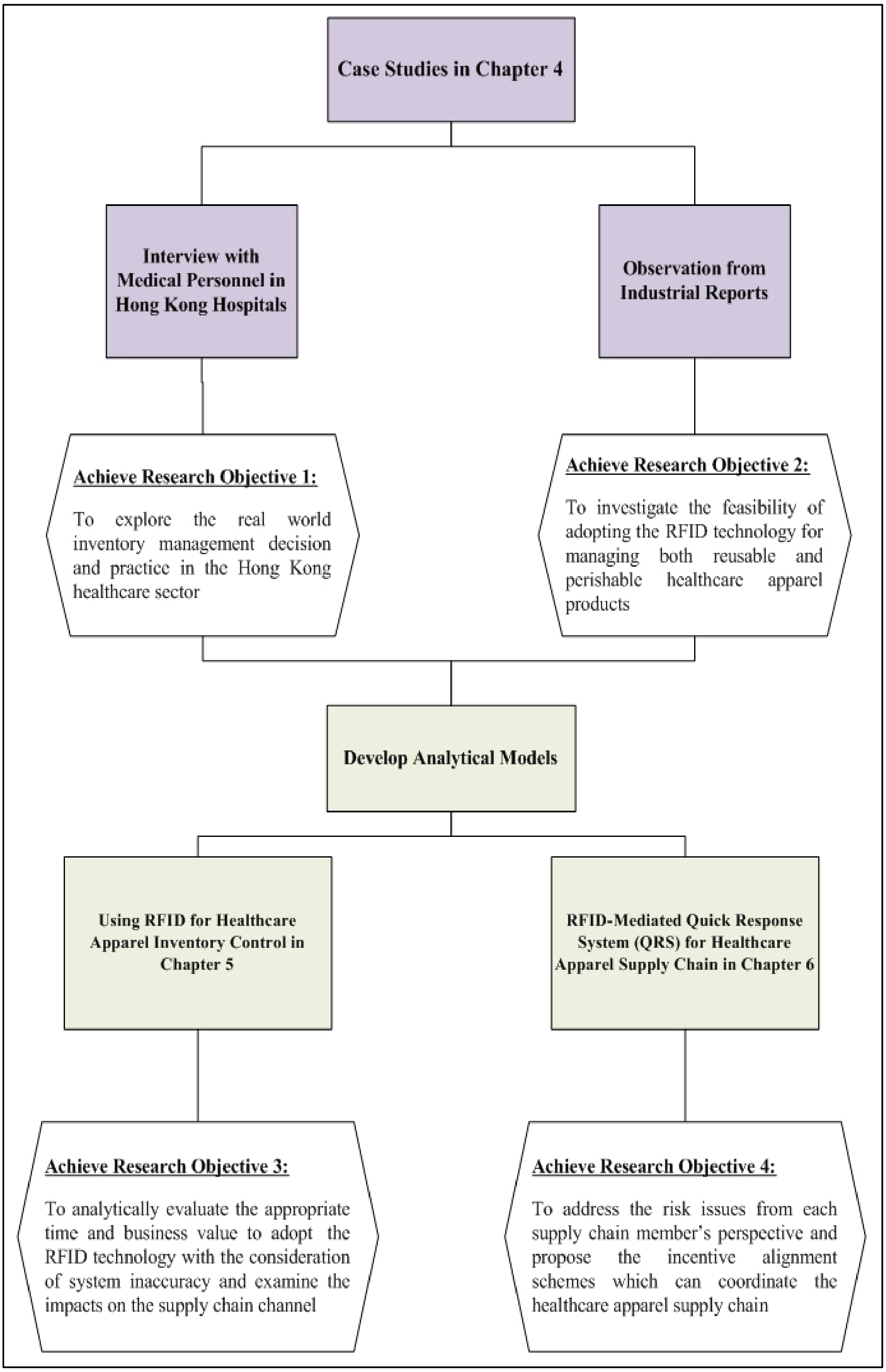
3.2. Observation from the Industrial Reports

Since the RFID system was less matured than the bar-coding system and its application in the healthcare industry was ambiguous, the information provided by the industrial reports helped to indicate the latest application and business value of the RFID application in the healthcare industry. Therefore, this observation generated from the industrial reports could help to achieve the research objective 2: "*To investigate the feasibility of adopting the RFID technology for managing both reusable and perishable healthcare apparel products*".

3.3. Develop Analytical Models

Based on the observation on the real industrial practice, two analytical studies were developed. In Chapter 5, the model explored the case when the healthcare organization is planning to use the RFID for healthcare apparel inventory control and the consequence that would be brought. Chapter 5 aimed at achieving research objective 3: "*To analytically evaluate the appropriate time and business value to adopt the RFID technology with the consideration of system inaccuracy and examine the impacts on the supply chain channel*". In Chapter 6, it examined a strategy execution, namely Quick Response System (QRS), with the use of the RFID system in the supply chain context. It addressed important issues such as the value of information with the use of the scanning system under the QRS for better cope with the real need of the patients and the impact of the QRS adoption in terms of the payoff and risk. Here, research objective 4: "*To address the risk issues from each supply chain member's perspective and propose the incentive alignment schemes which can coordinate the healthcare apparel supply chain*" was achieved.

Figure 3.1 Outline of methodology and the research objectives achieved



4. Case studies

In order to learn about the real world operations of the healthcare organizations and their strategies on handling a wide variety of healthcare apparel products, interviews were conducted with medical personnel and nurses who were responsible for making decision on sourcing the suppliers, and ordering the apparel products (in terms of when and how many to order) in the Hong Kong public hospital and Hong Kong private hospital, respectively. In this chapter, the preliminary interview results are first present in Section 4.1 and Section 4.2, and the observations on the RFID system applications in the healthcare industry are reported in Section 4.3. All the findings are summarized in Section 4.4. Note that some of these important findings are critical as they guide the analytical research studies in Chapter 5 and Chapter 6.

4.1. Case One – A Hong Kong Public Hospital

Site visiting and interviews were conducted during the period from January 2012 to September 2012 with an inventory manager who was working in a Hong Kong public hospital (Hospital X)[1]. Hospital X is a large-scale hospital which consists of about 1,400 beds and provides wide range of services including in-patient, day-patient, out-patient and community care services.

4.1.1. Overview of the Product-Types

Generally, healthcare apparel products consumed in Hong Kong public hospitals could be classified into two different categories as perishable products

[1]Hospital X is a fictitious name for a real public hospital in Hong Kong.

and reusable products. The major suppliers who supplied the healthcare apparel products to the Hong Kong public hospital (Hospital X) were Hospital Authority (HA), Correctional Service Department (CSD) and other outsource suppliers. Figure 4.1 indicates the categories of the healthcare apparel products and the corresponding suppliers in the Hospital X.

All perishable products such as surgical gloves, surgical masks, surgical gowns were supplied by the Hospital Authority (HA), therefore, the Hospital X placed a replenishment order of these products directly to the HA. The HA consolidated the orders from each public hospital and acted as a group purchasing organization for ordering large quantities of perishable products at one time so as to enjoy the economies of scale and lower the purchasing costs. Regarding the reusable products that were commonly used among the public hospitals, namely standard items, were supplied by Correctional Service Department (CSD). The CSD is a government department which guards and looks after prisoners. It encourages adult prisoners to participate in industrial activities and craft work such as carpentry, metalwork and garment making. It provided about 50 different reusable standard healthcare apparel products for the public hospitals such as patients' and medical staffs' uniforms, bed sheets and pillow covers according to the quality and quantity requirements of the hospitals. In this supply chain, the CSD was the supplier whereas the HA acted as a coordinator between the CSD and the public hospitals. Apart from ordering the healthcare apparel products from the HA and the CSD, Hospital X might also source others suppliers for special reusable items (i.e., non-standardize items) that were not commonly requested among hospitals. This was because each public hospital possessed different functionality and specialist clinic, and required different healthcare apparel products to best fit the patients' needs. For example, Hospital X demanded tailor-made bed sheets for bedridden patients. In order to support and relieve the pressure of their lying down position, it was more comfortable for them to sleep on air-filled cushion beds. However, when the air was filled into the cushion bed, the standard size bed sheet could not fully cover the bed, and hence, a relative larger bed sheet is needed.

4.1.2. Management of the Reusable Healthcare Apparel Products

Hospital X forecasted the demand of each reusable healthcare apparel products for each quarter every year and placed a replenishment order to the suppliers every season. It believed that such practice (i.e., products delivered to the hospital four times a year with variant quantity) could reduce the inventory level at the warehouse. There were several factors which determined the forecasting quantity, they were: experience of the manager, number of products had been condemned, number of products were used, special quantity requirement from the wards, historical consumption rate and the on-hand inventory level at the warehouse. Hospital X would base on the forecasted demand to sign an annual contract with suppliers for supporting the quantity requirement for the coming year. Regarding the time for placing an order, the Hospital X had different replenishment frequencies for standard and special reusable items. Since the order quantity of the standard reusable items are relatively higher than that of the special non-standardize items, therefore, the Hospital X would inform the CSD about the quantity requirement for each season prior to the start of each year. On the other hand, those outsource suppliers would be informed twice a year (i.e. supplier would know the quantity requirement for the coming two seasons). No matter whom the suppliers were, the Hospital X would place a replenishment order at the end of each season just to clarify the delivery date. Besides, there was no further adjustment or amendment on the initial forecasted demand in each quarter; therefore, the managerial staff member had to carefully plan the order quantity for each season. As a remark, the Hong Kong public hospitals reserved the safety stock at the CSD for the emergency consumption such as the outbreak of SARS which was unpredictable and would definitely lead to a sharp increase in the demand. Figure 4.2, at the end of Chapter 4, indicate the flow of the reusable healthcare apparel products in the Hospital X.

In the interview, it was commented that losing the reusable healthcare apparel products frequently was the most serious inventory management problem that the Hospital X was facing. These products included uniforms of the patients, mattress covers used in Occupational Safety and Health Department (OSH) as well as safety vests worn by the wheelchair patients. The type of product being lost was dependent of the hospital's nature. For example, the Hospital X was an acute hospital which provided emergency service to the patients. When good conditions were observed, patients together with the uniforms that they were wearing would be transferred to an extended-care hospital for further convalescence. Since an acute hospital had to provide treatment following the accident, the Hospital X offered large or extra-large uniforms to the patients only (so that the medical personnel could work conveniently while the patients were more comfortable). However, the Hospital X might receive cleaned small-size uniforms from the CSD or other hospitals after laundry. This was because the CSD did not have special mechanism or tool to identify or distinguish the uniforms of one hospital from another. These small-size patients' uniforms would be accumulated at the Hospital X's warehouse for storage only. One might think that the Hospital X could print its name on the uniform for identify which hospital it belonged to, however, this measure was tried but ineffectual. Therefore, enhancing the visibility and traceability of the perishable healthcare apparel products was a critical concern in the healthcare supply chain.

4.1.3. Management of the Perishable Healthcare Apparel Products

It was found that the bar-coding system had been adopted in the Hospital X to assist in inventory record for items such as surgical tape, wound dressing, and support wrap. For instance, it was used to capture the information such as names of the products, and number of items had been consumed. Even though the bar-coding system helped in the daily operations, the Hospital X also conducted manual checking and counting the on-hand inventory level of the perishable apparel products (such as bandages and support tapes) at each ward every week. If the inventory fell below a level, then the product would be ordered up to the predetermined level. Therefore, the Hospital X executed the periodic review (s,S) policy for managing the perishable apparel products.

4.1.4. Summary of the Interview Results

After conducting an interview with the manager who worked in Hong Kong public hospital, the crucial findings are summarized as follows:

i. Based on the nature of the products, there were three types of suppliers who supplied the healthcare apparel products to the Hong Kong public hospital, they were Hospital Authority (HA), Correctional Service Department (CSD) and other outsource suppliers. Standardized apparel products (i.e., commonly used among the public hospitals) were offered by the HA and the CSD, in which the HA and the CSD was responsible for the perishable and reusable products, respectively. In case there was a special product requirement, sourcing the outside suppliers was the practice for supplying the non-standardized healthcare apparel products.

ii. Ordering decision of the reusable apparel products was based on the following factors: experience of the inventory manager, number of products had been condemned; number of products had been used; special quantity requirement from the wards; historical consumption rate and the on-hand inventory level. The decision was made prior to the start of each year and the order quantity could not be revised. Hence, there was a lack of systematic measure to determine the appropriate order quantity.

iii. Periodic review (s, S) policy was adopted to manage the perishable healthcare apparel products. Even though the products handling and information (such as consumption rate) was recorded by the bar-coding system, manual checking regularly on the on-hand inventory level at each ward was still required.

iv. It was commented that the Hospital X suffered the inefficient inventory management as it lost the reusable healthcare apparel products frequently in which it would increase the operations cost. Since this type of product played a significant role and it was necessary to have sufficient quantity for curing and protecting the patients. Therefore, the Hospital X had to find an effective and efficient way to enhance the visibility and traceability of the healthcare apparel products.

4.2. Case Two – A Hong Kong Private Hospital

In Case One, it was obvious that the Hospital X introduced different kinds of inventory management policies. For example, it decided the order quantity of non-standardize reusable apparel products based on the experience and historical demand data but adopted the periodic review policy with the use of the bar-coding system for managing the perishable apparel products. In order to generate more insights, another interview was conducted during the period from October 2012 to March 2013 with a senior registered nurse who made the inventory planning decision in a Hong Kong private hospital, Hospital Y[2]. Hospital Y is a well-establish hospital which has been founded for more than 40 years in Hong Kong. It has more than 700 beds and provides both in-patient and out-patient service to the community.

4.2.1. Management of the Perishable Healthcare Apparel Products[3]

Similar to the public hospital, the Hospital Y also adopted the bar-coding system to handle the perishable healthcare apparel products. Every week, a preassigned nurse had to conduct inventory taking of the perishable healthcare apparel products and ordered the products up to the predetermined level. Hence, it executed the periodic review (R,S) policy. The predetermined level was a fixed quantity and was decided according to the past demand data. Since the inventory decision was not determined based on a scientific measure, it was commented that stock-out problem existed. Besides, it was also difficult to

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[2]Hospital Y is a fictitious name for a real private hospital in Hong Kong.

[3]Since the laundry of the reusable healthcare apparel products in the Hospital Y is outsourced, therefore, the study of the RFID technology application on such products is not the main focus of this dissertation.

borrow the products from other deparments, and hence, the medical personnel (such as nurses and physicians) would substitute those shortage products by using the one with similar functions and properties.

In order to evaluate how to better forecast the consumption demand of the perishable product, data about the demand of various perishable healthcare appeal products were collected from the Endoscopy Centre in the Hospital Y during the period from February 2013 to August 2013 to examine the correlation among the products. To do so, the value of correlation coefficient r and correlation of determination r^2 of each perishable product was evaluated. Correlation coefficient (also called Pearson Correlation) was introduced by Pearson in 1895 to indicate the degree and direction of a linear relationship between two factors (Bluman, 1997). The range of a correlation coefficient is $-1.0 \le r \le +1.0$, where $r = +1.0$ represents two factors are perfectly positively correlated. On the other hand, correlation of determination r^2 was developed by Rao (Rao, 1973) which is used to measure the probability of variance that can be explained by the regression model of estimating the dependent variable from the independent variable successfully (Nagelkereke, 1991). In other words, it indicates how well the regression line that can be used to represent the data (Gomes et al., 2011). Through evaluating the value of correlation coefficient, it was found that demands of the some perishable healthcare apparel products were positively correlated. For instance, surgical face mask was positively correlated with N95 face mask (with $r = 0.6215$ and $r^2 = 0.3863$) as well as latex gloves (in XS size) (with $r = 0.6241$ and $r^2 = 0.3895$).

4.2.2. Summary of the Interview Results

In Case Two, it revealed the real-world practices and the problem encountered with the existing inventory decision in a Hong Kong private hospital (Hospital Y). Hospital Y also decided the ordering quantity based on the experience and historical demand data. This non-scientific decision led to inventory shortage as commented by the interviewee. As inspired by the literature that the managerial could better predict the demand after observing the market information, therefore the consumption rates of the perishable healthcare apparel products were collected for further analysis. Based on a simple calculation, it was found that demands of some perishable apparel products were positively correlated. With this observation, it was believed Quick Response System (QRS) could be applied to better cope with the demand change and had a more accurate forecast based on the observation of the correlated products.

4.3. Review of New Area for Applying the RFID System in the Healthcare Industry

In the exiting literature, it was reported that the RFID system had been used to track the location of expensive assets or visualize the flow of the medicine along the supply chain in the healthcare industry. Nowadays, the application of the RFID system is spread over to manage the reusable healthcare apparel products. In 2006, a large healthcare center in Norway, St. Olav's Hospital, implemented an RFID-based uniform-tracking system to replace traditional paper-based system to cope with more than 130,000 work garments in real time basis (O' Connor, 2007). Under the new system, employees had to access the uniform storage room using their personal RFID-enabled identity cards. Once the uniforms were taken away, the interrogator would read the tags of the remaining stored uniforms and update the inventory record automatically. If the number of uniforms inside the storage room reached the threshold level, a message would send to the inventory software to alert for replenishment. On the other hand, when the used garment was put in a specific bin for laundry, data such as time and garment IDs would transmitted to the backend software for visualize the flow of the inventory. In the traditional system, staff members had to do the application through filling the forms in order to get clean uniforms and the garments were delivered form the laundry to the storage facility by the convey system. Therefore, it required extensive manual efforts and was time-consuming. With the use of the new RFID-base system, it generated significant saving (about $6 million) on storage space for the removal of conveyor system and the hospital believed in several savings each year on enhancing the inventory accuracy and reducing the labor requirement when compared to the traditional manual system. Another promising RFID adoption occurred in Switzerland. Four Geneva-based university hospitals were merged to form the University Hospitals of Geneva (HUG) in 1995 (Vilamovska, et al. 2009). HUG was a large scaled hospital that offered both inpatient and outpatient services and comprised more than 2,000 beds. In order to manage the patients' garments for automated distribution across different HUG's facilities, an RFID-enable system was employed to trace the uniforms. The patient's garment was sewn with a RFID tag which storesd only the item ID and information related to laundry service. Interestingly, this RFID system was used to identify and match the tops with the bottoms of the patient/staff garments, as well as the whole set of garment with the corresponding site after laundering. The automated garment distribution provided 24 hours 7 days a week service to employees and smoothened the garment handling process of collection, ironing, redistribution across 4 sites with 7 distributors, and 28,000 garments allocation per week efficiently. Besides, it monitored the number of times that a piece of garment has been washed for determining whether the garments fulfilled the quality claimed by the suppliers. This RFID system helped the hospital to reduce the garment inventory level and save up to 30% of the total garment expenditure. Apart from tracking both staff members' and patients' uniforms, a public hospital in Germany, Bielefeld City Clinics, launched trail tests to examine the feasibility and the potential benefits of deploying an RFID-enable system to facilitate beds and mattresses cleaning in a time and cost efficient manner (Wessel, 2007). This system worked as follows: a RFID tag protected by a plastic cover was attached to the mattress, while another tag was placed at the platform support of a bed. When a bed was released, a nurse had to determine what type of cleaning should be performed on each bed and mattress based on the patient illness level and disease suffered, and input the data into the bed-management software. For example, if the patient was suffered from a highly infectious disease, then the mattress had to be completely disinfected. Once the beds and mattresses arrived at the central holding room, an interrogator would read the attached tags to distinguish one and other such that it guided where they should be appropriately sent and the corresponding cleaning type. Once the laundering was completed, another tag interrogation was conducted and the system was updated to show the number of clean beds and mattresses were available. The clinic was expected to acquire cost saving from reducing the stock level of beds and mattresses, and working time of the staff for washing.

These three cases extracted from the industrial reports revealed that the RFID system was capable to manage the reusable healthcare apparel products, and the healthcare organization could be benefited in reducing the manual efforts so that they could focus more on providing treatment to the patients.

4.4. Summary for Chapter 4 and Discussion

In Section 4.2, three case studies on the RFID system applications in healthcare industry were reviewed. It was believed that the RFID system could be adopted not only on the patient identification and assets tracking areas, but also on the reusable products management. In all case studies, it was found that that both public and private hospital was using the bar-coding system to manage the apparel products. When comparing with the RFID system, the bar-coding system required more manual effort and only one item could be scanned each time, it seemed that the healthcare organization might benefit more with the use of the RFID system in term of the operation efficiency, ability of tracking the products and significant cost saving generation by reducing the number of labor requirements. However, prior empirical studies illustrated that the (observed) successful read rate in real world RFID applications was only between 60-70%; therefore, it partially explained the reason for RFID system had not been commonly utilized in the healthcare industry for apparel product management. Here, several questions such as "should the healthcare organization replace the bar-coding system by the RFID system? If yes, what is the business value of the healthcare organization when it switches the scanning system from the bar-coding to the RFID system?" arise.

Besides, as the healthcare appeal products were vital to cure and protect the patients, having sufficient quantity of these products should be the prime concern of the healthcare organization. Observing from the industrial practice, it was known that the determination of the order decision of the apparel products was based on the decision maker's personal experience and historical consumption data; therefore, problems such as shortage and overstocking were also realized. During the outbreak of Severe Acute Respiratory Syndrome (SARS) in 2003, hospitals in Hong Kong had a serious shortage of surgical masks. However, in 2012, it was reported that millions of obsolete masks (as there was an expiry date for masks) were found in the warehouse and had to be disposed (and hence wasted). As a result, the hospitals had to make a trade-off on its inventory decision so as to avoid shortage while not keeping excessive stock. Indeed, after exploring the inventory management mechanism and practice, it was believed that exercising the Quick Response System (QRS) was a possible way to improve the existing inventory decision. Again, information technology was also an important supporting tool which potentially enhanced the implementation of the QRS. For example, the healthcare organization could capture the demands of the correlated products through the information technology to improve the initial demand predication which leads to better inventory planning. However, using the RFID incurs costs and thus it is interesting to explore the value that can be brought by the use of the RFID for exercising the QRS and answer the question on when the RFID implementation is especially significant for facilitating the QRS.

By reviewing the existing inventory decision in both Hong Kong public hospital and private hospital, this chapter provided a clear picture on the real world industrial practice. The identified underlying shortcomings and potential problems would provide the motivation for the technical analyses on the appropriate inventory management decision in the next chapters.

Figure 4.1: Categories of the healthcare apparel products and corresponding suppliers in Hospital X

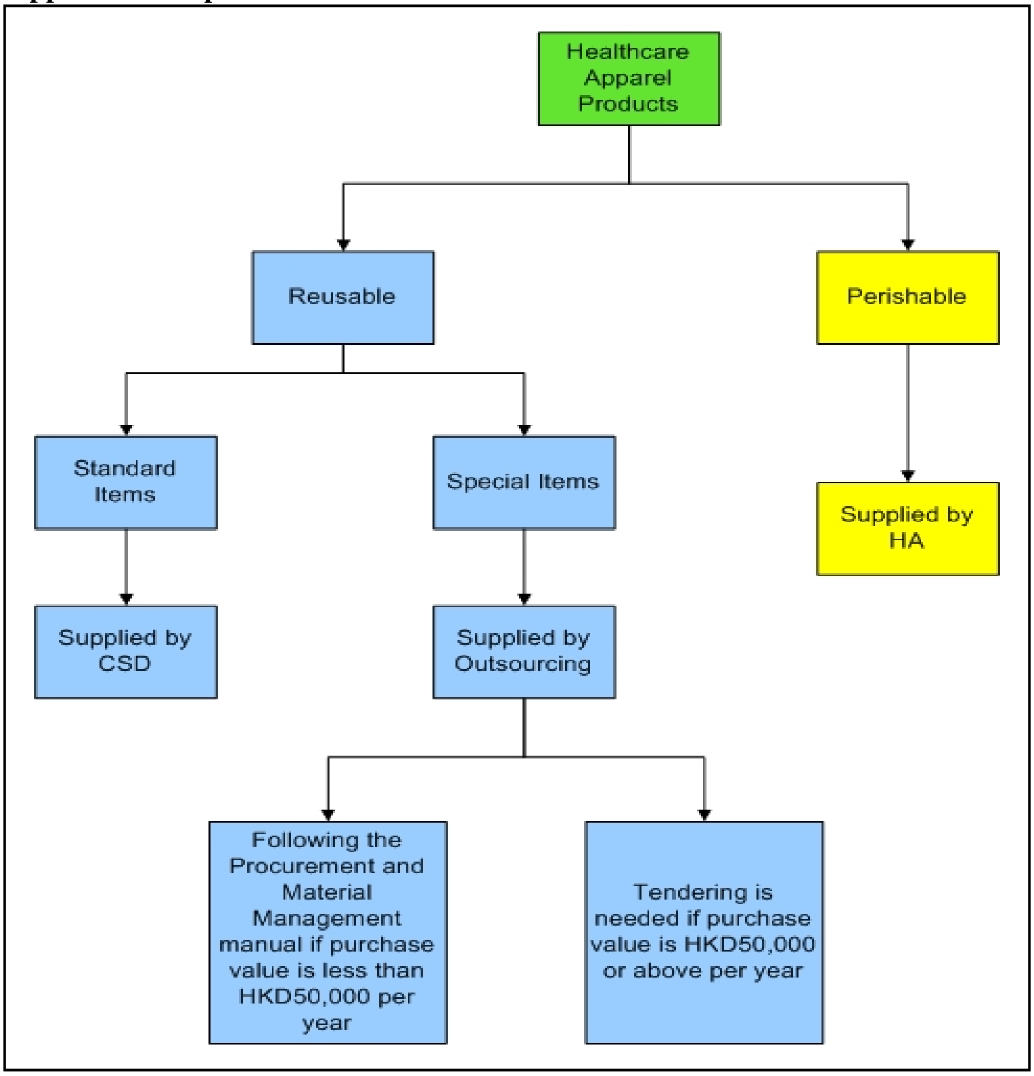
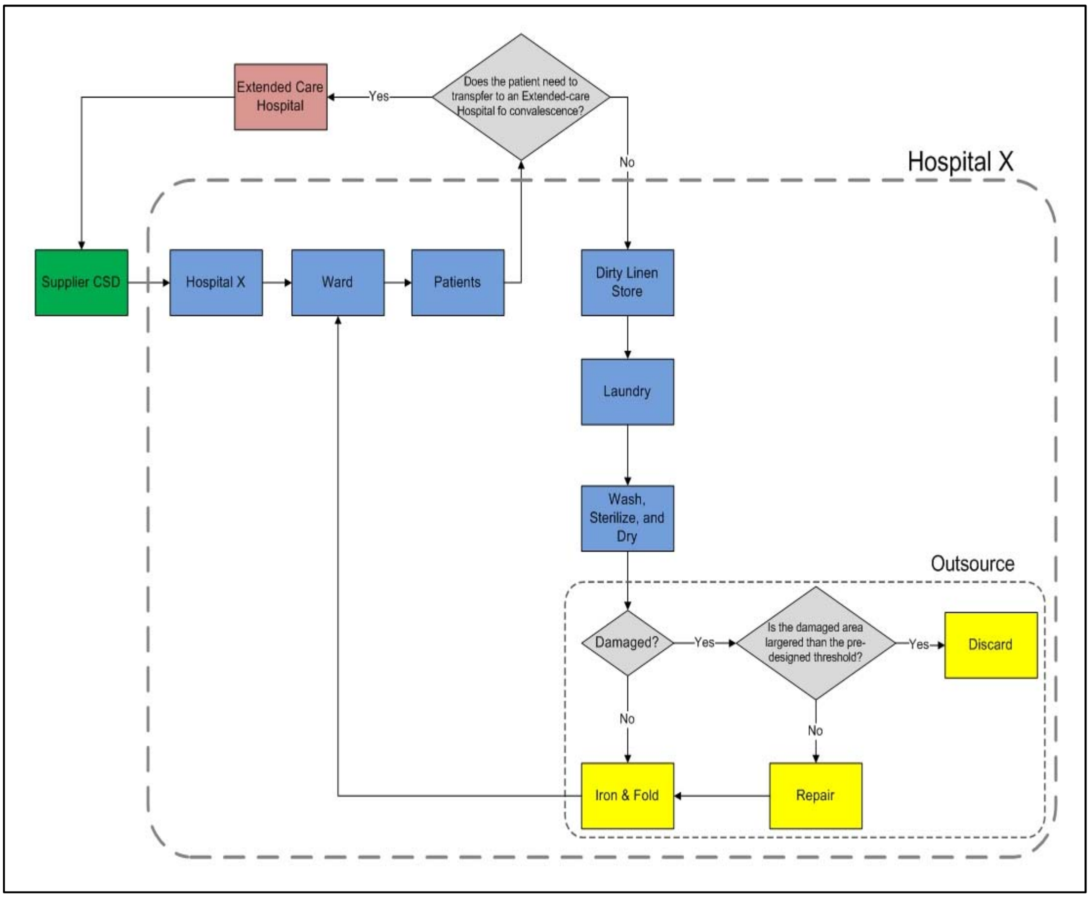


Figure 4.2: Flowchart of the reusable healthcare apparel products in Hospital X



5. Using RFID for Healthcare Apparel Inventory Control[4]

From the case studies reported in Chapter 4, it was found that the healthcare organization adopted the bar-coding system to manage the apparel products. On the other hand, some reported real case studies in Norway, Switzerland, and Germany indicated that the RFID system was a promising tool which could enhance the operations efficiency and achieve significant cost saving when it was applied to manage the healthcare apparel products. Motivated by this fact and the observed industrial practices of apparel control in the healthcare organizations, in this chapter, an analytical study is firstly conducted to reveal when the RFID system will outperform the bar-coding system in terms of reduction of the safety stock requirement. This analysis is further extended to a supply chain context which includes the upstream apparel-product supplier and the downstream healthcare organization.

[4]This chapter was published in a journal paper: "Chan, H.L., T.M. Choi, and C.L. Hui. 2012. RFID versus bar-coding systems: transactions errors in healthcare apparel inventory control. *Decision Support Systems*. 54(1), 803-811."

5.1. Introduction

In the healthcare industry, information system is critically important for inventory management of the healthcare apparel products. With the help of the information system, it mitigates the workload of the medical personnel (who can focus more on providing treatment to the patients) and enhances the daily operation efficiency (e.g., reducing paperwork and time when recording which types and the corresponding quantities needed). In Chapter 4, it was reported that healthcare organizations in Hong Kong were adopting a bar-coding system to help for inventory planning and controlling of the apparel products. Besides, the case studies presented in Chapter 4 along with the literature reviewed in Chapter 2 also well-supported that the RFID was another promising information technology which could be adopted in healthcare industry for real time asset tracking, patient's identification as well as apparel products management to improve the operations efficiency and attain substantial saving. Even though the RFID system was more advanced than that of the bar-coding system, existing studies also commented that none of the scanning system was 100% reliable and error-free to reflect the real data and physical inventory level (Michael and McCathie, 2005; Chowdhury et al. 2008;). Indeed, the RFID system was also suffering read rate inaccuracy (Smith, 2005; Tu and Piramuthu, 2008; Tu et al., 2009) and the observed successful read rate in real world RFID application was often just in between 60-70% (Floerkemeier and Lampe, 2004; Jeffery et al., 2006; Derakhshan et al., 2007). There were hence beliefs on the fact that the RFID systems needed not outperform the traditional systems such as the bar-coding systems because the bar-coding system possessed a higher reliability on read rate (Chen et al. 2005; Lee et al., 2010). There were actually failure cases with the use of the RFID technologies in inventory management (see

Roberti, 2004; Weinstein, 2005 for details). The stability of the RFID system reading the tag depended on various environment factors such as tagged object, tag placement, angle or rotation, and read distance (Ohashi et al., 2008; Yao et al., 2010). As a result, one could not simply conclude that the RFID was more superior to the bar-coding system in all situations without any in-depth investigation. This chapter aims at analytically comparing the inventory accuracy issue between the RFID and the bar-coding systems based on the respective transaction errors. To be specific, an analytical model on the conditions in which the RFID systems would be preferred when compared to the bar-coding systems for apparel inventory control in the healthcare sectors is firstly developed. Next, the respective business value of switching from the bar-coding to the RFID systems is explored. It is then extended to a supply chain context (which includes an upstream supplier and the downstream healthcare organization) and investigates whether and how win-win situation (i.e. both the supplier and the healthcare organization can have cost or profit improvement with the change of the scanning system) can be achieved in the supply chain.

5.2. Notation[5]

The notations used in this chapter are summarized in Table 5.1 for reference.

Table 5.1 Summary of notation

Notation	*Meaning*
c	Unit production cost
w	Unit wholesale price
w_S	Unit wholesale price under surplus sharing contract with $w > w_s$
f	A fraction of the healthcare organization's surplus
h	Inventory carrying cost per item per period
s	Probability of having sufficient inventory shown in the data-file but insufficient inventory in physical inventory due to scanning error
C_1	Fixed cost of conducting stock taking
C_2	Time-dependent cost of conducting stock taking
T_i	Time required to conduct stock taking with system i
$e_{i,t}$	Transaction data error of the scanning system i at period t
σ_i^2	Error variation parameter for the scanning system i
J_i	Cost of conducting stock checking with system i
$\xi_i(N_i)$	Safety stock requirement per period with N_i stock checking frequency
$K_i(N_i)$	Total inventory cost per period with N_i stock checking frequency
ΔK	Difference between the optimal inventory cost with the RFID system and the optimal inventory cost with the bar-coding system
$\tau_{R/B}$	Error variation ratio (RFID to Bar-coding)
$\rho_{B/R}$	Stock-taking cost ratio (Bar-coding to RFID)
ΔS	Difference between safety stock requirement with the RFID system and the bar-coding system under optimal stock checking frequency
π_i	Supplier's profit when the healthcare organization adopts system i
$\Delta\pi_{O,R}$	Healthcare organization's surplus under the wholesale pricing contract when the RFID system is adopted
$\Delta\pi_{O,R}^{SS}$	Healthcare organization's surplus under the surplus sharing contract when the RFID system is adopted
$\Delta\pi_{S,R}$	Profit change of the supplier under the wholesale pricing contract when the healthcare organization adopts the RFID system
$\Delta\pi_{S,R}^{SS}$	Profit change of the supplier under the surplus sharing contract when the healthcare organization adopts the RFID system
I	Cycle stock level of the healthcare organization

[5]The notations defined in Table 5.1 are applied "locally" for this chapter only.

5.3. Model Development

Following the work by Iglehart and Morey (1972), this chapter considers that there is a challenge on the inventory accuracy level due to the existence of data error such as scanning error (i.e., the computer record does not give the true information on inventory level) for apparel items in a healthcare organization. To be specific, this chapter focuses on one product item and considers the healthcare organization is employing a multi-period periodic review inventory system with a stationary (s, S) policy. Demand is stochastic and would come from time to time. In the healthcare organization, transactions are recorded electronically by scanning methods. Two data scanning systems, RFID (*R*) and bar-coding (*B*), are compared.

Since there are data errors, periodic stock checking is necessary. Suppose that there are N_i periods between stock checking, where $i \in \{B, R\}$. Let h be the inventory carrying cost per item per period and J_i be the cost of conducting stock checking, where $i \in \{B, R\}$; J_i is given by $C_1 + C_2 T_i$, where C_1 refers to the fixed cost of conducting stock-taking (e.g., the use of full-time staff members), C_2 refers to the time-dependent cost of conducting stock-taking (e.g., the use of part time staff), and T_i represents the time required to conduct stock-taking for $i \in \{B, R\}$. Notice that in this chapter, the commonly observed case is considered in which J_i is a much bigger expense compared to the inventory holding cost incurred for an item. Following the literature of DeHoratius et al. (2008); Iglehart and Morey (1972); Kök and Shang (2007), data error $e_{i,t}$, for $t = 1,2,\ldots N_i$, is modeled as an independent, identically distributed (iid) random variable following a normal distribution with a zero mean and variance σ_i^2 (where σ_i^2 the error variation parameter for system $i \in \{B, R\}$),

$$e_{i,t} \sim N(0, \sigma_i^2) \ . \tag{5.1}$$

In light of the presence of $e_{i,t}$, in order to ensure that the data error will not deplete the safety stock between stock checking by a chance larger than $1-s$ (s represents the probability of having sufficient inventory shown in the data-file but insufficient inventory in physical inventory due to scanning error), it is vital to find the required amount of safety stock $\xi_i(N_i)$ and determine the optimal frequency of stock checking N_i to correct the discrepancy between the data record and the actual inventory in-stock. Following Iglehart and Morey (1972), it is easy to find that $\xi_i(N_i)$ can be derived as below,

$$\xi_i(N_i) = \sigma_i \sqrt{N_i}\gamma(s), \tag{5.2}$$

where $\gamma(s) = \Phi^{-1}[(1-(s/2)] > 0$ and $i \in \{B, R\}$.

The total inventory cost per period with $\xi_i(N_i)$ is denoted by $K_i(N_i)$ and it is given as follows,

$$K_i(N_i) = h\xi_i(N_i) + (C_1 + C_2T_i)/N_i, \ i \in \{B, R\} . \tag{5.3}$$

Notice that in $K_i(N_i)$, since $(C_1 + C_2T_i)/N_i = J_i/N_i$ is the cost of conducting stock checking (including manpower cost) per period, this chapter considers the commonly observed case that it is bigger than the inventory holding cost for an item per period, i.e. $J_i/N_i > h\xi_i(N_i)$.

The optimal N_i which minimizes $K_i(N_i)$, N_i^*, can be derived by solving the first order condition:

$$dK_i(N_i)/dN_i = 0.5h\sigma_i\gamma(s)N_i^{-0.5} - (C_1 + C_2T_i)N_i^{-2} = 0 \Rightarrow$$

$$N_i^* = \left(\frac{C_1 + C_2T_i}{0.5h\sigma_i\gamma(s)}\right)^{2/3}. \tag{5.4}$$

Notice that $K_i(N_i)$ is a strictly convex function (refer to Appendix (B1) for the details).

Putting Eq. (5.4) back into Eq. (5.3) yields the optimal total cost for employing a scanning system $i \in \{B, R\}$,

$$K_i(N_i^*) = l\alpha_i\sigma_i^{\frac{2}{3}} \tag{5.5}$$

where

$$\alpha_i = (C_1 + C_2T_i)^{\frac{1}{3}},$$

$$l = 3(0.5h\gamma(s))^{\frac{2}{3}}. \tag{5.6}$$

5.4. RFID System versus Bar-coding System

Next, it is to compare the business values of the RFID system and the bar-coding system. Define:

$$\Delta K = K_R(N_R^*) - K_B(N_B^*). \tag{5.7}$$

It is obvious that ΔK represents the difference between the optimal inventory cost with the RFID system and the optimal inventory cost with the bar-coding system. When ΔK is negative, it means the RFID system outperforms the bar-coding system (in yielding a smaller inventory cost) whereas a positive ΔK means the bar-coding system performs better than the RFID system.

Examining ΔK thus reveals the analytical conditions for one system to outperform the other one. From Eq. (5.7), it shows that

$$\Delta K = l(\Omega - \delta), \tag{5.8}$$

where

$$\Omega = \alpha_R \sigma_R^{\frac{2}{3}}, \tag{5.9}$$

$$\delta = \alpha_B \sigma_B^{\frac{2}{3}}. \tag{5.10}$$

With ΔK expressed in Eq. (5.7), by simple reflection, Lemma 5.1 and Lemma 5.2 are developed.

Lemma 5.1. *Suppose that a healthcare organization switches its scanning system from a bar-coding system to an RFID system, the expected business value of the RFID system is equal to* $-\Delta K$.

Lemma 5.1 shows the closed-form expression of the benefit brought by switching the scanning system from the bar-coding to the RFID. To be specific, from Eq. (5.10), it reveals the benefit of switching to the RFID system is larger with the following cases: (i) larger α_B and/or larger σ_B (i.e. δ is larger), (ii) smaller α_R and/or smaller σ_R (i.e. Ω is smaller), and (iii) larger h and/or smaller s (i.e. l is larger). Here, case (i) "larger α_B and/or larger σ_B" and case (ii) " smaller α_R and/or smaller σ_R" are very intuitive because they refer to the cases in which it is less beneficial to employ the bar-coding system. In practice, if the RFID system keeps upgrading such that its error variation is reduced, a more significant inventory cost saving will result. This illustrates the happening of case (ii) (which is more natural to be realized compared to case (i)). For case (iii), having a larger *h* and/or a smaller *s* tends to yield a higher benefit when the healthcare organization switches to the RFID. It is thus interesting to note that the benefit of using the RFID system is related to the holding cost *h* and also the probability of having sufficient inventory shown in the data-file but insufficient inventory in physical inventory due to scanning error (*s*). As a remark, in any of the above cases, the condition of $\Omega < \delta$ must be held, otherwise, the healthcare organization does not have the motivation to switch to the RFID system when no cost saving can be attained.

Lemma 5.2. *(a) The RFID system outperforms the bar-coding system if and only if* $\Omega < \delta \Leftrightarrow \left(\frac{C_1 + C_2 T_R}{C_1 + C_2 T_B}\right) < \left(\frac{\sigma_B}{\sigma_R}\right)^2$. *(b) The bar-coding system outperforms the RFID system if and only if* $\Omega > \delta \Leftrightarrow \left(\frac{C_1 + C_2 T_R}{C_1 + C_2 T_B}\right) > \left(\frac{\sigma_B}{\sigma_R}\right)^2$.

Lemma 5.2 further shows the necessary and sufficient conditions for the RFID systems to outperform the bar-coding system (and vice versa). A closer examination of the conditions reveal that they are all based on the two systems' stock-taking times (and hence costs) and error variations. Moreover, since there is a power of 2 for the ratio of error variations, the relative significance of the error variations ratio is higher than the stock-taking costs ratio. Last but not least, as the conditions are neat and easily computable, they help healthcare organizations to check and see whether the RFID system or the bar-coding system is more preferred. Define:

Error variation ratio (R to B): $\tau_{R/B} \equiv \left(\frac{\sigma_R}{\sigma_B}\right)$,

Stock-taking cost ratio (B to R): $\rho_{B/R} \equiv \left(\frac{C_1 + C_2 T_B}{C_1 + C_2 T_R}\right)$.

As a remark, in many cases, it is well-argue that $\sigma_B < \sigma_R$ (because the RFID system tends to yield a larger variation of errors compared to the more stable bar-coding system (White et al., 2007). Moreover, since RFID can help to reduce the time required for stock-taking in the healthcare organization, hence, it results in: $T_B > T_R$. In this case, the analytical sufficient condition in which the bar-coding system outperforms the RFID system is developed and summarized in Lemma 5.3.

Lemma 5.3. *When* $\sigma_B < \sigma_R$ *and* $T_B > T_R$ *, the bar-coding system outperforms the RFID system if* $\rho_{B/R} < \tau^2{}_{R/B}$.

Proof of Lemma 5.3: All proofs are included in the Appendix (B3).

Lemma 5.3 shows an interesting result (under the specific special case when $\tau_{R/B} > 1$ and $\rho_{B/R} > 1$) which suffices to let the managerial check if the bar-coding system is better than the RFID system. Since it is totally possible to have the conditions in Lemma 5.3 all being satisfied, it is argued that the commonly adopted bar-coding system can outperform the RFID system in some cases and hence it is important for the healthcare organization to double check the respective parameters before proceeding to conduct the switch of scanning system from the bar-coding to the RFID.

5.5. Changing Scanning System and Scenario Analysis

In the previous section, analytical results are explored by comparing the performance between the RFID and the bar-coding systems. Lemma 5.2 gives the closed-form conditions under which the RFID outperforms the bar-coding system or vice versa from the perspective of the healthcare organization.

Suppose that currently, the healthcare organization is using system *B* and after checking the conditions in Lemma 5.2, the healthcare organization will prefer system *R* and make a change of the scanning system[6] . This decision is naturally beneficial (and indeed optimal) to the healthcare organization. However, is the change also beneficial to the supplier who supplies the product to the healthcare organization? Is it beneficial to the whole supply chain? The answers to these questions will be explored in this section.

First of all, it is assumed that supplier produces the product at a unit production cost of *c* and supplies the product to the healthcare organization at a wholesale price *w* (i.e., a wholesale pricing contract). The supplier adopts the make-to-order strategy in which it does not hold inventory in advance before the healthcare organization's order comes. As a result, the supplier's profit is equal to the unit profit margin times the healthcare organization's order quantity. Obviously, when comparing the healthcare organization's selection decision on the scanning system (i.e., choosing either *B* or *R*), the only implied difference in terms of quantity for the supplier is the corresponding amount of safety stock that the healthcare organization will hold[7]. Thus, the effective profit that needed

[6] Of course, if the healthcare organization finds that it is optimal to stay without a change after checking Lemma 5.2, there will be no change. To be specific, this section focuses on the case when a change is desirable and explores the associated issues in the supply chain context.

[7] The healthcare organization will keep cycle stock and safety stock to satisfy the demand and fight against stock- out. Irrespective of the choice on the scanning system, the expected demand is the same as it will not affect the end customer demand of the healthcare organization between stock checking; this implies that it does not affect the total cycle stock. However, when there is a variation on the scanning system accuracy (i.e. data error is present), it will directly affect the safety stock requirement between stock checking for each scanning system. As such, this chapter focuses on the safety stock analysis.

to consider for the supplier with respect to the healthcare organization's choice of scanning system is given below,

$$\pi_i = (w - c)\xi_i(N_i^*), \quad i \in \{B, R\}. \tag{5.11}$$

Define:

$$\Delta S = \xi_R(N_R^*) - \xi_B(N_B^*). \tag{5.12}$$

ΔS represents the difference between safety stock requirement with the RFID system and the bar-coding system under optimal stock checking frequency.

From the definition in Eq. (5.12), it is crystal clear that $\Delta S > 0$ implies the situation in which the supplier will be benefited when the healthcare organization changes the scanning system from the bar-coding to the RFID. It is easy to further derive that:

$$\Delta S = \frac{\sqrt{3}\gamma(s)}{\sqrt{l}}(\Omega - \delta). \tag{5.13}$$

With respect to the healthcare organization's optimal choice as shown in Lemma 5.2, it illustrates that the healthcare organization prefers *R* to *B* if and only if $\Omega < \delta$. By assuming that the condition of $\alpha_B > \alpha_R$ is held (White et al., 2007), in the following, it analyzes the scenario in which it is optimal for the healthcare organization to make a change in the scanning system from *B* to *R*, and examines its impact on the supplier's effective profit.

Consider that the healthcare organization originally uses *B* and then changes to *R* because the condition of $\Omega < \delta$ is satisfied (i.e. $\Delta K < 0$), in such case, the supplier will also be benefited if and only if $\Delta S > 0$. <u>All proofs are included in the Appendix (B2)</u>

Case 1: If $\sigma_B \geq \sigma_R$, and $\alpha_B > \alpha_R$;

Since $\frac{\alpha_R}{\alpha_B} < 1$ and $\left(\frac{\sigma_B}{\sigma_R}\right)^{2/3} \geq 1$, it is always true that $\frac{\alpha_R}{\alpha_B} < \left(\frac{\sigma_B}{\sigma_R}\right)^{2/3}$.

Therefore, it generates $\Omega < \delta$ which implies $\Delta K < 0$ and $\Delta S < 0$.

Case 2: If $\sigma_B < \sigma_R$, and $\alpha_B > \alpha_R$;

(i) When $\frac{\alpha_R}{\alpha_B} < \left(\frac{\sigma_B}{\sigma_R}\right)^{2/3}$, then $\Omega < \delta$ which implies $\Delta K < 0$ and $\Delta S < 0$.

(ii) When $\frac{\alpha_R}{\alpha_B} > \left(\frac{\sigma_B}{\sigma_R}\right)^{2/3}$, then $\Omega > \delta$ which implies $\Delta K > 0$ and $\Delta S > 0$.

From the above scenario analysis, Lemma 5.4 is developed as below.

Lemma 5.4. *When the healthcare organization changes its scanning system, the healthcare organization will be benefited under Case 1, and Case 2(i); while the supplier will be better off under Case 2(ii).*

Lemma 5.4 indicates an interesting result: When examining all the cases under which it is optimal for the healthcare organization to make a change of its scanning system, none of them will benefit the supplier. Thus, it is found that none of these cases will lead to a win-win situation in the supply chain for both the healthcare organization and the supplier at the same time. This is because healthcare organization switches from the bar-coding to the RFID system if and only if $\Delta K < 0$, however, it will lead to a reduction on the safety stock requirement ($\Delta S < 0$) and the supplier will suffer. In addition, it is interesting to note that ΔK and ΔS have the same direction which implies that win-win situation will not be achieved automatically. From the supply chain perspective, the occurrence of win-win situation has to satisfy a pre-requisite that the supply chain's performance ("total piece of cake") must first be improved upon the change of the scanning system (or else there is only a win-lose situation). However, the above analysis indicates that with the change of the scanning system, the supply chain's performance may or may not be improved as the overall supply chain's surplus upon the change depends on the amount of improvement the healthcare organization receives and the amount of loss the supplier suffers. Lemma 5.5 summarizes the results.

Lemma 5.5. *With the healthcare organization's optimal change of the scanning system, the supply chain's performance under Case 1 and Case 2(i) will: (a) be enhanced if* $|\Delta K| > |(w-c)\Delta S|$*, (b) be worse-off if* $|\Delta K| < |(w-c)\Delta S|$.

5.6. Achieving Win-Win: Surplus Sharing Contract

In Section 5.4, even though the change of inventory scanning system can help to reduce the healthcare organization's amount of required safety stock (and hence the corresponding inventory cost), it is found that the supplier is not benefited and suffered under the wholesale pricing contract. This will bring an issue that the supplier will be discouraged to work faithfully with the healthcare organization when the new scanning system is in place. This is obviously un-desirable in the context of supply chain management. As a result, a surplus sharing contract is proposed to help to achieve win-win improvement for both the supplier and the healthcare organization in this section. To be specific, when the supply chain's surplus upon the change of scanning system is positive (Lemma 5.5), i.e. $|\Delta K| > |(w-c)\Delta S|$, one way to compensate for the supplier's loss when the healthcare organization changes its inventory scanning system is to share a fraction of surplus generated by the healthcare organization with the supplier. Under a surplus-sharing contract, the supplier offers a lower wholesale price w_S (i.e. $w > w_s$) to the healthcare organization but receives a fraction, f, of the healthcare organization's surplus from inventory cost so that both parties will have the incentive to adopt the contract. To closely investigate this surplus-sharing contract, its manipulation and impact is illustrated as follows:

(a) Consider the initial stage in Case 1 that no contract is executed in the supply chain. The healthcare organization (O) switches from B to R due to its better scanning performance, and it will attain a cost saving $\Delta\pi_{O,R}$ as follows:

$$\Delta\pi_{O,R} = -\Delta K - w\Delta S\ . \tag{5.14}$$

Yet, the supplier (S) will suffer from selling fewer safety stocks to the healthcare organization under Case 1 and Case 2(i). As a result, it will diminish the profit revenue of the supplier and the profit change is defined as $\Delta\pi_{S,R}$ and shown in Eq. (5.15):

$$\Delta\pi_{S,R} = (w - c)\Delta S\ . \tag{5.15}$$

Now, the profit change of the total supply chain (SC) before the surplus sharing contract execution is denoted as $\Delta\pi_{SC,R}$ as follows:

$$\Delta\pi_{SC,R} = -\Delta K - c\Delta S\ . \tag{5.16}$$

(b) If a surplus sharing contract is executed in the supply chain, the healthcare organization will share a fraction of surplus from inventory cost with the supplier, but enjoy a lower purchasing price (i.e., wholesale price). The actual benefit of the healthcare organization is dependent of the parameters, f and w_S. Assume the order quantities of using the bar-coding and the RFID system are $I + \xi_B(N_B^*)$ and $I + \xi_R(N_R^*)$, respectively, where I is the cycle stock level. The surplus of the healthcare organization (O) with the surplus-sharing contract (SS) is denoted as $\Delta\pi_{O,R}^{SS}$ as follows:

$$\Delta\pi_{O,R}^{SS} = -(1-f)\Delta K + (w - w_S)I + w\xi_B(N_B^*) - w_S\xi_R(N_R^*)\,. \tag{5.17}$$

On the other hand, the supplier receives a fraction of the healthcare organization's surplus but has to offer a lower wholesale price w_S. The profit change of the supplier with the surplus sharing contract (SS) is $\Delta\pi_{S,R}^{SS}$ and presented in Eq. (5.18) below:

$$\Delta\pi_{S,R}^{SS} = -f\Delta K - (w - w_s)I - w\xi_B(N_B^*) + w_S\xi_R(N_R^*) - c\Delta S\,. \tag{5.18}$$

The profit change of the entire supply chain (SC) with surplus sharing (SS) contract is represented by $\Delta\pi_{SC,R}^{SS}$.

$$\Delta\pi_{SC,R}^{SS} = -\Delta K - c\Delta S\,. \tag{5.19}$$

With the above analysis, the analytical surplus and profit change of each party are summarized in Table 5.2.

Table 5.2: Summary of the wholesale pricing contract and the proposed surplus sharing contract implementation under Case 1 and Case 2(i)

Under Case 1 and Case 2(i)	Under Wholesale pricing contract	Under Proposed Surplus Sharing Contract
Healthcare organization's surplus	$\Delta\pi_{O,R} = -\Delta K - w\Delta S$	$\Delta\pi_{O,R}^{SS} = -(1-f)\Delta K + (w-w_S)I$ $+ w\xi_B(N_B^*) - w_S\xi_R(N_R^*)$
Supplier's profit change	$\Delta\pi_{S,R} = (w-c)\Delta S$	$\Delta\pi_{S,R}^{SS} = -f\Delta K - (w-w_s)I$ $- w\xi_B(N_B^*) + w_S\xi_R(N_R^*) - c\Delta S$
Total Supply Chain surplus	$\Delta\pi_{SC,R} = -\Delta K - c\Delta S$	$\Delta\pi_{SC,R}^{SS} = -\Delta K - c\Delta S$

By comparing the total supply chain surplus when there is a change of the scanning system, it is obvious that the performance of the entire supply chain is enhanced in both scenarios if the surplus-sharing contract is implemented when $|\Delta K| > |(w-c)\Delta S|$. Lemma 5.6 summarizes this finding.

Lemma 5.6. *When the healthcare organization switches the scanning system and under the condition that* $|\Delta K| > |(w-c)\Delta S|$ *, a win-win situation can be achieved by using the surplus sharing contract when* $\Delta\pi_{O,R}^{SS} > 0$ *and* $\Delta\pi_{S,R}^{SS} > 0$ *under Case 1 and Case 2(i).*

Notice that Lemma 5.6 means that both supply chain members will be better off if the surplus-sharing contract is properly set and adopted under Case 1 and Case 2(i) with the condition that $|\Delta K| > |(w-c)\Delta S|$ is satisfied. The key factors to successfully implement the surplus sharing contract depend on two factors: First, the benefit enjoyed by the healthcare organization from a lower purchasing price should be "attractive" when comparing to the surplus shared with the supplier from the inventory cost. Second, the supplier is able to receive substantial benefit from sharing the healthcare organization, in which it should be larger than the revenue loss from offering a lower wholesale price w_S.

5.7. Numerical Analyses

In Section 5.7, numerical analyses are conducted to evaluate the impact of each parameter on each channel member under the wholesale pricing contract and the proposed surplus sharing contract. The setting of each parameter under the wholesale pricing contract is as follows: $\sigma_B = 1.6$, $\sigma_R = 2$, $s = 0.1$, $C_1 = 1500$,

$C_2 = 6.25$, $T_B = 60$, $T_R = 4$, $c = 2$, $w = 10$, $h = 18$, $\alpha_B = 12.33$, $\alpha_R = 11.51$. It firstly illustrates the numerical business value of the RFID system when the healthcare organization switches its scanning system from the bar-coding system to the RFID system (as shown in Lemma 5.1) in Table 5.3 and Table 5.4. Next, by assuming that it is optimal for the healthcare organization to adopt the RFID system, the following parameter setting is considered to numerically demonstrate the performance of each channel member and the impact of each parameter under the wholesale pricing contract and the proposed surplus-sharing contract from Table 5.5 to Table 5.14 (such that Lemma 5.2(a) is satisfied), they are: $\sigma_B = 4$, $f = 0.7$, $w_S = 9.9$, $I = 200$.

Table 5.3 and Table 5.4 visualize the expected business value of the RFID system illustrated in Lemma 5.1 with respect to the parameter of δ and Ω, respectively. Table 5.3 demonstrates that when δ is larger (because of a longer time required to conduct stock taking under the bar-coding system T_B and hence a larger α_B), ΔK becomes smaller and results in a negative value (i.e., adopting the RFID system over the bar-coding system will generate a larger cost saving and hence the RFID system is more preferable). Specifically, under our parameter setting, the healthcare organization can attain more benefits by switching to the RFID system (in term of a smaller inventory cost incurred) if $T_B > 141$. On the other hand, Table 5.4 shows that ΔK decreases and becomes more negative when σ_R decreases (which will also generate a smaller Ω). In other words, a significant cost saving (i.e., $\Delta K < 0$) is achieved when the RFID system is upgraded to a level that its scanning error variation is $\sigma_R < 1.8$ under our parameter setting.

Table 5.3 Numerical example of the expected business value of the RFID system with respect to δ in Lemma 5.1

T_B	α_R	α_B	σ_R	σ_B	Ω	δ	ΔK
60	11.51	12.33	2.00	1.60	18.27	16.87	25.38
80	11.51	12.60	2.00	1.60	18.27	17.24	18.74
100	11.51	12.86	2.00	1.60	18.27	17.59	12.38
141	11.51	13.35	2.00	1.60	18.27	18.27	0.07
160	11.51	13.57	2.00	1.60	18.27	18.57	-5.33
176	11.51	13.75	2.00	1.60	18.27	18.81	-9.75
200	11.51	14.01	2.00	1.60	18.27	19.17	-16.17
216	11.51	14.22	2.00	1.60	18.27	19.45	-21.35
240	11.51	14.42	2.00	1.60	18.27	19.73	-26.37

Table 5.4: Numerical example of the expected business value of the RFID system with respect to Ω in Lemma 5.1

α_R	α_B	σ_R	σ_B	Ω	δ	ΔK
11.51	12.33	2	1.60	18.27	16.87	25.38
11.51	12.33	1.9	1.60	17.66	16.87	14.27
11.51	12.33	1.8	1.60	17.03	16.87	2.96
11.51	12.33	1.7	1.60	16.40	16.87	-8.56
11.51	12.33	1.6	1.60	15.75	16.87	-20.31
11.51	12.33	1.5	1.60	15.08	16.87	-32.30
11.51	12.33	1.4	1.60	14.40	16.87	-44.56
11.51	12.33	1.3	1.60	13.71	16.87	-57.12
11.51	12.33	1.2	1.60	13.00	16.87	-70.01

In Lemma 5.4, it addresses that the supplier is always suffered when the healthcare organization optimally switches to the RFID system, and hence a surplus sharing contract is proposed to help to achieve the win-win improvement. The impact of the major parameters in the surplus sharing contract is evaluated from Table 5.5 to Table 5.13 in details. As a remark, the numerical analyses from Table 5.5 to Table 5.13 represent the situation in Section 5.5 Case 1 that $\sigma_B \geq \sigma_R$, and $\alpha_B > \alpha_R$; while Table 5.13 indicates the situation in Section 5.5 Case 2 that $\sigma_B < \sigma_R$, and $\alpha_B > \alpha_R$.

Table 5.5 shows the performance of each channel member under the wholesale pricing contract and the proposed surplus sharing contract. It demonstrates that the supplier's profit change is $\Delta\pi_{S,R} < 0$ which means that the supplier is suffered when the healthcare organization optimally changes the scanning system from the bar-coding system to the RFID system under the wholesale pricing contract. However, if the healthcare organization partially shares its surplus with the supplier whiles the supplier offers a lower wholesale price under the surplus sharing contract, it will generate a positive healthcare organization's surplus $\Delta\pi_{O,R}^{SS}$ and a positive supplier's profit change $\Delta\pi_{S,R}^{SS}$. Even though the surplus of the healthcare organization is fewer than before, both channel members are still better off and a win-win situation is achieved under the surplus sharing contract.

Table 5.5 Performance of each channel member under different contracts implementation

	Under Wholesale Pricing Contract	Under Proposed Surplus Sharing Contract
Healthcare organization's surplus	$\Delta\pi_{O,R}$ = 317.28	$\Delta\pi_{O,R}^{SS}$ = 176.43
Supplier's profit change	$\Delta\pi_{S,R}$ = -68.60	$\Delta\pi_{S,R}^{SS}$ = 72.24
Total Supply Chain surplus	$\Delta\pi_{SC,R}$ = 248.68	$\Delta\pi_{SC,R}^{SS}$ = 248.68

With the proposed contract, the healthcare organization will compensate the supplier's loss for optimally switching the scanning system with fewer safety stock requirements. In Table 5.6, it reveals how the healthcare organization properly set the surplus sharing fraction under the surplus sharing contract. Numerical results illustrate an intuitive finding that the surplus of the healthcare organization $\Delta\pi_{O,R}^{SS}$ decreases while the profit change of the supplier $\Delta\pi_{S,R}^{SS}$ increases and becomes positive when the surplus sharing fraction f increases. Specifically, according to the manipulated parameter settings, both channel members will be better off and it will result in a win-win situation when the surplus sharing fraction is set over the range of $0.4 \leq f \leq 1$. Note that both channel members can also be better off even when $f = 1$.

Table 5.6 Impact of f toward each channel member under surplus sharing contract with respect to Case 1

f	Under Wholesale Pricing Contract			Under Proposed Surplus Sharing Contract			
	$\Delta\pi_{O,R}$	$\Delta\pi_{S,R}$	$\Delta\pi_{SC,R}$	$\Delta\pi_{O,R}^{SS}$	$\Delta\pi_{S,R}^{SS}$	$\Delta\pi_{SC,R}^{SS}$	Is Win-Win Situation Achieved?
0.000	317.28	-68.60	248.68	338.50	-89.82	248.68	No
0.100	317.28	-68.60	248.68	315.35	-66.67	248.68	No
0.200	317.28	-68.60	248.68	292.20	-43.52	248.68	No
0.208	317.28	-68.60	248.68	290.34	-41.67	248.68	No
0.300	317.28	-68.60	248.68	269.04	-20.37	248.68	No
0.400	317.28	-68.60	248.68	245.89	2.79	248.68	Yes
0.500	317.28	-68.60	248.68	222.74	25.94	248.68	Yes
0.600	317.28	-68.60	248.68	199.59	49.09	248.68	Yes
0.700	317.28	-68.60	248.68	176.43	72.24	248.68	Yes
0.800	317.28	-68.60	248.68	153.28	95.40	248.68	Yes
0.900	317.28	-68.60	248.68	130.13	118.55	248.68	Yes
1.000	317.28	-68.60	248.68	106.97	141.70	248.68	Yes

On the other hand, in order to provide an incentive for the healthcare organization to share its surplus with the supplier, the supplier has to offer a lower wholesale price w_S under the surplus sharing contract. The impact of w_S on each channel member under the wholesale pricing contract and surplus sharing contract is shown in Table 5.7. Table 5.7 reflects that the surplus of the healthcare organization increases while the profit change of the supplier decreases (and becomes negative) when the supplier offers a lower wholesale price w_S. As a result, the supplier should carefully determine the new wholesale price even the healthcare organization is willing to provide subsidization. Based on the manipulated parameter settings, the appropriate range of w_S is $9.500 < w_S \le 9.990$ for $f = 0.7$ such that both channel members are better off simultaneously.

Table 5.7 Impact of w_s toward each channel member under different contracts

w_s	Under Wholesale Pricing Contract			Under Proposed Surplus Sharing Contract			
	$\Delta\pi_{O,R}$	$\Delta\pi_{S,R}$	$\Delta\pi_{SC,R}$	$\Delta\pi_{O,R}^{SS}$	$\Delta\pi_{S,R}^{SS}$	$\Delta\pi_{SC,R}^{SS}$	Is Win-Win Situation Achieved?
9.990	317.28	-68.60	248.68	157.33	91.35	248.68	Yes
9.900	317.28	-68.60	248.68	176.43	72.24	248.68	Yes
9.800	317.28	-68.60	248.68	197.66	51.02	248.68	Yes
9.700	317.28	-68.60	248.68	218.88	29.80	248.68	Yes
9.500	317.28	-68.60	248.68	261.33	-12.65	248.68	No
9.000	317.28	-68.60	248.68	367.45	-118.77	248.68	No
8.500	317.28	-68.60	248.68	473.57	-224.89	248.68	No
8.000	317.28	-68.60	248.68	579.69	-331.01	248.68	No
7.500	317.28	-68.60	248.68	685.81	-437.13	248.68	No
5.000	317.28	-68.60	248.68	1216.41	-967.73	248.68	No
3.000	317.28	-68.60	248.68	1640.89	-1392.21	248.68	No
2.500	317.28	-68.60	248.68	1747.01	-1498.33	248.68	No

From the supplier's perceptive, it is interesting to examine the effect of its profit change of which type of product (with respect to the different unit production cost and hence the unit profit margin). Table 5.8 shows the impact of the production cost c on each channel member under the wholesale pricing and surplus sharing contracts. In Table 5.8, it demonstrates that the surplus of the healthcare organization is independent of the unit production cost c but the profit change of the supplier increases when c increases no matter it is under the wholesale pricing contract or the surplus sharing contract. Under the wholesale pricing contract, the supplier is always suffered but the loss is the least when the healthcare apparel product with the highest unit production cost (i.e., the lowest profit margin product) is sold to the healthcare organization. Similarly, supplier also benefits more for supplying a lower profit margin product to the healthcare organization under the surplus sharing contract. One possible reason for this phenomenon is that the profit change of the supplier depends on the total profit margin generated from the change of the safety stock requirement of the healthcare organization when switching to the RFID system. With a higher unit production cost (and hence a lower unit profit margin), supplier is suffered from a relatively smaller loss under the RFID system owing to the smaller amount of safety stock needed.

Table 5.8 Impact of c toward each channel member under different contracts

c	Under Wholesale Pricing Contract			Under Proposed Surplus Sharing Contract			
	$\Delta\pi_{O,R}$	$\Delta\pi_{S,R}$	$\Delta\pi_{SC,R}$	$\Delta\pi_{O,R}^{SS}$	$\Delta\pi_{S,R}^{SS}$	$\Delta\pi_{SC,R}^{SS}$	Is Win-Win Situation Achieved?
0.050	317.28	-85.32	231.96	176.43	55.52	231.96	Yes
0.100	317.28	-84.89	232.38	176.43	55.95	232.38	Yes
0.500	317.28	-81.46	235.81	176.43	59.38	235.81	Yes
0.750	317.28	-79.32	237.96	176.43	61.53	237.96	Yes
1.000	317.28	-77.18	240.10	176.43	63.67	240.10	Yes
1.500	317.28	-72.89	244.39	176.43	67.96	244.39	Yes
2.000	317.28	-68.60	248.68	176.43	72.24	248.68	Yes
3.000	317.28	-60.03	257.25	176.43	80.82	257.25	Yes
5.000	317.28	-42.88	274.40	176.43	97.97	274.40	Yes
7.500	317.28	-21.44	295.84	176.43	119.41	295.84	Yes
8.000	317.28	-17.15	300.13	176.43	123.69	300.13	Yes
9.000	317.28	-8.58	308.70	176.43	132.27	308.70	Yes
9.500	317.28	-4.29	312.99	176.43	136.56	312.99	Yes

Regarding the healthcare organization, the inventory holding cost and the stock-taking cost do also affect its expected profit. Table 5.9 presents the impact of the inventory holding cost on each channel member under the wholesale pricing contract and surplus sharing contract. It illustrates that both the channel members will benefit more when the inventory holding cost h is large (which is consistent with the finding as shown in Lemma 5.1). Yet, if the inventory holding cost of a particular item is significant low, offering the surplus sharing contract may not be a good measure for the suppliers.

Table 5.9 Impact of h toward each channel member under different contracts

h	Under Wholesale Pricing Contract			Under Proposed Surplus Sharing Contract			
	$\Delta\pi_{O,R}$	$\Delta\pi_{S,R}$	$\Delta\pi_{SC,R}$	$\Delta\pi_{O,R}^{SS}$	$\Delta\pi_{S,R}^{SS}$	$\Delta\pi_{SC,R}^{SS}$	Is Win-Win Situation Achieved?
8	247.20	-89.89	157.31	174.42	-17.11	157.31	No
9	253.89	-86.43	167.46	173.34	-5.88	167.46	No
10	260.78	-83.45	177.33	172.74	4.59	177.33	Yes
11	267.78	-80.84	186.94	172.51	14.43	186.94	Yes
12	274.85	-78.53	196.32	172.57	23.75	196.32	Yes
13	281.95	-76.46	205.49	172.85	32.64	205.49	Yes
14	289.06	-74.60	214.46	173.32	41.14	214.46	Yes
15	296.15	-72.90	223.25	173.93	49.32	223.25	Yes
16	303.23	-71.35	231.88	174.67	57.21	231.88	Yes
17	310.27	-69.92	240.35	175.51	64.84	240.35	Yes
18	317.28	-68.60	248.68	176.43	72.24	248.68	Yes
19	324.24	-67.38	256.87	177.43	79.44	256.87	Yes
20	331.17	-66.23	264.93	178.49	86.45	264.93	Yes

Table 5.10 demonstrates the impact of the difference on the stock-taking cost under the wholesale pricing contract and the surplus sharing contact. This difference is measured by the ratio of J_B / J_R. Results illustrate that when the ratio of J_B / J_R becomes larger (i.e., stock-taking cost under the bar-coding

system is much higher than that under the RFID system), the healthcare organization will obtain a higher level of surplus but it will also intensify the supplier's loss under the wholesale pricing contract. In contrary, both channel members will result in receiving more surpluses when the J_B / J_R ratio is larger under the surplus sharing contract. Therefore, under the proposed surplus sharing contract, the supplier will attain a higher surplus when the healthcare organization is able to enjoy a relatively lower stock-talking cost under the RFID system adoption.

Table 5.10 Impact of J_B / J_R on each channel member under different contracts

$\frac{J_B}{J_R}$	Under Wholesale Pricing Contract			Under Proposed Surplus Sharing Contract			
	$\Delta\pi_{O,R}$	$\Delta\pi_{S,R}$	$\Delta\pi_{SC,R}$	$\Delta\pi_{O,R}^{SS}$	$\Delta\pi_{S,R}^{SS}$	$\Delta\pi_{SC,R}^{SS}$	Is Win-Win Situation Achieved?
1.02	271.87	-58.78	213.08	154.22	58.87	213.08	Yes
1.05	276.67	-59.82	216.85	156.57	60.28	216.85	Yes
1.07	281.40	-60.84	220.56	158.88	61.68	220.56	Yes
1.11	290.70	-62.85	227.85	163.43	64.41	227.85	Yes
1.15	299.77	-64.81	234.95	167.87	67.09	234.95	Yes
1.19	308.62	-66.73	241.89	172.20	69.69	241.89	Yes
1.23	317.28	-68.60	248.68	176.43	72.24	248.68	Yes
1.27	325.74	-70.43	255.31	180.57	74.74	255.31	Yes
1.31	334.03	-72.22	261.80	184.63	77.18	261.80	Yes

Apart from investigating the impact of each cost component, factors related to the scanning system's accuracy level are also examined in Table 5.11 and Table 5.12. In Table 5.11, it explores the impact of the scanning error occurrence probability s due to the scanning system adoption under the wholesale pricing contract and the surplus sharing contract. Numerical results illustrate that both the surplus of the healthcare organization and the profit change of the supplier decreases when s increases under the surplus sharing contract. This implies that if both scanning systems are not stable and have a higher chance to encounter a scanning error, then the healthcare organization can enjoy little benefit only when it optimally switches the scanning system from the bar-coding to the RFID system.

Table 5.11 Impact of s on each channel member under different contracts

s	Under Wholesale Pricing Contract			Under Proposed Surplus Sharing Contract			
	$\Delta\pi_{O,R}$	$\Delta\pi_{S,R}$	$\Delta\pi_{SC,R}$	$\Delta\pi_{O,R}$	$\Delta\pi_{S,R}$	$\Delta\pi_{SC,R}$	Is Win-Win Situation Achieved?
0.10	317.28	-68.60	248.68	176.43	72.24	248.68	Yes
0.20	268.65	-58.09	210.56	152.45	58.11	210.56	Yes
0.30	233.19	-50.42	182.77	134.98	47.80	182.77	Yes
0.40	202.97	-43.89	159.09	120.07	39.01	159.09	Yes
0.50	175.12	-37.86	137.26	106.34	30.91	137.26	Yes
0.60	148.07	-32.01	116.05	93.00	23.05	116.05	Yes
0.70	120.57	-26.07	94.50	79.45	15.05	94.50	Yes
0.80	91.17	-19.71	71.45	64.95	6.51	71.45	Yes
0.90	57.12	-12.35	44.77	48.17	-3.39	44.77	No
0.95	35.94	-7.77	28.17	37.72	-9.55	28.17	No

Finally, Table 5.12 investigates the impact of standard deviation of the data error on each channel member under the wholesale pricing contract and the surplus sharing contract. The effect of the relative variation of the data error under each scanning system is measured by the ratio of σ_B / σ_R. Results reveal that the surplus of both channel members decrease when the difference of the data error variation between the bar-coding system and the RFID system diminishes (i.e., a smaller value of σ_B / σ_R). To some extent, the supplier even may not be able to attain any positive net income if the ratio of σ_B / σ_R is significantly small.

Table 5.12 Impact of σ_B / σ_R toward each channel member under different contracts

$\frac{\sigma_B}{\sigma_R}$	Under Wholesale Pricing Contract			Under Proposed Surplus Sharing Contract			
	$\Delta\pi_{O,R}$	$\Delta\pi_{S,R}$	$\Delta\pi_{SC,R}$	$\Delta\pi_{O,R}^{SS}$	$\Delta\pi_{S,R}^{SS}$	$\Delta\pi_{SC,R}^{SS}$	Is Win-Win Situation Achieved?
40.00	708.69	-153.23	555.46	366.85	188.61	555.46	Yes
8.00	590.43	-127.66	462.77	309.32	153.45	462.77	Yes
4.00	484.86	-104.83	380.03	257.96	122.07	380.03	Yes
2.67	396.31	-85.69	310.62	214.88	95.74	310.62	Yes
2.00	317.28	-68.60	248.68	176.43	72.24	248.68	Yes
1.60	244.64	-52.89	191.74	141.09	50.65	191.74	Yes
1.33	176.72	-38.21	138.51	108.05	30.46	138.51	Yes
1.14	112.49	-24.32	88.17	76.81	11.36	88.17	Yes
1.07	81.53	-17.63	63.90	61.75	2.16	63.90	Yes
1.03	63.29	-13.68	49.60	52.87	-3.27	49.60	No

In Section 5.5, Lemma 5.6 addressed that the win-win situation could be achieved with the help of the surplus sharing contract under Case 1 and Case 2, given that the condition of $|\Delta K| > |(w-c)\Delta S|$ was satisfied. Now, it is processed to evaluate how the win-win situation can be achieved under Case 2(i) and the parameter of σ_R is revised from $\sigma_R = 2$ to $\sigma_R = 4.05$ such that $\sigma_B < \sigma_R$ (while other parameters remain the same). Numerical results shown in Table 5.13 indicate that the healthcare organization has to share more surplus generated from the inventory cost saving to the supplier so as to achieve the win-win situation. To be specific, the healthcare organization has to set the surplus fraction over the range of $0.9 < f \leq 1$ to achieve the win-win situation. By comparing the results shown in Table 5.6 (with $\sigma_B \geq \sigma_R$ and the conditions in Case 1 are satisfied) and Table 5.13 (with $\sigma_B < \sigma_R$ and the conditions in Case 2(i) are satisfied), the supply chain's surplus improvement is smaller in Case 2(i) than that in Case 1. Therefore, it provides a higher motivation to the healthcare organization to optimally switch to the RFID system if the RFID system is more stable than that of the bar-coding system (i.e., $\sigma_B \geq \sigma_R$) in order to enjoy more benefits brought by changing the scanning system.

Table 5.13 Impact of f toward each channel member under different contracts with respect to Case 2

f	Under Wholesale Pricing Contract			Under Proposed Surplus Sharing Contract			
	$\Delta\pi_{O,R}$	$\Delta\pi_{S,R}$	$\Delta\pi_{SC,R}$	$\Delta\pi_{O,R}^{SS}$	$\Delta\pi_{S,R}^{SS}$	$\Delta\pi_{SC,R}^{SS}$	Is Win-Win Situation Achieved ?
0.000	45.28	-9.79	35.49	67.24	-31.75	35.49	No
0.100	45.28	-9.79	35.49	63.93	-28.44	35.49	No
0.200	45.28	-9.79	35.49	60.63	-25.14	35.49	No
0.208	45.28	-9.79	35.49	60.36	-24.88	35.49	No
0.300	45.28	-9.79	35.49	57.32	-21.84	35.49	No
0.400	45.28	-9.79	35.49	54.02	-18.53	35.49	No
0.500	45.28	-9.79	35.49	50.72	-15.23	35.49	No
0.600	45.28	-9.79	35.49	47.41	-11.92	35.49	No
0.700	45.28	-9.79	35.49	44.11	-8.62	35.49	No
0.800	45.28	-9.79	35.49	40.80	-5.32	35.49	No
0.900	45.28	-9.79	35.49	37.50	-2.01	35.49	No
0.970	45.28	-9.79	35.49	35.19	0.30	35.49	Yes
1.000	45.28	-9.79	35.49	34.20	1.29	35.49	Yes

5.8. Managerial Implications and Conclusion

In this chapter, it focused on the data error of the scanning systems to reflect its accuracy on recording the inventory of apparel items in a healthcare organization. This was the performance indicator for system selection (either the RFID or the bar-coding system) from the healthcare organization's perspective because it related to the amount of required safety stock and hence the inventory cost. From the analytical analysis, the closed-form expression was firstly developed that the ratios between the two systems' stock-taking costs and error variations would determine whether the RFID system would outperform the bar-coding system. Besides, the corresponding implications were illustrated which include: (i) When the healthcare organization contemplated the switch of scanning system, the relative significance of the error variations ratio should be higher than the stock-taking costs ratio (because of the "squared" effect). (ii) When it was optimal for the healthcare organization to switch from the bar-coding to the RFID scanning system, if the holding cost was higher or the probability of having sufficient inventory shown in the data-file but insufficient inventory in physical inventory due to scanning error was lower, the benefit of switching from the bar-coding system to the RFID system was larger. Next, the analysis was extended to a supply chain context which included an upstream supplier and the healthcare organization (as the downstream buyer). The supply chain was examined in different cases and it was mathematically showed that if the healthcare organization switched its scanning system from the bar-coding to the RFID, it benefited the healthcare organization but the supplier would always suffer. Hence, a new contract scheme known as "surplus sharing contract" was proposed and how the healthcare organization could achieve a win-win situation under which both the supplier and the healthcare organization could have improvement (in cost or profit) with the change of the scanning system was also illustrated.

With the supplement of numerical analysis, it also generated some important insights as follows: (1) Supplier could enjoy a larger benefit when supplying a lower profit margin healthcare apparel item to the healthcare organization under the wholesale pricing contract or the proposed surplus sharing contract; (2) When considering the case with $\alpha_B < \alpha_R$, the healthcare organization would have a higher incentive to optimally switch to the RFID system if the RFID system was more stable than that of the bar-coding system (i.e., $\sigma_B \geq \sigma_R$) so that it could enjoy more benefits brought by changing the scanning system.

Finally, this contract was important because it could guarantee that both the supplier and the healthcare organization would be benefited under the change of the scanning system and hence they would faithfully work together as supply chain partners in inventory management with respect to the changing the scanning system.

6. RFID-Mediated Quick Response System (QRS) for Healthcare Apparel Supply Chain[8]

In Chapter 2, existing literature illustrated that the Quick Response System (QRS) shortened the delivery lead time and this strategy was also beneficial to the hospital in the sense that it improved the initial forecast quantity and hence the ordering decision was more accurate and precise with respect to the real need of patients. This chapter considers a scenario that the healthcare organization can make use of the information system (i.e., bar-coding or RFID systems) to capture the demand information of a pool of the healthcare products to have a better inventory planning. To be specific, it analytically investigates the inventory decision of a hospital which is currently using a bar-coding system and considering switching to the RFID system to facilitate the QRS. Besides, it also evaluates the impact of the RFID-mediated QRS towards the expected profit and level of risk of each channel member and the entire supply chain efficiency. Since supply chain coordination cannot be achieved automatically, two policies, namely the Service-level Commitment Policy (SCP) and the Minimum Quantity with Price Commitment Policy (MQPCP), are proposed to achieve the mean-risk win-win situation.

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[8] The chapter was extracted from a submitted journal paper: "Chan, H.L., T.M. Choi, C.L. Hui, and S.F. Ng. 2014. Quick response healthcare apparel supply chains: Value of RFID and coordination, *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, DOI: 10.1109/TSMC.2014.2371891, in press".

6.1. Introduction

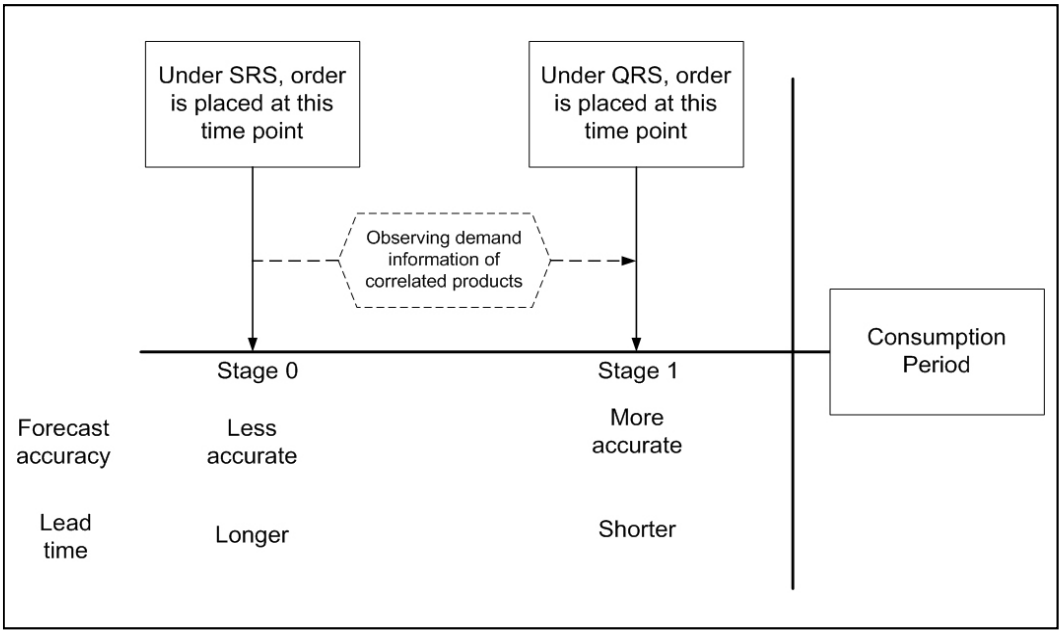
In Chapter 5, it investigated when the healthcare organization should switch from the bar-coding system to the RFID system under a periodic review policy. In addition to implementing appropriate information system to enhance the operation efficiency, proper inventory planning and controlling for the healthcare apparel products is also a curial and timely issue. Similar to pharmaceutical products, various perishable healthcare apparel products (e.g., surgical masks, gloves and gowns) also have expiration restriction, i.e., these products will be disposed if they are not consumed before the expiry date due to the hygienic reason. On the other hand, it is well-agreed that the healthcare organizations should provide a high inventory service level to the patients; yet, it will increase the inventory carrying cost if they order too many. As a result, the healthcare organizations have to make a trade-off on its inventory decision to prevent shortage from happening while not keeping unnecessarily excessive stock. This dilemma is well illustrated by the following case: In Hong Kong, with the outbreak of SARS in 2003, hospitals in Hong Kong had a serious shortage of surgical masks. Ironically, in 2012, it was reported that millions of obsolete masks (as there was an expiry date for masks) were found in the warehouse and had to be disposed (and hence wasted) which were accounted for USD60,000. In fact, as reflected by a piece of recent news that some healthcare organizations were suffering a huge loss and they were seeking ways to recover from the loss (Tsang, 2014). There is no doubt that the hospitals, especially the private commercial ones, aim at maximizing their profit and providing a high (inventory) service level to the patients (which is a kind of service delivery when providing treatment). Thus, the classical newsvendor inventory model becomes the building block for the analytical analysis in this chapter because it captures the inventory planning for perishable items which also considers both the profit and the service level issue in the model formulation (Petruzzi and Dada, 1999)[9].

In the healthcare industry, it is interesting to observe that many healthcare organizations are having a long lead time in terms of getting its supply of healthcare apparel products. This traditional yet commonly seen scenario is named as slow response system (SRS) and the ordering time point with a long lead time is called Stage 0. However, triggered by the operational challenge and business loss incurred in recent years, healthcare organizations are now moving towards the quick response system (QRS) with a shortened lead time (and called the respective ordering time point Stage 1). In fact, the QRS is well-known in the commercial world which is a strategy that enables companies to postpone the ordering decision to a time point that is closer to the selling season launches (i.e., shorter lead time) (Hammond, 1990). Comparing between the SRS and the QRS, it is crystal clear that the healthcare organizations can collect information between Stage 0 and Stage 1 which can potentially enhance the inventory planning. To be specific, the healthcare organizations can observe the demand information of some correlated products and adjust the initial demand forecast for the product under planning. Therefore, it decreases the forecast error, and the ordering decision placed at the Stage 1 is more accurate and precise with respect to the real need of patients (Iyer and Bergen, 1997). Besides, the QRS also requires a faster response from the supplier when there is

[9] In this chapter, it focuses on the perishable products. To our best knowledge, the work conducted by Alwan et al. (2014) also addressed this aspect. Alwan et al. (2014) adopted the newsvendor model to decide the stocking quantity of the perishable products (such as blood) and compare the performance of the traditional newsvendor model with the proposed dynamic forecast-based implementation methodologies with respect to various forecasting techniques.

a change of the market demand which improves both the service and treatment quality. Note that the collection of information is not free. It requires both staff members' working time and other operational steps. Thus, the healthcare organizations will not make use of the demand information of all available correlated items in enhancing its forecast for the product under planning. In this chapter, for both analytical tractability and also based on real observed industrial practice, under the QRS, it is considered the case in which the private hospital can make observations (about the demand information of multiple correlated products) between Stage 0 and Stage 1 and has one ordering opportunity at Stage 1. Figure 6.1 depicts the details.

Figure 6.1 Sequence of actions done under QRS and SRS



In Figure 6.1, it shows that order is placed at Stage 0 (with a longer lead time) under slow response system (SRS) while it is occurred at Stage 1 under quick response system (QRS). The scanning system, i.e., RFID or bar-coding, helps with the collection of demand information of the correlated items in the time interval between Stages 0 and 1. Suppose that a healthcare organization is focusing on the inventory planning for a surgical mask for men in the upcoming consumption period, the correlated products can be the child surgical mask, the N95 mask (more sophisticated ones for double protection), the face mask, which are currently being used in the hospital.

Based on the importance of the inventory management of the perishable healthcare apparel products as discussed above, in this chapter, it analytically investigates the inventory decision of a hospital which is currently using a bar-coding system and considering switching to the RFID system to facilitate the QRS. By formulating the information updating process using a formal analytical Bayesian approach, it then addresses the expected value of information acquisition and examines when the QRS should be executed. In addition, impact of the QRS towards the expected profit and level of risk on each channel member as well as the supply chain efficiency with the use of the RFID system are evaluated. The analytical results show that the mean-risk win-win situation[10] under the RFID system cannot be achieved under the QRS alone. To achieve the mean-risk win-win situation, two policies namely the service-level commitment policy and the minimum quantity with price-commitment policy, are proposed which can be properly designed to help via both analytical proof and numerical examples. Numerical analyses are also carried out and results are reported.

As a remark, in this chapter, the level of "risk" faced by a channel member

[10] An MV win-win situation is achieved if both the supplier and the retailer are better off in terms of an improved expected profit and a lower variance of profit (which denotes risk) under the Mean-Variance (MV) approach. The formal definition is given in Section 6.4.

is quantified by the "variance of profit". It is believed that the managerial in the healthcare industry is risk averse that they seek for a higher expected profit and a lower variance of profit. Since the demand is uncertain and will not be realized until the consumption period starts, it will definitely lead to profit uncertainty of each channel member under the QRS. This kind of profit uncertainty is a kind of risk that the channel members have to consider.

6.2. Notation[11]

The notations used in this chapter are independent of those defined in Chapter 5.

Table 6.1 summarizes the definition of each notation in Chapter 6 for reference.

Table 6.1 Summary of notation

Notation	*Meaning*
r	Unit revenue of the private hospital
c	Unit wholesale price
m	Unit production cost
s	Inventory service level
R	RFID system
B	Bar-coding system
ℓ	Scanning system, $\ell \in \{R, B\}$
i	Stage, $i \in \{0,1\}$
n_ℓ	No. of correlated product/observation targets
ε_{mazx}	Maximum error of the boundary estimation of the optimal n_ℓ
$a^\ell(n_\ell)$	Information acquisition cost
k_ℓ	Cost for taking observation form one observation target
w_ℓ	Future fixed cost when system ℓ is adopted
σ_{1,n_ℓ^*}	Demand variance at Stage 1 when the optimal number of observations with the use of system ℓ is considered
ρ	Operational cost factor associated with the RFID system
Ω	Cost threshold
γ	Importance level of the patients' welfare from the hospital's perspective
EP	Expected profit
VP	Variance of profit
EVI_ℓ	Expected value of information under system ℓ
H	Private hospital
M	Supplier
SC	Supply Chain

[11] The notations defined in Table 6.1 are applied "locally" for this chapter only.

6.3. Model Development

This chapter considers a simple healthcare supply chain (SC) that consists of a single-buyer (i.e., the private hospital) and a single-supplier[12] and the order of the perishable products can be placed to the supplier once before the consumption period starts. The primary objective of the private hospital is to maximize its expected profit and provide a high inventory service level to the patient. It is assumed that the supplier produces the product at a unit cost m, offers a wholesale pricing contract and supplies the product to the private hospital at a unit wholesale price c. The product will generate a unit revenue of r when it is consumed by the patient. For those leftovers, it is assumed that they will be disposed afterward (i.e., no salvage value) because of the hygiene matter and this can ensure that a high quality of product is distributed to the patients. To avoid trivial cases, it results in $r > c > m$. This disposal scheme is also consistent with the industrial practice observed in many private hospitals.

Under the QRS, the initial forecast quantity is updated based on the information collected from the correlated products. It is assumed that the private hospital collects n observations about demand information between the two stages, where Stage 0 and Stage 1 represent the time points far away from and closer to the consumption period, respectively. In the following, the term "hospitals" is used to represents "private hospitals" which aim at achieving profit maximization.

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[12] Notice that this chapter only focuses on examining the two-echelon supply chain with the hospital and the product supplier. This is partially for the analytical tractability reason (as we wish to have more closed form results), and partially for the fact that the respective healthcare supply chain management (e.g., on mask) is mainly operated in a one-to-one strategic alliance manner.

Following the basic demand uncertainty structure as adopted in (Pratt et al., 1995; Iyer and Bergen, 1997) that the predicted demand of a product (e.g. *the face mask for adults*) at Stage 0 is x_0 and it is normally distributed with a mean θ_0 and a variance δ as follows:

$$x_0|\theta \sim N(\theta, \delta). \tag{6.1}$$

θ is denoted as a random variable which is also normally distributed with a mean μ_0 and a variance d_0 as below:

$$\theta \sim N(\mu_0, d_0). \tag{6.2}$$

Furthermore, the unconditional distribution of x_0 at Stage 0 can be derived as a normal distribution with a mean μ_0 and a variance $d_0 + \delta$:

$$x_0 \sim N(\mu_0, d_0 + \delta). \tag{6.3}$$

Under QRS, between Stage 0 and Stage 1, the hospital needs to make a decision on n from a product set Ω with a mean of $\widetilde{m}$, where n is the number of correlated products/observation targets (e.g. *the face mask for children, the surgical face mask, the face mask with shield, the N95 masks, the surgical gown, the isolation gown, etc*) to be employed in the observation process. According to Pratt et al. (1995) by Bayesian theory, the distribution of θ is updated and it follows a normal distribution with a mean μ_1 and a variance d_1 as follows:

$$\theta|\Omega \sim N(\mu_1, d_1),$$

where $\mu_1 = (\delta\mu_0 + \widetilde{m}nd_0)(\delta + nd_0)^{-1}$, (6.4) and $d_1 = \delta d_0 (\delta + n d_0)^{-1}$. (6.5)

Notice that $d_1 < d_0$ (Iyer and Bergen, 1997; Choi et al., 2003). At Stage 1, the distribution of the predicted demand x_1 under the QRS is shown respectively as below:

$$x_1 \sim N(\mu_1, d_1 + \delta), \tag{6.6}$$

and $\mu_1 \sim N(\mu_0, \sigma_\mu^2)$, (6.7)

where $\sigma_\mu^2 = n d_0^2 (\delta + n d_0)^{-1}$.

Here $\phi(\cdot)$ is denoted as the standard normal density function, $\Phi(\cdot)$ as the standard cumulative distribution function, and $\Phi^{-1}(\cdot)$ as the inverse function of $\Phi(\cdot)$. $\psi(x)$ is the standard normal linear loss function which is represented by $\psi(x) = \int_x^\infty (y - x)\phi(y)dy$. Besides, s is the inventory service level which is defined by $s = (r - c)/r$. Following the real industrial practice in the hospital environment, it is considered the case in which s is always larger than 50%. For the notation purpose, in the following, the variance of the unconditional distribution of x_0 and x_1 is denoted as $\sigma_0^2 = d_0 + \delta$ and $\sigma_1^2 = d_1 + \delta$, respectively.

At Stage 0, similar to the approach adopted by (Iyer and Bergen, 1997; Choi and Chow, 2008), the expected profit of the hospital is denoted as $EP_{0,H}$ (where the first subscript 0 represents Stage 0 and the second subscript H represents hospitals) with the following expression:

$$EP_{0,H} = r\mu_0 - cq_0 - r\sigma_0 \psi[(q_0 - \mu_0)/\sigma_0]. \tag{6.8}$$

Since $EP_{0,H}$ is a strictly concave function in q_0 (which can be verified easily by the second order condition), the optimal order quantity of the hospital can be calculated by solving $\arg\{dEP_{0,H} / dq_0 = 0\}$ as follows:

$$q_0^* = \mu_0 + \sigma_0 \Phi^{-1}(s) . \tag{6.9}$$

With Eq. (6.9), the optimal expected profit of the hospital at Stage 0 is:

$$EP_{0,H}(q_0^*) = r\mu_0 - cq_0^* - r\sigma_0 \psi[\Phi^{-1}(s)] \ . \tag{6.10}$$

Between Stage 0 and Stage 1, to run the QRS, the hospital is currently adopting the bar-coding system (B), and is considering to use the RFID system (R), to capture the demand information which will incur an information acquisition cost denoted respectively $a^{\ell}(n_{\ell}) = k_{\ell} n_{\ell} + w_{\ell}$, where ℓ represents the system being adopted, i.e., $\ell \in \{R, B\}$; k_{ℓ} is the cost for taking observation from one observation target (including the corresponding operational cost, such as the label/tag cost); n_{ℓ} is the number of observation targets taken with the scanning system ℓ, (and the number of observation target is bounded above by N); and w_{ℓ} is the future fixed cost that will be incurred when system ℓ is adopted (e.g., maintenance, upgrading and staffing costs to ensure that the device can be functioned properly in hospital (Mun et al., 2007), where n_{ℓ} =0,1,2,… As the RFID system is more advanced and less matured compared with the bar-coding system, the maintenance cost and upgrade cost of the RFID system is believed to be higher than that of the bar-coding system, i.e., $w_R > w_B$ [13]. Beside, even though the labeling and printing cost associated with the bar-coding system is much cheaper than that of the tag cost of the RFID

[13]Note that even though we argue this assumption is valid in the real world, we can conduct the same analysis without this assumption but it will also mean more cases which complicate the analysis.

system, it requires a lot of manpower resource and time to scan the objects physically one by one. On the contrary, the RFID system can count inventory automatically and quickly. Therefore, it is argued that the marginal cost for collecting the demand information using the RFID is less than that of the bar-coding system, which means $k_R < k_B$ [14].

Similar to the case at Stage 0, at Stage 1, the expected profit and the optimal order quantity of the hospital under the QRS can be derived respectively as follows:

$$EP_{1,H}^{\ell}\Big|_{\mu_1} = r\mu_1 - cq_1 - r\sigma_{1,n_\ell}\psi[(q_1 - \mu_1)/\sigma_{1,n_\ell}] - a^{\ell}(n_\ell), \tag{6.11}$$

and $q_1^* = \mu_1 + \sigma_{1,n_\ell}\Phi^{-1}(s)$. (6.12)

Putting Eq. (6.12) into Eq. (6.11) yields the optimal conditional expected profit of the hospital (for a given μ_1) under the QRS:

$$EP_{1,H}^{\ell}\Big|_{\mu_1} = r\mu_1 - cq_1^* - r\sigma_{1,n_\ell}\psi[\Phi^{-1}(s)] - a^{\ell}(n_\ell). \tag{6.13}$$

Here, the estimation of the hospital's unconditional optimal expected profit at Stage 1 under the QRS becomes:

$$\underset{\mu_1}{E}\left[EP_{1,H}^{\ell}\Big|_{\mu_1}\right] = EP_{1,H}^{\ell}(n_\ell)$$

$$= (r-c)\mu_0 - c\sigma_{1,n_\ell}\Phi^{-1}(s) - r\sigma_{1,n_\ell}\psi[\Phi^{-1}(s)] - a^{\ell}(n_\ell). \tag{6.14}$$

From Eq. (6.14), it is obvious that the optimal expected profit of the hospital at Stage 1 depends on prior standard deviation of demand and is directly proportional to the prior mean of demand.

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[14]Note that the cost of installing RFID is excluded in this costing analysis because the implementation cost is a kind of investment and sunk cost. We mainly compare the operational cost here.

Proposition 6.1. *$EP_{1,H}^{\ell}(n_{\ell})$ is a strictly concave function of n_{ℓ} for $n_{\ell} > 0$ and a unique optimal n_{ℓ} exists.*

Proof of Proposition 6.1: All proofs are included in Appendix (C1).

From Proposition 6.1, since $EP_{1,H}^{\ell}(n_{\ell})$ is a strictly concave function in n_{ℓ}, the optimal n_{ℓ} can be uniquely determined by solving $\arg\{dEP_{1,H}^{\ell}(n_{\ell})/dn_{\ell} = 0\}$. As a remark, since the optimal n_{ℓ} has to be an integer, it is necessary to compare the values of $EP_{1,H}^{\ell}(n_{\ell})$ at the two closet integer neighbors (one larger and one smaller) of $\arg\{dEP_{1,H}^{\ell}(n_{\ell})/dn_{\ell} = 0\}$. To be specific, the optimal number of market observations is denoted as n_{ℓ}^{*}. Appendix (C2) discusses the analytical results of finding n_{ℓ}^{*}. As an information acquisition cost is incurred when system ℓ is adopted to capture the demand information, therefore, it is interesting to evaluate the impact of the QRS with information updating in terms of the hospital's expected profit. This effect is measured by the expected value of information EVI_{ℓ} which is defined as the difference between the expected profits of the hospital at Stage 1 (as shown in Eq. (6.14)) and at Stage 0 (as shown in Eq. (6.8)) as follows:

$$EVI_{\ell} = EP_{1,H}^{\ell}(n_{\ell}) - EP_{0,H}. \qquad (6.15)$$

If $EVI_{\ell} > 0$, it implies that the hospital is benefited by the QRS with the use of the information system ℓ and hence it should exercise the QRS with system ℓ. On the other hand, once n_{ℓ}^{*} is determined, putting n_{ℓ}^{*} into EVI_{ℓ} yields the optimal expected value of information EVI_{ℓ}^{*} with the scanning system $\ell \in \{R, B\}$.

$$EVI_{\ell}^{*} = EVI_{\ell}(n_{\ell}^{*}). \qquad (6.16)$$

For a notational purpose, if the optimal number of observations is n_R^*, σ_{1,n_R^*} is denoted as the corresponding demand variance at Stage 1. Now, if the hospital switches from the bar-coding to the RFID, the following expressions are considered:

Define

$\rho = [(k_R n_R^* - k_B n_B^*) + (w_R - w_B)]/(\sigma_{1,n_B^*} - \sigma_{1,n_R^*})$,

$\Omega = r\psi[\Phi^{-1}(s)] + c\Phi^{-1}(s)$,

where $\Omega > 0$ for $s > 0.5$, and Ω denotes the cost threshold used to make decision on the system selection while ρ is the operational cost factor (associated with the RFID system). Proposition 6.2 shows that these two factors help to determine whether the RFID system outperforms the bar-coding system under the QRS.

Proposition 6.2. *In implementing QRS, the RFID system outperforms the bar-coding system if and only if* $\rho < \Omega$.

Proposition 6.2 shows a neat analytical result on when the RFID is a preferred device over the bar-coding system. It is found that ρ and Ω play a crucial role in this aspect. In fact, the benefit of using the RFID for running the QRS is its niche in terms of the reduced demand variance generated by more demand information observations (from more observation targets). Notice that ρ depends not only on the predicted demand variance improvement (i.e., $\sigma_{1,n_B^*} - \sigma_{1,n_R^*}$) but also the Relative Increased Information Acquisition Cost (RIIAC) associated with the RFID (i.e., $(k_R n_R^* - k_B n_B^*) + (w_R - w_B)$). It is obvious that when (i) k_R decreases (which results in a smaller $k_R n_R^*$ and hence yields a greater difference of $\sigma_{1,n_B^*} - \sigma_{1,n_R^*}$), and (ii) w_R decreases, it will lead to a smaller ρ. When $\rho < \Omega$, adopting the RFID system will generate a higher expected value of information than that of the bar-coding system. Overall, the RFID system should be adopted when $\rho < \Omega$ which can be achieved if there is a significant reduction on the RIIAC associated with the RFID system or a sufficiently large predicted demand variance improvement (when compared with the bar-coding system).

6.4. Supply Chain Mean-Variance (MV) Win-Win Coordination

In this section, the situation under which the RFID system outperforms the bar-coding system (i.e., the necessary and sufficient condition in Proposition 6.2 holds) is considered and the respective supply chain coordination challenge is explored. To be specific, it focuses on examining the impacts of the QRS with the RFID system towards each channel member and the entire supply chain (i.e., the RFID-mediated QRS supply chain) via the Mean-Variance (MV) approach. Note that under the MV framework, the payoff and the risk of the channel members are measured by the expected profit and variance of profit, respectively. Besides, the measures under which the hospital and supplier can achieve the MV win-win coordination in which: (i) both members achieve "MV win-win" (i.e., they both have an improved expected profit and/or a lower variance of profit) and (ii) the supply chain profitability (measured by the expected profit) is maximized, after adopting the QRS with the RFID system.

Under the RFID-mediated QRS, the expected profit of the hospital at Stage 0 $EP_{0,H}$ is the same as the one shown in Eq. (6.10) while that at Stage 1

$EP^R_{1,H}(n^*_R)$ can be revised from Eq. (6.14) easily. In the following, the variance of profit of hospital at different stages to evaluate the corresponding risk level is developed:

$$VP_{0,H} = (r\sigma_0)^2 \hat{\xi}[\Phi^{-1}(s)], \quad (6.17)$$

$$VP_{1,H}(n^*_R) = (r\sigma_{1,n^*_R})^2 \hat{\xi}[\Phi^{-1}(s)], \quad (6.18)$$

where $\hat{\xi}[\Phi^{-1}(a)] = a\phi(a) + \Phi(a) + a^2\Phi(a) - (\phi(a) + a\Phi(a))^2$.

According to the hospital's optimal order quantities as shown in Eq. (6.9) and Eq. (6.12), the corresponding expected profit and variance of profit of the supplier is derived as follows:

$$EP_{0,M} = (c-m)[\mu_0 + \sigma_0\Phi^{-1}(s)], \quad (6.19)$$

$$EP_{1,M}(n^*_R) = (c-m)[\mu_0 + \sigma_{1,n^*_R}\Phi^{-1}(s)], \quad (6.20)$$

$$VP_{0,M} = 0, \quad (6.21)$$

$$VP_{1,M}(n^*_R) = 0. \quad (6.22)$$

The change of optimal expected profit and change of the variance of profit under the RFID-mediated QRS of the hospital and supplier is denoted as ΔEP^R_H, ΔEP_M ,and ΔVP^R_H, ΔVP_M, respectively and they are defined as below:

$$\Delta EP^R_H = EP^R_{1,H}(n^*_R) - EP_{0,H} = (\sigma_0 - \sigma_{1,n^*_R})\{c\Phi^{-1}(s) + r\psi[\Phi^{-1}(s)]\} - (k_R n^*_R + w_R),$$

(6.23)

$$\Delta EP_M = EP_{1,M}(n^*_R) - EP_{0,M} = (\sigma_{1,n^*_R} - \sigma_0)(c-m)\Phi^{-1}(s), \quad (6.24)$$

$$\Delta VP^R_H = VP^R_{1,H}(n^*_R) - VP_{0,H} = r^2(\sigma_{1,n^*_R} + \sigma_0)(\sigma_1 - \sigma_0)\hat{\xi}[\Phi^{-1}(s)], \quad (6.25)$$

$$\Delta VP_M = VP_{1,M}(n^*_R) - VP_{0,M} = 0. \quad (6.26)$$

As a benchmark for exploring the MV win-win coordination, the centralized SC is examined. First, the centralized SC's optimal expected profit at Stage 0 is denoted as $EP_{0,SC}$ and at Stage 1 under the RFID-mediated QRS as $EP_{1,SC}^{R}(n_R^*)$. Second, their closed-form expressions are derived and summarized in Table 6.2.

Table 6.2 The optimal expected profits of the centralized supply chain under QRP with RFID

	Centralized supply chain
$EP_{0,SC}$	$(r-m)\mu_0 - m\sigma_0\Phi^{-1}(s_{SC}) - r\sigma_0\psi[\Phi^{-1}(s_{SC})]$
$EP_{1,SC}^{R}(n_R^*)$	$(r-m)\mu_0 - m\sigma_{1,n_R^*}\Phi^{-1}(s_{SC}) - r\sigma_{1,n_R^*}\psi[\Phi^{-1}(s_{SC})] - (k_R n_R^* + w_R)$

Define $s_{sc} = (r-m)/r$. The change of the centralized SC's optimal expected profit is denoted as ΔEP_{SC} and it is defined as below:

$$\Delta EP_{SC}^{R} = (\sigma_0 - \sigma_{1,n_R^*})\{r\psi[\Phi^{-1}(s_{sc})] + m[\Phi^{-1}(s)]\} - (k_R n_R^* + w_R). \tag{6.27}$$

Before indicating the Lemma 6.3, the formal definitions for the MV win-win situation[15], and the MV win-win coordination are defined as follows:

Definition 6.1. *In the RFID-mediated QRS supply chain, an MV win-win situation is attained if and only if (i)* $\Delta EP_H^R \geq 0$ *and* $\Delta VP_H^R \leq 0$*; and (ii)* $\Delta EP_M \geq 0$ *and* $\Delta VP_M \leq 0$*, and at least one component condition in (i) and one component condition in (ii) being strict inequalities.*

[15] Notice that the MV win-win situation refers to the situation in which both the supplier and the hospital are benefited in the MV domain after adopting the QRS with the RFID (as compared to the case without QRS).

Definition 6.2. *In the RFID-mediated QRS supply chain, the MV win-win coordination is achieved if (i) the supply chain's expected profit is maximized, and (ii) the MV win-win situation is attained.*

Lemma 6.3. *Under the RFID-mediated QRS, (a) the hospital can enjoy a higher optimal expected profit if and only if* $(\sigma_0 - \sigma_{1,n_R^*}) > (k_R n_R^* + w_R)\{c\Phi^{-1}(s) + r\psi[\Phi^{-1}(s)]\}^{-1}$*; (b) the supplier always suffers a loss ; (c) the SC is not optimal (i.e., uncoordinated); (d) the MV win-win coordination will not exist automatically.*

Lemma 6.3(a) illustrates the insight that the hospital very likely can get a higher optimal expected profit by implementing the QRS with the RFID (of course, it does depend on the RFID system execution cost). Yet, the supplier always earns less than before which will reduce its willingness to cooperate with the hospital under the QRS. Furthermore, it is realized that the SC is not optimal and hence the MV win-win coordination cannot be achieved in the RFID-mediated QRS supply chain automatically.

In the following, two different policies are proposed which can help to attain the MV win-win coordination.

6.4.1. Service-level Commitment Policy (SCP)

Under the SCP, the hospital has to commit to a higher service level s^{SCP} (i.e., $s^{SCP} > s$) when the order is placed at Stage 1 (i.e., with the RFID supported QRS). The optimal expected profit of each channel member under the QRS with RFID in the presence of SCP is given in Table 6.3 while the corresponding change of the expected profit is shown as below:

$$\Delta EP_H^{R,SCP} = c\{\sigma_0\Phi^{-1}(s) - \sigma_{1,n_R^*}\Phi^{-1}(s^{SCP})\} + r\{\sigma_0\psi[\Phi^{-1}(s)] - \sigma_{1,n_R^*}\psi[\Phi^{-1}(s^{SCP})]\} - (k_R n_R^* + w_R),$$

$$\Delta EP_M^{MQPCP} = (c_1 - c)\mu_0 + (c_1 - m)\sigma_{1,n_R^*}\Phi^{-1}(s_{sc}) - (c - m)\sigma_0\Phi^{-1}(s),$$

$$\Delta VP_H^{R,MQPCP} = r\{\sigma_{1,n_R^*}^2\hat{\xi}[\Phi^{-1}(s_{sc})] - \sigma_0^2\hat{\xi}[\Phi^{-1}(s)]\},$$

$$\Delta VP_M^{SCP} = 0.$$

Table 6.3 Optimal expected profits and variance of profits of each channel member under the RFID-mediated QRS with SCP

	Hospital	Supplier
$EP_1^{R,SCP}(n_R^*)$	$(r-c)\mu_0 - c\sigma_{1,n_R^*}\Phi^{-1}(s^{SCP})$ $-r\sigma_{1,n_R^*}\psi[\Phi^{-1}(s^{SCP})] - (k_R n_R^* + w_R)$	$(c-m)[\mu_0 + \sigma_{1,n_R^*}\Phi^{-1}(s^{SCP})]$
$VP_1^{R,SCP}(n_R^*)$	$(r\sigma_{1,n_R^*})^2\hat{\xi}[\Phi^{-1}(s^{SCP})]$	0

Define $\zeta(\cdot) = cr^{-1}\Phi^{-1}(\cdot) + \psi[\Phi^{-1}(\cdot)]$, $\zeta^{-1}(\cdot)$ is an inverse function of $\zeta(\cdot)$, $s_{H,EP} = \zeta^{-1}[\sigma_0(\sigma_{1,n_R^*})^{-1}\zeta(s) - (k_R n_R^* + w_R)(r\sigma_{1,n_R^*})^{-1}]$, $s_{M,EP} = \Phi[\sigma_0(\sigma_{1,n_R^*})^{-1}\Phi^{-1}(s)]$, $s_{H,VP} = \Phi[\hat{\xi}^{-1}(s_{M,VP})]$, and $s_{M,VP} = [\sigma_0(\sigma_{1,n_R^*})^{-1}]^2\hat{\xi}[\Phi^{-1}(s)]$.

Lemma 6.4. *In the presence of SCP, by setting (i)* $s_{M,EP} < s^{SCP} \le s_{H,EP}$ *for* $s_{M,VP} > 1$*; (ii)* $s_{M,EP} < s^{SCP} \le \min\{s_{H,EP}, s_{H,VP}\}$ *for* $s_{M,VP} \le 1$ *and* $s_{H,EP} \ne s_{H,VP}$*; (iii)* $s_{M,EP} < s^{SCP} < s_{H,EP}$ *for* $s_{M,VP} \le 1$ *and* $s_{H,EP} = s_{H,VP}$*; an MV win-win situation can be achieved in the supply chain under the RFID-mediated QRS if and only if* $s_{M,EP} < s_{H,EP}$ *.*

Lemma 6.4 shows the sufficient conditions to achieve the MV win-win situation in the supply chain under the RFID-mediated QRS by using SCP. Observe that

Lemma 6.4 also implies the hospital is actually quite flexible in terms of the parameter setting to achieve the MV win-win coordination because a wide range of the committed service levels can help. More findings will be reported in Section 6.5 via numerical analysis.

Proposition 6.5. *If Lemma 6.4 holds and* $s_{M,EP} < s_{sc} < s_{H,EP}$*, the MV win-win coordination can be achieved when the inventory service level is set at* $s^{SCP} = s_{sc}$.

Proposition 6.5 indicates that if the hospital adopts SCP and commits to set the inventory service level at s_{sc} under the RFID-mediated QRS, the most desirable outcome on the MV win-win coordination can be achieved. Since the supply chain's profitability is maximized (because it is "coordinated") and both the supplier and the hospital are benefited by using the RFID-mediated QRS (i.e. "MV win-win"), this measure provides full incentive for both the hospital and the supplier to adopt. It also helps to enhance the competitiveness of the whole supply chain system.

6.4.2. Minimum Quantity with Price Commitment Policy (MQPCP)

Under the QRS, Lemma 6.3(b) reveals that the supplier always suffers a loss because the hospital will order in a smaller quantity. Hence, the second method is proposed, namely the Minimum Quantity with Price Commitment Policy (MQPCP). Under the QRS with MQPCP, the supplier charges the hospital with a higher wholesale price c_1 (i.e., $c_1 > c$) along with a minimum order quantity requirement. It is assumed that the supplier's minimum order quantity requirement is set as the optimal quantity under the centralized system, i.e.,

$q_1^{MQPCP} \geq q_{1,sc}^* = \mu_1 + \sigma_1 \Phi^{-1}(s_{sc})$. From Section 6.3, it is obvious that the hospital will always order $q_{1,sc}^*$ under the QRS with MQPCP as $m < c \Leftrightarrow s_{sc} > s \Leftrightarrow q_{1,sc}^* > q_1^*$. Table 6.4 shows the corresponding expected profit of each member when MQPCP is exercised. The change of the expected profit and variance of profit of the hospital and supplier under RFID-mediated QRS with MQPCP are developed respectively as follows:

$$\Delta EP_H^{R,MQPCP} = c[\mu_0 + \sigma_0 \Phi^{-1}(s)] - c_1[\mu_0 + \sigma_{1,n_R^*} \Phi^{-1}(s_{sc})]$$
$$+ r\{\sigma_0 \psi[\Phi^{-1}(s)] - \sigma_{1,n_R^*} \psi[\Phi^{-1}(s_{sc})]\} - (k_R n_R^* + w_R),$$

$$\Delta EP_M^{MQPCP} = (c_1 - c)\mu_0 + (c_1 - m)\sigma_{1,n_R^*} \Phi^{-1}(s_{sc}) - (c - m)\sigma_0 \Phi^{-1}(s),$$

$$\Delta VP_H^{R,MQPCP} = r\{\sigma_{1,n_R^*}^2 \hat{\xi}[\Phi^{-1}(s_{sc})] - \sigma_0^2 \hat{\xi}[\Phi^{-1}(s)]\},$$

$$\Delta VP_M^{MQPCP} = 0.$$

Table 6.4 Optimal expected profits and variance of profits of each channel member under RFID-mediated QRS with MQPCP

	Hospital	Supplier
$EP_1^{MQPCP}(n_R^*)$	$(r - c_1)\mu_0$ $- \sigma_{1,n_R^*}\{c_1 \Phi^{-1}(s_{sc}) + r\psi[\Phi^{-1}(s_{sc})]\}$ $-(k_R n_R^* + w_R)$	$(c_1 - m)[\mu_0 + \sigma_{1,n_R^*} \Phi^{-1}(s_{sc})]$
$VP_1^{MQPCP}(n_R^*)$	$(r\sigma_{1,n_R^*})^2 \hat{\xi}[\Phi^{-1}(s_{sc})]$	0

Define:

$$c_H = \arg_{c_1}\{\Delta EP_H^{R,MQPCP}(c_1) = 0\},$$

$$c_M = \arg_{c_1}\{\Delta EP_M^{MQPCP}(c_1) = 0\},$$

$\overline{c_H} = \min\{c_H, r\}$,

$$\lambda = \left(\frac{\sigma_0}{\sigma_1}\right)^2 \hat{\xi}[\Phi^{-1}(s)],$$

$$\beta = \Phi[\hat{\xi}^{-1}(\lambda)].$$

Lemma 6.6. *In the presence of MQPCP, by setting $c_M < c_1 \leq \overline{c_H}$, the MV win-win coordination can be achieved under the RFID-mediated QRS if and only if $s_{sc} \leq \beta$.*

Lemma 6.6 indicates that the supplier can execute MQPCP to achieve the MV win-win coordination under the RFID-mediated QRS. The range of the wholesale price which achieves coordination is rather flexible which provides freedom for the supplier and the hospital to negotiate. Note that there does exist a condition on the service level to ensure the achievability of MV win-win coordination because the service level affects the change of variance of profit (see the proof for the details). Last but not least, the use of MQPCP relates to the practice of minimum order quantity (MOQ) as reported widely in the literature and implemented in practice. Thus, the proposed scheme based on MQPCP is in fact motivated by the industrial practice.

6.5. Numerical Analyses

In this section, a numerical illustration is firstly conduct to show the proper device selection under the QRS. Next, impact brought by different major parameter values towards the expected value of information under the RFID-mediated QRS when the supplier offers the wholesales pricing contract to the hospital is also numerically visualized. Finally, various numerically analyses are conducted to demonstrate the possible setting of the parameters to achieve the MV win-win situation with the proposed policies (i.e., SCP and MQPCP). In the following, the parameter setting follows the study of Choi and Chow (2008) as our initial setting, i.e., $\mu_0 = 12, d_0 = 14$, $\delta = 2$, $r = 22$, $c = 10$, $m = 2$, $k_R = 0.05$, $k_B = 0.6$, $w_R = 5$, $w_B = 2$ (and $s = 0.5455$) because this set of parameters satisfy all the conditions for the analytical model and also looks consistent with the observed industrial practice.

6.5.1. Information System Selection under the QRS

In Proposition 6.2, it is revealed that the RFID system outperforms the bar-coding system if and only if $\rho < \Omega$. In Table 6.5 and Table 6.6, they further demonstrate when the hospital should switch to the RFID system (from the bar-coding system) in order to facilitate the implementation of the QRS. In Table 6.5, it demonstrates that a smaller information collection cost (per each observation) k_R will lead to a more optimal observation targets n_R^* and enlarge the predicted demand variance improvement ($\sigma_{1,n_B^*} - \sigma_{1,n_R^*}$). Under our numerical setting, the RFID system should be adopted when $k_R \le 0.015$ (i.e. sufficiently small). On the other hand, in Table 6.6, it demonstrates that the variation of w_R will affect the relative increased information acquisition cost associated with the RFID system (i.e., $(k_R n_R^* - k_B n_B^*) + (w_R - w_B)$), and the RFID system should be adopted when $w_R < 4.6$ (i.e. sufficiently small).

Table 6.5 Numerical example on the impact of k_R toward the system selection

k_R	n_R^*	$k_R n_R^*$	EVI_R^*	EVI_B^*	$(k_R n_R^* + w_R) - (k_B n_B^* + w_B)$	$\sigma_{1,n_B^*} - \sigma_{1,n_R^*}$	ρ	Ω	Which device should be selected?
0.050	11	0.550	16.456	16.921	1.750	0.147	11.874	8.72	Barcode
0.045	11	0.495	16.511	16.921	1.695	0.147	11.501	8.72	Barcode
0.040	12	0.480	16.570	16.921	1.680	0.152	11.024	8.720	Barcode
0.035	13	0.455	16.632	16.921	1.655	0.157	10.564	8.720	Barcode
0.030	14	0.420	16.699	16.921	1.620	0.160	10.104	8.720	Barcode
0.025	15	0.375	16.772	16.921	1.575	0.164	9.632	8.720	Barcode
0.020	15	0.300	16.847	16.921	1.500	0.164	9.173	8.720	Barcode
0.015	15	0.225	16.922	16.921	1.425	0.164	8.714	8.720	RFID
0.010	15	0.150	16.997	16.921	1.350	0.164	8.256	8.720	RFID
0.005	15	0.075	17.072	16.921	1.275	0.164	7.797	8.720	RFID
0.001	15	0.015	17.132	16.921	1.215	0.164	7.430	8.720	RFID

Table 6.6 Numerical example on the impact of w_R toward the system selection

w_R	EVI_R^*	EVI_B^*	$(k_R n_R^* + w_R) - (k_B n_B^* + w_B)$	$\sigma_{1,n_B^*} - \sigma_{1,n_R^*}$	ρ	Ω	Which device should be selected?
5.0	16.456	16.921	1.750	0.147	11.874	8.720	Barcode
4.8	16.656	16.921	1.550	0.147	10.517	8.720	Barcode
4.6	16.856	16.921	1.350	0.147	9.160	8.720	Barcode
4.4	17.056	16.921	1.150	0.147	7.803	8.720	RFID
4.2	17.256	16.921	0.950	0.147	6.446	8.720	RFID
4.0	17.456	16.921	0.750	0.147	5.089	8.720	RFID
3.8	17.656	16.921	0.550	0.147	3.732	8.720	RFID
3.6	17.856	16.921	0.350	0.147	2.375	8.720	RFID
3.4	18.056	16.921	0.150	0.147	1.018	8.720	RFID
3.2	18.256	16.921	-0.050	0.147	-0.339	8.720	RFID
3.0	18.456	16.921	-0.250	0.147	-1.696	8.720	RFID

6.5.2. RFID-Mediated QRS with Wholesale Pricing Contract

In Eq. (6.16), it is defined that the performance of the QRS with the use of the RFID system can be evaluated based on the value of EVI_R^*. In order to visualize the impact of each parameter towards the RFID-mediated QRS, in this sub-section, a numerical sensitivity analysis on EVI_R^* is conducted and the results are shown in Table 6.7; and from Figure 6.2 to Figure 6.4.

In Table 6.7, it shows that the higher the value of the retail price r or the wholesale price c is, the larger the optimal number of observations targets with the use of RFID n_R^* and the respective expected value of information EVI_R^* will be. It means that if a particular healthcare apparel product is more costly, then the hospital should employ more observation targets and conduct more market observations, and the benefit generated by the QRS with the use of RFID will also be larger. On the other hand, the impact of k_R and w_R is quite intuitive: When k_R or w_R increases, the benefit of using the RFID system for facilitating the QRS diminishes. In other words, the hospital should carefully evaluate the RFID operational cost (e.g., tag cost), the total cost for collecting the demand information as well as the future fixed cost of the RFID system (e.g., maintenance cost) before deciding to adopt the RFID system.

Table 6.7 Summary of the impact of each parameter under RFID-medicated QRS

Parameter	s	n_R^*	EVI_R^*
r ↑	↑	↑	↑
c ↑	↓	↑	↑
k_R ↑	no change	↓	↓
w_R ↑	no change	no change	↓

Figure 6.2 Impact of selling price

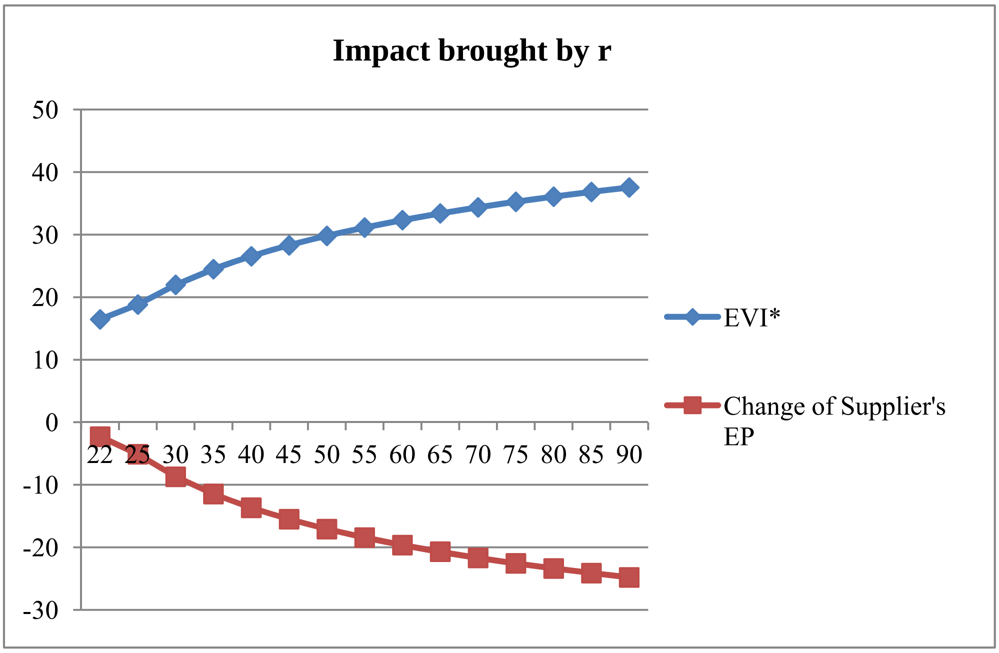


Figure 6.3 Impact of wholesale price

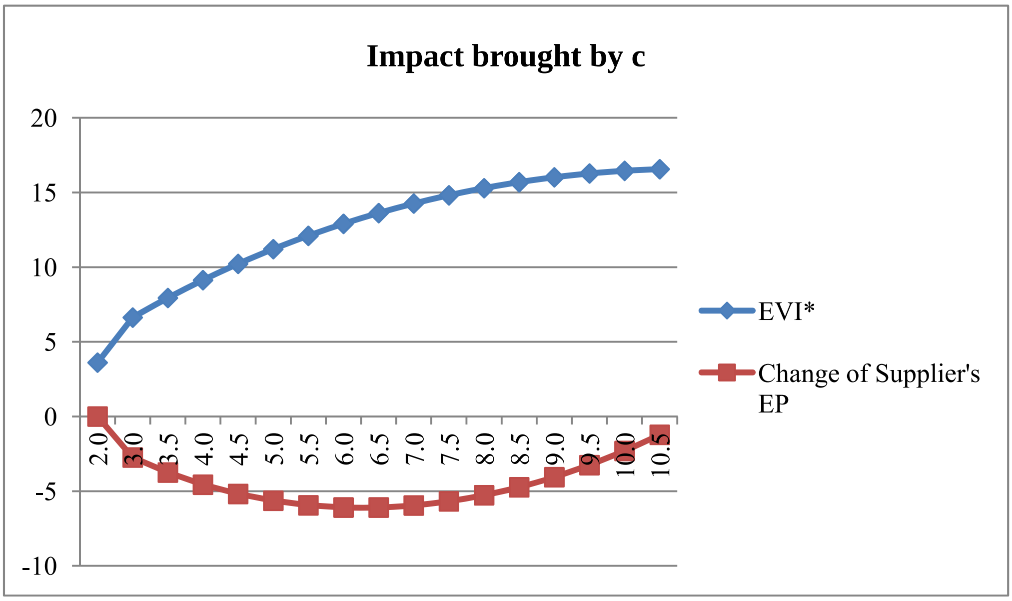
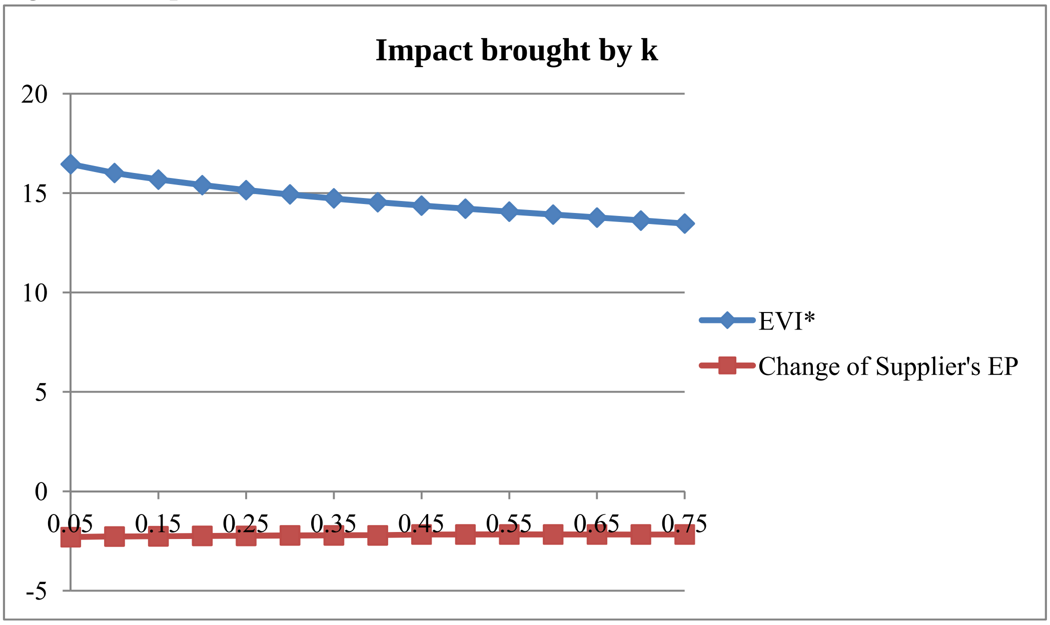


Figure 6.4 Impact of data collection cost



6.5.3. RFID-Mediated QRS with SCP

In Section 6.4, it is proposed that the service-commitment policy (SCP) can achieve the MV win-win coordination. In this sub-section, another numerical analysis is conducted to demonstrate the proper setting of this policy with the consideration of the industrial observation that the inventory service level in the hospital environment is always higher than 50%. When SCP is implemented, the hospital has to commit a higher inventory service level threshold than before (i.e., $s^{SCP} > s$). Thus, the effect of s^{SCP} over the range from 0.5455 to 0.9900 on the expected profit of each channel member is explored. Results are presented in Table 6.8 and the observations are summarized as follows: First, it is apparent that the MV win-win situation is achieved if the hospital sets the inventory service level within the range of 0.6215 $< s^{SCP} \leq$ 0.9758 based on our numerical setting. This shows that there is high flexibility for the hospital to set the service level in order to achieve the MV win-win situation. Second, if the hospital commits the service level at a level of $s^{SCP} = s_{sc} = (22-2)/22 = 0.9091$, the MV win-win coordination is achieved in which the SC's profitability is maximized. Last but not least, when s^{SCP} within the range increases, it is observed that $\Delta EP_H^{R,SCP}$ decreases while ΔEP_M^{SCP} increases. This implies that under the MV win-win situation, the higher inventory service level that the hospital commits under the SCP, the more the expected profit that the supplier will receive. Even though the hospital will earn less when s^{SCP} is larger, the performance of the decentralized SC (i.e., $\Delta EP_{H+M}^{SCP} > 0$) under the MV win-win situation is in fact enhanced which means the supply chain is more efficient. As such, the proper setting of the service level depends on the bargaining powers of the supplier and the hospital. Last but not least, ideally, the supplier and the hospital should set s^{SCP} = $s_{sc} = 0.9091$ which achieves the MV win-win coordination. In order to ensure both sides will get a "fair" share of the supply chain surplus generated by the coordination, the supplier and the hospital can discuss further on using a simple credit transfer scheme to further share the benefit.

Table 6.8 Numerical examples of achieving an MV win-win situation under QRS with SCP

s^{SCP}	Hospital		Supplier		Is MV win-win achieved ?	Decentralized SC
	ΔEP_H^{SCP}	ΔVP_H^{SCP}	ΔEP_M^{SCP}	ΔVP_M^{SCP}		ΔEP_{H+M}^{SCP}
0.5455	16.46	-2591.85	-2.30	0	No	14.15
0.6000	16.33	-2529.57	-0.66	0	No	15.67
0.6215	16.21	-2504.00	0.00	0	No	16.21
0.6500	15.99	-2469.23	0.90	0	Yes	16.89
0.7000	15.40	-2405.77	2.54	0	Yes	17.94
0.7500	14.53	-2343.57	4.29	0	Yes	18.81
0.8000	13.28	-2273.97	6.25	0	Yes	19.53
0.8500	11.52	-2205.40	8.51	0	Yes	20.03
0.9091	8.28	-2118.69	11.98	0	Yes	20.26
0.9500	4.44	-2056.23	15.56	0	Yes	20.00
0.9758	0.02	-2016.11	19.36	0	Yes	19.38
0.9825	-1.85	-2012.17	20.89	0	No	19.04
0.9850	-2.71	-2003.40	21.60	0	No	18.89
0.9900	-4.92	-1997.56	23.38	0	No	18.46

6.5.4. RFID-Mediated QRS with MQPCP

Apart from SCP, Section 6.4 shows that that the MV win-win coordination can be achieved with help of MQPCP. In this sub-section, another numerical analysis is also conducted to evaluate the impact of the MQPCP over the range of $10.0 < c_1 \leq 14.0$ and demonstrate the proper setting of this policy in Table 6.9. With MQPCP, by forcing the order quantity at the optimal supply chain quantity under the RFID-mediated QRS[16], the numerical data manifests that ΔEP_H^{MCPCP} decreases (and becomes negative) with $\Delta VP_H^{MQPCP} < 0$ while ΔEP_M^{MQPCP} increases (and becomes positive) with $\Delta VP_M^{MQPCP} = 0$ when c_1 increases. Besides, the MV win-win coordination can be achieved when c_1 is properly set over the range of $10.0 < c_1 < 10.60$. With the help of MQPCP, the MV win-win situation is achieved and the decision of c_1 will affect the profit allocation between the hospital and the supplier from the optimal supply chain (and that is the reason the decentralized SC's expected profit improvement remains unchanged over the range of $10.0 < c_1 < 10.6$).

[16] Since the real SC optimal quantity under the RFID-mediated QRS depends on the number of observation targets which is not fixed before Stage 1, we simply use the expected optimal quantity but setting $\mu_1 = \mu_0$ in this illustrative numerical analysis.

Table 6.9 Numerical examples of achieving an MV win-win situation under QRS with MQPCP

c_1	Hospital		Supplier		Is MV win-win achieved ?	Decentralized SC
	ΔEP_H^{MQPCP}	ΔVP_H^{MQPCP}	ΔEP_M^{MQPCP}	ΔVP_M^{MQPCP}		ΔEP_{H+M}^{MQPCP}
10.00	8.28	-2118.70	11.98	0	Yes	20.26
10.10	6.89	-2118.70	13.37	0	Yes	20.26
10.20	5.49	-2118.70	14.77	0	Yes	20.26
10.30	4.09	-2118.70	16.16	0	Yes	20.26
10.40	2.70	-2118.70	17.56	0	Yes	20.26
10.50	1.30	-2118.70	18.95	0	Yes	20.26
10.59	0.05	-2118.70	20.21	0	Yes	20.26
10.60	-0.09	-2118.70	20.35	0	No	20.26
10.70	-1.49	-2118.70	21.74	0	No	20.26
10.80	-2.88	-2118.70	23.14	0	No	20.26
10.90	-4.28	-2118.70	24.54	0	No	20.26
11.00	-5.67	-2118.70	25.93	0	No	20.26
12.00	-19.62	-2122.55	39.84	0	No	20.22
13.00	-33.57	-2125.92	53.75	0	No	20.18
14.00	-47.52	-2125.92	67.70	0	No	20.18

6.6. Extension One – Patients' Welfare Consideration

In Section 6.3, it addressed that the hospital aimed at maximizing the profit and providing a high inventory service level to the patients to determine its the optimal ordering decision under the QRS. Indeed, the patients' welfare is also an important factor that should be considered for inventory planning in the healthcare industry. For example, the sterilized gowns are extremely critical for both patients and medical personnel during the surgery. In this section, it extends the model developed in Section 6.3 by considering the patients' welfare under the QRS and explores its impact toward the information system selection decision. Patients' welfare (similar to the consumer welfare) which is defined as the benefit of the patient such as the patients' perceived service quality based on the product availability because it can ensure that the best treatment can be provided to the patients. This factor is measured by γ which is defined as the importance level of the patients' welfare that a hospital perceived.

With the consideration of the patients' welfare, the expected profit of the hospital at each stage under the QRS is revised as follows:

At Stage 0, the expression of the hospital's expected profit is derived in Eq. (6.28):

$$EP_{0,H}\Big|_{\gamma} = (r+\gamma)\mu_0 - cq_0 - (r+\gamma)\sigma_0\psi[(q_0-\mu_0)/\sigma_0]. \tag{6.28}$$

Similar to Eq. (6.9), through deriving the second order condition, it is proven that $EP_{0,H}\Big|_{\gamma}$ is also a strictly concave function in $q_0^*\Big|_{\gamma}$. Besides, the optimal order quantity of the hospital is determined by solving $\arg\{d\,EP_{0,H}\Big|_{\gamma} / dq_0 = 0\}$ as follows:

$$q_0^*\Big|_{\gamma} = \mu_0 + \sigma_0\Phi^{-1}(s_\gamma), \tag{6.29}$$

where $s_\gamma = (r+\gamma-c)/(r+\gamma)$.

Now, with Eq. (6.29), the optimal expected profit of the hospital at Stage 0 is:

$$EP_{0,H}\Big|_{\gamma}(q_0^*) = (r+\gamma-c)\mu_0 - c\sigma_0\Phi^{-1}(s_\gamma) - r\sigma_0\psi[\Phi^{-1}(s_\gamma)]. \tag{6.30}$$

By assuming the hospital incurs the same information acquisition cost as in Section 6.3 with an expression $a^{\ell}(n_\ell) = k_\ell n_\ell + w_\ell$ when the information system ℓ is adopted to collect the demand information of the correlated product to update a particular product's demand distribution, where $\ell \in \{R, B\}$, the expected profit and the optimal order quantity of the hospital under the QRS can be derived respectively as in Eq. (6.31) and Eq. (6.32):

$$EP_{1,H}^{\ell}\Big|_{\mu_1,\gamma} = (r+\gamma)\mu_1 - cq_1 - (r+\gamma)\sigma_{1,n_\ell}\psi[(q_1-\mu_1)/\sigma_{1,n_\ell}] - a^{\ell}(n_\ell), \tag{6.31}$$

and $q_1^* = \mu_1 + \sigma_{1,n_\ell}\Phi^{-1}(s_\gamma)$. (6.32)

The unconditional optimal expected profit of the hospital at Stage 1 under the QRS becomes:

$$EP_{1,H}^{\ell}\Big|_{\gamma}(n_\ell) = (r+\gamma-c)\mu_0 - c\sigma_{1,n_\ell}\Phi^{-1}(s_\gamma) - (r+\gamma)\sigma_{1,n_\ell}\psi[\Phi^{-1}(s_\gamma)] - a^{\ell}(n_\ell)\,. \tag{6.33}$$

With Eq. (6.33), Proposition 6.7 and Proposition 6.8 are developed.

Proposition 6.7. *$EP_{1,H}^{\ell}\Big|_{\gamma}(n_{\ell,\gamma})$ is a strictly concave function of $n_{\ell,\gamma}$ for $n_{\ell,\gamma}>0$ and a unique optimal $n_{\ell,\gamma}$ exists.*

Proposition 6.7 also shows that $EP_{1,H}^{\ell}\Big|_{\gamma}(n_{\ell,\gamma})$ is a strictly concave function in $n_{\ell,\gamma}$, and the optimal $n_{\ell,\gamma}$ (which is denoted as $n_{\ell,\gamma}^*$) can be uniquely determined by solving $\arg\{d\,EP_{1,H}^{\ell}\Big|_{\gamma}(n_{\ell,\gamma})/dn_{\ell,\gamma}=0\}$. By comparing the hospital's unconditional optimal expected profit at Stage 1 under QRS as in Eq. (6.14) and in Eq. (6.33) which associated with the patients' welfare factor, it is obvious that the analytical expression of finding $n_{\ell,\gamma}^*$ will be the same as n_ℓ^* except the parameter "r" is replaced by "$r+\gamma$". Once $n_{\ell,\gamma}^*$ is determined, the performance of the bar-coding and the RFID system can be evaluated.

Define:

$$\rho\big|_{\gamma} = [(k_R n_{R,\gamma}^* - k_B n_{B,\gamma}^*) + (w_R - w_B)]/(\sigma_{1,n_{B,\gamma}^*} - \sigma_{1,n_{R,\gamma}^*}),$$

$$\Omega\big|_{\gamma} = (r+\gamma)\psi[\Phi^{-1}(s_\gamma)] + c\Phi^{-1}(s_\gamma).$$

where $\Omega\big|_{\gamma} > 0$ for $s_\gamma > 0.5$, and $\Omega\big|_{\gamma}$ denotes the cost threshold used to make decision on the system selection when patients' welfare is considered while $\rho\big|_{\gamma}$ is the operational cost factor associated with the RFID system. Proposition 6.8 demonstrate the condition in which the RFID system is superior to the bar-coding system under QRS when patients' welfare is considered.

Proposition 6.8 *In implementing the QRS with the patients' welfare consideration, the RFID system outperforms the bar-coding system if and only if* $\rho|_{\gamma} < \Omega|_{\gamma}$.

From Proposition 6.8, the analytical condition, illustrates when the RFID system is a preferred device over the bar-coding system, is very similar to that presented in Proposition 6.2. Indeed, both $\rho|_{\gamma}$ and $\Omega|_{\gamma}$ help to compare the performance between the RFID and the bar-coding systems. Based on the analytical results shown in Proposition 6.7 and Proposition 6.8, it is easy to derive the MV win-win situation under the proposed policies as in Section 6.4 by substituting the parameter "r" by "$r+\gamma$".

6.6.1. Numerical Analysis with the Patients' Welfare Consideration

In order to have a closer look on the impact of the patients' welfare toward the information system selection decision, a numerical example is conducted as in Table 6.10.

Table 6.10 shows that both the inventory service level s_{γ} and the optimal number of demand information observation n_{ℓ}^{*} increase when the hospital's perceived importance of the patients' welfare γ is higher. To be specific, the hospital should provide a higher inventory service level to the patients and conduct more observations to update the demand information if it values much on the patient's welfare. Besides, it also reveals that $\rho|_{\gamma}$ decreases gradually but $\Omega|_{\gamma}$ increases significantly when the value of γ is higher. With our parameter setting, it also demonstrates that the hospital should switch to execute the RFID system when $\gamma \geq 10$. Overall, this finding implies that the hospital should switch to adopt the RFID system to capture the demand information of the correlated products when patient welfare is a significant important issue to a hospital.

Table 6.10 Numerical examples of the impact of patients' welfare toward the information system selection

γ	s_γ	$n^*_{R,\gamma}$	$n^*_{B,\gamma}$	$EVI^*_R\big\|_\gamma$	$EVI^*_B\big\|_\gamma$	$\rho\big\|_\gamma$	$\Omega\big\|_\gamma$	Which device should be selected?
1	0.565	11	3	137.085	137.501	11.874	9.053	Barcode
5	0.630	12	3	183.396	183.642	11.811	10.963	Barcode
10	0.688	12	3	241.732	241.806	11.811	12.939	RFID
15	0.730	13	3	300.394	300.326	11.809	14.390	RFID
25	0.787	14	4	418.326	418.093	11.574	15.825	RFID
30	0.808	14	4	477.497	477.200	11.574	16.658	RFID
40	0.839	14	4	596.109	595.705	11.574	17.546	RFID
60	0.878	15	4	834.025	833.459	11.687	18.578	RFID
80	0.902	15	4	1072.488	1071.800	11.687	19.400	RFID

6.7. Extension Two – Hybrid System Consideration

Despite it is more expensive to launch the RFID system than that of the bar-coding system in term of the future fixed cost (e.g., higher maintenance and upgrade cost that $w_R > w_B$), the RFID is less time-consuming to collect the demand information of the correlated products for demand distribution updating. Therefore, Proposition 6.2 and Proposition 6.8 analytically investigated when the RFID system was superior to the bar-coding system for inventory management with and without the patients' welfare consideration under the QRS, respectively. Instead of strictly switching to the RFID system, in this section, it is proposed that the hospital may launch a hybrid system which is composed of both the bar-coding and the RFID systems simultaneously (i.e., $\ell \in \{R, B, R+B\}$) for inventory management. For example, the RFID system is used to capture demand information of the high turn-over rate products such as surgical face masks and isolation gowns while the bar-coding system is used to manage the relatively slow moving products such as N95 face masks and gloves. With this consideration, it is interesting to evaluate whether the hospital should switch from the bar-coding system to (a) the RFID system, or (b) the hybrid system, for capture the demand information under the QRS.

Suppose that the hospital plans for the stocking quantities of two homogenous products[17] at Stage 1 under the QRS, for the simplicity, it is assumed that these two products have the same characteristics (for instance, same selling price, wholesale price, predicted demand mean, as well as updated demand variance). Therefore, with Eq. (3.14), the estimation of the hospital's unconditional optimal total expected profit at Stage 1 under the QRS with the use of (a) RFID system, $TEP_{1,H}^{R}(n_R)$; (b) bar-coding system, $TEP_{1,H}^{B}(n_B)$; and (c) hybrid system, $TEP_{1,H}^{R+B}(n_{R+B})$, is defined respectively as follows:

$$TEP_{1,H}^{R}(n_R) = 2EP_{1,H}^{R}(n_R), \tag{6.34}$$

$$TEP_{1,H}^{B}(n_B) = 2EP_{1,H}^{B}(n_B), \tag{6.35}$$

$$TEP_{1,H}^{R+B}(n_{R+B}) = EP_{1,H}^{R}(n_R) + EP_{1,H}^{B}(n_B). \tag{6.36}$$

The analytical expressions from Eq. (6.34) to Eq. (6.36) show that $TEP_{1,H}^{R}(n_R)$ is a strictly concave function of n_R, $TEP_{1,H}^{B}(n_B)$ is a strictly concave function of n_B, and $TEP_{1,H}^{R+B}(n_{R+B})$ is a strictly concave function of n_R and n_B. Regarding the adoption of the hybrid system, this means that there should be

[17] Notice that the consideration of the hybrid system in this section can be extended to manage two heterogeneous healthcare apparel products and compare the performance among these three scanning systems. However, this evaluation will generate more complicated cases but the findings will be very similar.

n_R observation targets for the product using the RFID system and n_B observation targets for another one using bar-coding system. The finding of the optimal n_R and n_B would be the same as in Appendix (C2). When it is found that the RFID is superior to the bar-coding system when it is used to manage one single healthcare apparel product under the QRS (i.e., Proposition 6.2 holds), it helps to develop Proposition 6.9.

Proposition 6.9 *(a) If Proposition 6.2 holds, the RFID system will dominate both bar-coding and hybrid systems for facilitating the QRS. (b) The hybrid system is always not the best decision to the hospital.*

Proof of Proposition 6.9: All proofs are included in Appendix (C1).

Proposition 6.9 generates an important insight that it is more beneficial for the hospital to adopt the RFID system (bar-coding system) when it outperforms the bar-coding system (RFID system). Indeed, all the healthcare apparel products are of equal importance for both patients and medical personnel and thus, they should not be managed separately through two different kinds of scanning system. Furthermore, it will complicate the daily operations when adopting more than one scanning system in the healthcare sector. For instance, the medical personnel have to be aware of which kind of scanning system should be used for a particular product which will definitely increase their workload and burden. Fundamentally, the primary duty of the medical personnel is to take care of and provide best treatment for the patients; therefore, it is not the best decision for the hospital to implement hybrid system for inventory planning under the QRS.

6.8. Managerial Implications and Conclusion

Motivated by real world observations in local hospitals, this chapter evaluated the value of the RFID system and the coordination challenge with its implementation in a healthcare supply chain. To be specific, to investigate the value of the RFID, it examined when a hospital using a bar-coding system should switch to the RFID system with a formal analytical Bayesian model. The expected value of information acquisition was derived and it was revealed analytically that whether the RFID system outperformed the bar-coding system depended on the operational cost factor associated with the RFID system and the cost threshold.

After that, coordination challenge was considered and the impacts brought by the RFID-mediated QRS on the expected profit and level of risk of the hospital, the supplier and the supply chain were examined. Insights were generated and summarized as follows:

i. Under the QRS with a wholesale pricing contract, the benefit brought by the RFID system is larger when (i) this mechanism is applied for the healthcare apparel product with a higher value (e.g., the more expensive activated carbon mask versus the casual surgical mask); or (ii) the cost for collecting the demand information under the RFID is cheaper (which is expected as the RFID system gets more matured and price goes down).

ii. Compared between the supply chains with and without the RFID-mediated QRS in the presence of a pure wholesale pricing contract, the supplier always suffers a loss with the implementation the QRS regardless of how the parameter changes. It thus means that the supply chain fails to create the MV win-win situation automatically.

iii. In order to mitigate the negative effect brought by the QRS toward supplier, two different policies are proposed. If the hospital exercises the QRS with SCP, it is found that the "improved expected profit" of the hospital diminishes while that of the supplier increases when the committed service level is higher. On the other hand, the SCP dramatically reduces the hospital's variance of profit and maintains the supplier at the same risk level. Hence, the MV win-win situation can be achieved under the QRS with the help of SCP. It is interesting to note that the performance of the decentralized SC will also be improved with this increment of service level (within the bounds). To achieve the MV win-win coordination, there exists a unique service level $s^{SCP} = s_{sc}$ under which both channel members can achieve the MV win-win situation with the implementation of the RFID-mediated QRS, and the supply chain is optimal (with the maximized expected profit). Note that the SCP is a measure mainly led by the hospital side of the supply chain (i.e., a "hospital" driven measure).

iv. Apart from SCP, the supplier can execute MQPCP to achieve the MV win-win coordination. In fact, MQPCP forces the hospital to fulfill the minimum order requirement and provide a higher inventory service level eventually. With MQPCP, the changes of the expected profits of both channel members are contrary in the direction when the wholesale price increases under the MV win-win coordination. It is important to note that the value of c_1 affects the profit allocation between the supplier and the hospital. Therefore, the final decision on the value of c_1 will depend on several factors such as bargaining power. Note that the MQPCP is a measure mainly led by the supplier side of the supply chain (i.e., a "supplier" driven measure). It is usually implemented in the case when the supplier is more powerful.

v. When the hospital values much on the patients' welfare, firstly, it is more desirable to switch to adopt the RFID system to effectively capture the information. Besides, the hospital should also set a higher inventory service level and conduct more observations to update the initial demand forecast under the QRS.

vi. If it is found that the RFID system is superior to bar-coding system (or vice versa) for inventory planning of a particular healthcare product, the hybrid system is always not the best device when it comes to manage multiple products under the QRS.

It is believed that the above insights are timely and important because they can provide important guidance to the use of the RFID system for healthcare supply chain systems.

7. Conclusion, Limitations, and Future Research Directions

This dissertation addressed the inventory planning decision with the help of the scanning system in the healthcare industry. First, three successful case studies with the use of the RFID system were reported in Chapter 4. They illustrated that the RFID system would be another promising tool which could be adopted in the healthcare industry for apparel product management. In order to better understand the real world industrial inventory management practices in the Hong Kong healthcare industry, two interviewed were conducted. It was found that both Hong Kong public and private hospitals were using the bar-coding system to manage the apparel products. Even though the RFID system has some advantages over the bar-coding system such as a lower demand on manual effort and a higher batch scanning capability, prior empirical studies commented that the successful read rate of the RFID system was just between 60-70%. Thus, the business value of the RFID system under the case when the scanning's accuracy is not perfect deserved deeper exploration. On the other hand, both hospitals indicated that there was no scientifically sound and effective way to forecast the demand of the healthcare apparel product, and shortage and serious leftover problems were observed. Through analysing the real data, it was realized that demands of some healthcare apparel products were significantly correlated. Therefore, it was believed that the QRS, supported by information updating among demands of correlated items, could be applied to yield a more accurate forecast and improve inventory planning efficiency with the help of the RFID. These were the two main focal points of this dissertation and they were studied in Chapter 5 and Chapter 6, respectively.

In Chapter 5, considering the accuracy of scanning systems were imperfect, an analytical model was developed to explore when the RFID system will outperform the bar-coding system in terms of the amount of required safety stock reduction under the existing real industrial practice. It was then extended to evaluate the impact of changing the scanning system toward the upstream apparel-product supplier and the downstream healthcare organization in a supply chain context. Three important analytical findings were generated as follows: First, the ratios between the RFID and the bar-coding systems' stock-taking costs and error variations would determine whether one system outperformed the other one. Second, when the healthcare organization found that it was optimal to change its scanning system from the bar-coding to the RFID, the supplier would suffer a loss. Third, a carefully designed surplus sharing contract could create a win-win situation under which both the supplier and the healthcare organization would have improvement with the change of the scanning system. The numerical results further revealed that the supplier could enjoy more benefits when supplying a lower profit margin healthcare apparel item to healthcare organization no matter under the wholesale pricing contract or the proposed surplus sharing contract to achieve the win-win situation. Besides, the healthcare organization would have a higher incentive to optimally switch to the RFID system if the RFID system was more stable than that of the bar-coding system (in term of the error variation) so that they could share more benefits from a supply chain with larger surplus.

In Chapter 6, the impact of the hospital who considered employing the RFID system to facilitate the QRS was analytically examined in the supply chain context. Under the QRS, information updating process was formulated based on the Bayesian model. The analytical and numerical results yielded interesting findings summarized as follows: First, if the operational cost factor was smaller than a cost threshold, it would be more appropriate to adopt the RFID than the bar-coding system. Second, under the QRS, the benefit brought by the RFID system was larger when it was used to manage the high value healthcare apparel products or the data collection cost with the use of the RFID system was cheaper. Third, the RFID-mediated QRS supply chain (in the presence of a pure wholesale pricing contract) was inefficient and the MV win-win coordination would not exist automatically. Based on this important finding, two policies were proposed to mitigate the negative effect brought by the QRS: they were (hospital-side-driven) Service-level Commitment Policy (SCP) and (supplier-side-driven) Minimum Quantity with Price Commitment Policy (MQPCP). With the help of these measures, the MV win-win situation was achieved and the supply chain was optimized.

Despite obtaining many important research findings, these two chapters were subjected to the following limitations: First, Chapter 5 addressed solely the transaction errors problem of the scanning system and proposed one possible contract to achieve the win-win situation. Other inventory inaccuracy problems were ignored. Besides, in Chapter 6, it was assumed that the cost-revenue parameters of the supply chain were public information. All the supply chain members had full and perfect information for decision making. Furthermore, the model developed in Chapter 6 considered that the product supply was always reliable which meant the hospital could receive the healthcare products from the supplier on time with the exact quantity ordered. Finally, both Chapter 5 and Chapter 6 studied a simple supply chain with one supplier and one healthcare organization. Indeed, the healthcare organization could have multiple suppliers for supplying one kind of healthcare apparel product and there existed competition between the suppliers.

This dissertation research could also be extended further in a number of directions. First, in Chapter 5, the surplus sharing contract was proposed to achieve the win-win situation when the healthcare organization found that it was optimal to switch to the RFID system. Existing literature also commented that high maintenance cost and relatively more expensive system cost (than that of the bar-coding system) was the major obstacle of the RFID system (Buyuran and Hardgrave, 2011). Therefore, it will be interesting to consider this issue along with the possibility of the RFID cost sharing (Gaukler, 2011; Chen et al., 2014), and explore other feasible contracts that can be imposed in the healthcare supply chain. Second, Chapter 6 considered that the healthcare organization planned to switch to the RFID system to facilitate the QRS with a shorter required lead time. However, it assumed that the supply chain's cost-revenue parameters were public information. A natural extension is to consider a situation when there is information asymmetry. The works developed by Yue et al. (2006) and Zhu et al. (2011) are excellent references for this future research direction. On the other hand, Chapter 6 also assumed that the supply was always reliable. For future research, it would be promising to extend the problem to the case when the supply side is not always reliable. The study of Dada et al. (2007), Burke et al. (2009), and Tiwari et al. (2011) provide great reference on the uncertain supply yield issue. This extension would be an analytically challenging problem because the resulting mean-risk analysis has to consider two sources of uncertainties. In addition, both Chapters could also examine the situation with multiple suppliers and there existed competition between the suppliers such as the work conducted by Cachon and Kök, (2010) and Krishnan et al. (2010).

Apart from studying the impact of the RFID system for apparel product management in the healthcare industry, it is also promising to explore other information technologies such as Electronic Data Interchange (EDI). EDI facilitates data exchange in different departments in one organization or between different entities (Swatman et al., 1994). Existing literature also believes that the EDI is beneficial to the healthcare industry in which the resources can be allocated efficiently (Liang et al., 2004; Woodside, 2007). In the current mobile commerce era, how EDI can work with the RFID and mobile computing devices to facilitate inventory planning in healthcare organizations would be a timely and interesting topic. Studies such as Sounderpandian et al. (2007) and Lee and Lee (2010) provide good reference in this research area.

Appendix A – Interview Questions for Chapter 4

Part I: Information about the suppliers

1. a. Who are the suppliers of the healthcare apparel products?

   b. Are they local companies?

   c. Do they specialize in selling a particular healthcare apparel product?
2. How does the hospital rate a company as a qualified supplier?
3. When there is a need for a particular healthcare apparel product, how does the hospital select the suitable supplier(s) from the qualified supplier list for tendering?
4. Does the hospital sign a contract with the selected supplier? If yes, how long is each contract?

Part II: Information about the healthcare apparel products

1. Where are the healthcare apparels products produced?
2. Are there any special features of the healthcare apparel products?
3. a. Is there any regular evaluation on the quality of healthcare apparel products delivered to the hospital?

   b. If yes, is there any defective product found?

   c. What is the percentage of defective products?

   d. How would the hospital handle the defective apparel products?

   e. How long does it take to re-deliver the products to the hospital once the defective products are detected?

Part III: Managing the reverse flow of the healthcare apparel products

1. How would the hospital handle the used apparels for disposal?
2. How would the hospital handle the used and washable apparels so that they can be re-used afterward?
3. a. Which party is responsible for determining the disposal decision of the reusable apparel products, the nurse, or the supplier?

   b. What are the factors used to determine the disposal decision (e.g. no. of years used, condition of the products etc)?

   c. What is the life time of the reusable apparel product? Can the hospital identify the duration that a reusable apparel product has been used? If yes, how does it identify?

Part IV: Inventory management of the healthcare apparel products

1. Is there any central warehouse which consolidates different healthcare apparel products before delivering to the department storeroom? If yes, where does it locate?
2. Is the replenishment order placed directly to the suppliers or to the Hospital Authority?
3. How does the hospital place a replenishment order? Via fax, internet, phone or any other means?
4. Does the hospital review the inventory level of the healthcare apparel products regularly? If yes, how often?
5. Is there any information system for keeping track of the real time inventory level at the central warehouse/department storeroom?
6. a. How many healthcare apparel products are ordered each time?

   b. Is the order quantity fixed?

c. What are the factors to determine the order quantity?

7. a. Does the hospital keep excess amount of healthcare apparels to prevent demand and delivery time uncertainty? If yes, what is the proportion of this safety stock?

   b. How does the hospital determine the quantity of safety stock?

8. a. Is there any shortage of the healthcare apparel products? If yes, how frequent does it happen?

   b. How does the hospital react to the shortage?

9. a. How long is the product delivery lead time? It depends on the products and the delivery schedule of the suppliers.

   b. Is it stable?

10. a. Is there any outsourcing service when managing the healthcare apparel products? If yes, what kinds of healthcare apparel products are outsourced?

    b. What are the reasons for outsourcing? Since the hospital is a small scale one which does not have so much space, manpower, and capital to provide this service.

    c. Is there any sustainable cost saving?

11. Vendor Managed Inventory (VMI) system is a stock control system that the supplier takes the responsibility for inventory management at the customers' site and makes decision regarding replenishment. This system requires accurate information sharing between the suppliers (e.g. healthcare apparel manufacturers) and customers (e.g. hospital) on the current inventory level and the consumption rate.

    a. Is there any VMI system used for managing the healthcare apparels?

    b. What kinds of apparel products are managed by suppliers?

    c. Is the stock level at the hospital reduced? If yes, in what percent?

d. What are the perceived benefits using VMI system?

e. What are the difficulties when implementing VMI system?

12. Just-in-Time (JIT) system is another inventory management approach that requires the supplier (e.g. healthcare apparel manufacturers) to deliver the products just-in-time to be used. The customer (e.g. the hospital) has to further break down the bulky supplies into proper units of cases for the consumption. The objective of this system is to minimize the stocking quantity to a level that satisfies the customer demand (i.e. demand of the hospital).

    a. Is there any JIT system for managing healthcare apparel products?

    b. What kinds of healthcare apparel products are using JIT system?

    c. What are the difficulties when implementing JIT system?

    d. Does the hospital really keep the minimal amount of healthcare apparel products?

    e. Where does the supplier locate?

Part V: Information and communication technology

1. Do you use bar-coding/RFID system for keeping track of the inventory?
2. Is there any issue on error/accuracy of this system?
3. What is the rate of error/accuracy?
4. a. Can you locate what you want to find easily for healthcare apparels?

    b. Are there missing stocks?
5. Is inventory visibility well-achieved?

Appendix B – Mathematical Derivations and Proofs for Chapter 5

(B1) Detailed Derivations for Section 5.2

According to the Iglehart and Morey (1972), the amount of safety stock required is derived as:

$\xi_i(N_i) = \sigma_i \sqrt{N_i}\,\gamma(s)$,

where $\gamma(s) = \Phi^{-1}((1-(s/2)) > 0$ and $i \in \{B, R\}$. (B.1)

The total inventory cost per period with $\xi_i(N_i)$ is denoted by $K_i(N_i)$, and it is given as follows,

$K_i(N_i) = h\xi_i(N_i) + (C_1 + C_2T_i)/N_i$, $i \in \{B, R\}$. (B.2)

When (B.1) is substituted into (B.2),

$K_i(N_i) = h\sigma_i\sqrt{N_i}\gamma(s) + (C_1 + C_2T_i)/N_i$, and the optimal N_i which minimizes $K_i(N_i)$, is denoted as N_i^*, by solving the first order condition of $K_i(N_i)$:

$$dK_i(N_i)/dN_i = 0 \Rightarrow 0.5h\sigma_i\gamma(s)N_i^{-0.5} - (C_1 + C_2T_i)N_i^{-2} = 0$$

$$N_i^{\frac{3}{2}} = (C_1 + C_2T_i)/\left(0.5h\sigma_i\gamma(s)\right)^{-1}$$

$$N_i^* = \left(\frac{C_1 + C_2T_i}{0.5h\sigma_i\gamma(s)}\right)^{2/3} \quad . \quad \text{(B.3)}$$

Now, it is proceed to further check the second order condition of $K_i(N_i)$ to determine the condition that the total inventory cost per period is minimized:

$$d^2K_i(N_i)/dN_i^2 = -0.25h\sigma_i\gamma(s)N_i^{-1.5} + 2(C_1 + C_2T_i)N_i^{-3}$$

$$d^2K_i(N_i)/dN_i^{\,2} = \frac{1}{N_i^2}\left(\frac{2J_i}{N_i} - \frac{h\xi_i(N_i)}{4}\right)$$

$$\therefore \text{ If } \left(\frac{J_i}{N_i} - \frac{h\xi_i(N_i)}{8}\right) > 0, \qquad \text{(B.4)}$$

then $K_i(N_i)$ is a convex function.

Since $J_i / N_i > h\xi_i(N_i)$, (B.4) holds and hence $K_i(N_i)$ is a strictly convex function.

Now, if (B.3) is put into (B.2), it will yield the optimal total cost for employing a scanning system $i \in \{B, R\}$,

$$K_i(N_i^*) = h\sigma_i\left(\frac{C_1 + C_2T_i}{0.5h\sigma_i\gamma(s)}\right)^{\frac{2}{3}\cdot\frac{1}{2}} \gamma(s) + (C_1 + C_2T_i)\left(\frac{0.5h\sigma_i\gamma(s)}{C_1 + C_2T_i}\right)^{\frac{2}{3}}$$

$$K_i(N_i^*) = 3(C_1 + C_2T_i)^{\frac{1}{3}}\left(0.5h\sigma_i\gamma(s)\right)^{\frac{2}{3}}$$

$$K_i(N_i^*) = l\alpha_i\sigma_i^{\frac{2}{3}}. \qquad \text{(B.5)}$$

where $\alpha_i = (C_1 + C_2T_i)^{\frac{1}{3}}$, (B.6)

$$l = 3(0.5h\gamma(s))^{\frac{2}{3}}. \qquad \text{(B.7)}$$

(Q.E.D.)

(B2) Detailed Derivations for Section 5.5

The profit of the supplier depends on the corresponding amount of safety stock that the healthcare organization will hold. The effective profit of the supplier with respective to the healthcare organization's choice of scanning system is:

$$\pi_i = (w - c)\xi_i(N_i^*), \quad i \in \{B, R\}. \qquad \text{(B.8)}$$

The difference of the safety stock requirement between two scanning system is denoted as:

$$\Delta S = \xi_R(N_R^*) - \xi_B(N_B^*) . \tag{B.9}$$

By putting (A.3) and (A.1) back to (A.8), it becomes

$$\Delta S = \frac{\alpha_R \sigma_R^{\frac{2}{3}} (\gamma(s))^{\frac{2}{3}}}{(0.5h)^{\frac{1}{3}}} - \frac{\alpha_B \sigma_B^{\frac{2}{3}} (\gamma(s))^{\frac{2}{3}}}{(0.5h)^{\frac{1}{3}}}$$

$$\Delta S = \alpha_R \sigma_R^{\frac{2}{3}} (\gamma(s))^{\frac{2}{3}} \left[\frac{3^{\frac{1}{2}} (\gamma(s))^{\frac{1}{3}}}{l^{\frac{1}{2}}} \right] - \alpha_B \sigma_B^{\frac{2}{3}} (\gamma(s))^{\frac{2}{3}} \left[\frac{3^{\frac{1}{2}} (\gamma(s))^{\frac{1}{3}}}{l^{\frac{1}{2}}} \right]$$

$$\Delta S = \frac{\sqrt{3}\gamma(s)}{\sqrt{l}} (\Omega - \delta) . \tag{B.10}$$

The profit change of each party in the supply chain when the healthcare organization changes the scanning system from *B* to *R* is evaluated as follows:

(a) When a wholesale pricing contract is executed in the supply chain, the healthcare organization (O) switches from B to R due to its better scanning performance, and it will attain cost saving $\Delta\pi_{O,R}$ as follows:

$$\Delta\pi_{O,R} = [K_B(N_B^*) - K_R(N_R^*)] + w[\xi_B(N_B^*) - \xi_R(N_R^*)], \textit{ where } \xi_R(N_R^*) < \xi_B(N_B^*)$$

$$\Delta\pi_{O,R} = -\Delta K - w\Delta S \tag{B.11}$$

The supplier (S) will suffer from selling fewer safety stocks and the supplier's profit change $\Delta\pi_{S,R}$ is shown as below:

$$\Delta\pi_{S,R} = (w-c)\xi_R(N_R^*) - (w-c)\xi_B(N_B^*) , \textit{ where } \xi_R(N_R^*) < \xi_B(N_B^*)$$

$$\Delta\pi_{S,R} = (w-c)\Delta S . \tag{B.12}$$

Now, the profit change of the entire supply chain (SC) before the surplus sharing contract executed is denoted as $\Delta\pi_{SC,R}$:

$$\Delta\pi_{SC,R} = -\Delta K + w\Delta S + (w-c)\Delta S$$

$$\Delta\pi_{SC,R} = -\Delta K - c\Delta S \text{, } where\, \Delta K < 0 \;\; and \;\; \Delta S < 0 \text{.} \qquad \text{(B.13)}$$

(b) If a surplus sharing contract is executed in the supply chain, the healthcare organization will share a fraction of surplus from inventory cost with the supplier, but enjoy a lower wholesale price. Assume the order quantities of using bar-coding and RFID system are $I + \xi_B(N_B^*)$ and $I + \xi_R(N_R^*)$, respectively, where I is the cycle stock level. The surplus of the healthcare organization (O) with surplus sharing contract (SS) is denoted as $\Delta\pi_{O,R}^{SS}$:

$$\Delta\pi_{O,R}^{SS} = (1-f)\,[K_B(N_B^*) - K_R(N_R^*)] + w[I + \xi_B(N_B^*)] - w_S[I + \xi_R(N_R^*)]$$

$$\Delta\pi_{O,R}^{SS} = -(1-f)\,\Delta K + (w - w_S)I + w\xi_B(N_B^*) - w_S\xi_R(N_R^*) \text{.} \qquad \text{(B.14)}$$

The corresponding profit change of the supplier (S) with the surplus sharing contract (SS) is :

$$\Delta\pi_{S,R}^{SS} = f\,\,[K_B(N_B^*) - K_R(N_R^*)] + (w_S - c)[I + \xi_R(N_R^*)] - (w-c)[I + \xi_B(N_B^*)]$$

$$\Delta\pi_{S,R}^{SS} = -f\Delta K - (w - w_s)I - w\xi_B(N_B^*) + w_S\xi_R(N_R^*) - c\Delta S \;\; \text{.} \qquad \text{(B.15)}$$

The profit change of the entire supply chain (SC) with surplus sharing (SS) contract is represented by $\Delta\pi_{SC,R}^{SS}$:

$$\Delta\pi_{SC,R}^{SS} = -(1-f)\,\Delta K + (w - w_S)I + w\xi_B(N_B^*) - w_S\xi_R(N_R^*) - f\Delta K - (w - w_s)I$$

$$- w\xi_B(N_B^*) + w_S\xi_R(N_R^*) - c\Delta S$$

$$\Delta\pi_{SC,R}^{SS} = -\Delta K - c\Delta S \text{, } where\, \Delta K < 0 \;\; and \;\; \Delta S < 0 \text{.} \qquad \text{(B.16)}$$

(B3) Detailed Proofs of Lemma 5.3 and Lemma 5.4:

Proof of Lemma 5.3. First, from Lemma 5.2b, it is noticed that the bar-coding system outperforms the RFID system if and only if $\Omega > \delta$. As a result, it implies that:

$$\Omega > \delta \Leftrightarrow \alpha_R \sigma_R^{\frac{2}{3}} > \alpha_B \sigma_B^{\frac{2}{3}} \quad \Leftrightarrow \rho_{B/R} < \tau^2{}_{R/B}. \tag{B.17}$$

Second, since $T_B > T_R$ and $\sigma_R > \sigma_B$, hence, $\tau_{R/B} > 1$ and $\rho_{B/R} > 1$. Moreover, $\tau^2_{R/B} > \rho_{B/R} > 1$. Thus, (B.17) implies the following:

$$\rho_{B/R} < \tau^2{}_{R/B} \Rightarrow \Omega > \delta. \qquad \text{(Q.E.D.)}$$

Proof of Lemma 5.4. Under Case 1, the healthcare organization and the supplier will be benefited if $\Delta K < 0$ (i.e. $\Omega < \delta$) and $\Delta S > 0$ (i.e. $\Omega > \delta$) respectively and vice versa under Case 2. (Q.E.D.)

Appendix C – Mathematical Derivations and Proofs for Chapter 6

(C1) Detailed Proofs

Proof of Proposition 6.1. Based on Eq. (6.12), the expression of the second order condition is:

$$\frac{d^2 EP_{1,H}^{\ell}(n_\ell)}{dn_\ell^2} = -\frac{1}{4}\delta\left(r\psi[\Phi^{-1}(s)] + c\Phi^{-1}(s)\right)\left(\frac{d_0}{\delta + n_\ell d_0}\right)^3 \left(\frac{\delta d_0}{\delta + n_\ell d_0} + \delta\right)^{-\frac{3}{2}} \left(\frac{3\delta d_0}{\delta + n_\ell d_0} + 4\delta\right).$$

Therefore, $EP_{1,H}^{\ell}(n_\ell)$ is a strictly concave function for n_ℓ>0 and a unique optimal number of market observation exists. (Q.E.D.)

Proof of Proposition 6.2. With Eq. (6.14), the RFID system outperforms the bar-coding system under the QRS when $EVI_R^* - EVI_B^* > 0$ $\Leftrightarrow r(\sigma_{1,n_B^*} - \sigma_{1,n_R^*})\{\psi[\Phi^{-1}(s)] + c\Phi^{-1}(s)\} - (k_R n_R^* - k_B n_B^*) - (w_R - w_B) > 0$ $\Leftrightarrow$ $\frac{(k_R n_R^* - k_B n_B^*) + (w_R - w_B)}{\sigma_{1,n_B^*} - \sigma_{1,n_R^*}} < r\psi[\Phi^{-1}(s)] + c\Phi^{-1}(s) \Leftrightarrow \rho < \Omega$, where Ω is a constant that is greater than 0 for $s > 0.5$. This relationship illustrates that the hospital should switch to the RFID system when the operational cost factor associated with the RFID system ρ is smaller than the cost threshold Ω. Besides, it also reveals that ρ depends not only on the reduced demand variance (i.e., $\sigma_{1,n_B^*} - \sigma_{1,n_R^*}$) but also the relative increased information acquisition cost associated with RFID system (i.e., $(k_R n_R^* - k_B n_B^*) + (w_R - w_B)$; in other words, the hospital still needs to compare (1) the system information acquisition cost difference and (2) the demand variance difference simultaneously between the two systems to determine the value of ρ and compare it with Ω). (Q.E.D.)

Proof of Lemma 6.3. (a) is a simple reflection from Eq. (6.23). (b) From Eq. (6.24), it reveals that the supplier will suffer when $\Delta EP_M < 0$. Since $(c-m) > 0$, $\Phi^{-1}(s) > 0$ for $s > 0.5$, and $\sigma_{1,n_R^*} < \sigma_0$ (P.S.: $d_1 < d_0$), we have $\Delta EP_M < 0$. On the other hand, the optimal order quantity of the hospital under the QRS is $q_1^* = \mu_0 + \sigma_{1,n_\ell}\Phi^{-1}(s)$ while that under the SRS is $q_0^* = \mu_0 + \sigma_0\Phi^{-1}(s)$, it is obvious that $q_1^* < q_0^*$. (c) By comparing ΔEP_{H+M}^R and ΔEP_{SC}^R , we can observe that the decentralized SC can achieve coordination when $s = s_{SC}$. This can be accomplished if the supplier is willing to supply the products at cost (i.e., set $c = m$) because $s = (r-c)/r$ and $s_{SC} = (r-m)/r$.

(Q.E.D.)

Proof of Lemma 6.4. First, $\zeta(\cdot)$ is a monotonic increasing function as its first order condition, and is always greater than zero because $s^{SCP} > s > 0.5$. Thus, $\zeta^{-1}(\cdot)$ exists and it is a monotonic increasing function with which $s_{H,EP} \geq s^{SCP}$ for $\Delta EP_H^{R,SCP} \geq 0$. Second, it is known that both $\Phi(\cdot)$ and $\Phi^{-1}(\cdot)$ are increasing functions. When consider achieving $\Delta VP_H^{R,SCP} \leq 0$, it will result in $s^{SCP} \leq \Phi[\hat{\xi}^{-1}(s_{M,VP})]$. Given that $s_{M,EP} < s_{H,EP}$, (i) if $s_{M,VP} > 1$, it is always true for $s^{SCP} < \Phi[\hat{\xi}^{-1}(s_{M,VP})]$ because $\hat{\xi}(\cdot) \leq 1$; (ii) if $s_{M,VP} \leq 1$ and

$s_{H.EP} \neq s_{VP,EP}$, it is to find the range of the solution which satisfies $s^{SCP} \leq s_{H,EP}$ and $s^{SCP} \leq s_{VP,EP}$; and hence $s_{M.EP} < s^{SCP} \leq \min\{s_{H,EP}, s_{H,VP}\}$; (iii) if $s_{M,VP} \leq 1$ and $s_{H,EP} = s_{H,VP}$, $\Delta EP_H^{R,SCP} > 0$ and $\Delta VP_H^{\ell,SCP} < 0$ are resulted when $s_{H,EP} > s^{SCP}$. (Q.E.D.)

Proof of Proposition 6.5. By setting the inventory service at the level that is the same as the optimal decision from the entire supply chain's perspective (i.e., s_{sc}), then the hospital will order at the supply chain's optimal quantity. An optimal supply chain and MV win-win situation is achieved if Lemma 6.2 holds and $s_{M,EP} < s_{sc} < s_{H,EP}$. (Q.E.D.)

Proof of Lemma 6.6. Under the MV win-win situation, the hospital has to get $\Delta EP_H^{R,MQPCP} > 0$ and $\Delta VP_H^{R,MQPCP} \leq 0$. To achieve $\Delta VP_H^{R,MQPCP} \leq 0$, i.e., $r\{\sigma_{1,n_R^*}^2 \hat{\xi}[\Phi^{-1}(s_{sc})] - \sigma_0^2 \hat{\xi}[\Phi^{-1}(s)]\} < 0 \;\Leftrightarrow\; \hat{\xi}[\Phi^{-1}(s_{sc})] < \lambda \;\Leftrightarrow s_{sc} < \beta$, the hospital has to carefully check the inventory service level s_{sc} being committed and ensure that $s_{sc} < \beta$. As the $\Delta EP_H^{R,MQPCP}(c_1 + \Delta) - \Delta EP_H^{R,MQPCP}(c_1) < 0$ for $s_{sc} > 0.5$, $\Delta EP_H^{R,MQPCP}(c_1)$ is a decreasing function of c_1 and it implies $c_1 \leq c_H$ for $\Delta EP_H^{R,MQPCP}(c_1) \geq 0$. Regarding the supplier, it has to achieve $\Delta EP_M^{MQPCP}(c_1) > 0$ since $\Delta VP_M^{MQPCP} = 0$. Because $\Delta EP_M^{MQPCP}(c_1 + \Delta) - \Delta EP_M^{MQPCP}(c_1) > 0$ for $s_{sc} > 0.5$, $\Delta EP_M^{MQPCP}(c_1) > 0$ is an increasing function of c_1 and it means $c_1 > c_M$ for $\Delta EP_M^{MQPCP}(c_1) > 0$. To avoid trivial case, it assumes that $c_1 \le r$. By combining $c_1 \le c_H$, $c_1 > c_M$ and $c_1 \le r$, the condition to achieve an MV win-win situation is properly setting the wholesale price within the range of $c_M < c_1 \le \overline{c_H}$. (Q.E.D)

Proof of Proposition 6.9. (a) If Proposition 6.2 holds, it implies that the RFID system outperforms the bar-coding system no matter it is used for making ordering decision for one or multiple healthcare apparel products. Besides, it also means that the RFID system outperforms the hybrid system because the hybrid system incorporates both the bar-coding and the RFID systems. (b) If bar-coding system outperforms the RFID system when it is used for manage one single product, it will also dominate the RFID and hybrid systems when it comes to manage multiple products, and hence, the hybrid system is always not the best decision to the hospital. (Q.E.D)

<u>Appendix (C2): Finding the optimal *n*</u>

As a remark, as a shortcut to estimate the value of n_ℓ^*, the upper bound (UB) and lower bound (LB) of n_ℓ^* can be analytically be derived. Obviously, having the analytical UB and LB helps to identify n_ℓ^* quickly (by any numerical searching method such as the bisection method). Define: $\alpha = 0.5\delta\{c\Phi^{-1}(s) + r\psi[\Phi^{-1}(s)]\}$.

The UB of the optimal n_ℓ^* is:

$$n_\ell^* < (\alpha k_\ell^{-1})^{1/2} - \delta\sigma_0^{-2}, \quad \text{(C.1)}$$

while the LB of the optimal n_ℓ^* is:

$$n_\ell^* > \delta^{-1}(\alpha k_\ell^{-1})^{1/2} - \delta\sigma_0^{-2} - 1. \tag{C.2}$$

Both (C.1) and (C.2) incur an error on estimating the boundary of the optimal n_ℓ^*. The following is the expression of maximum error of the boundary estimation:

$$\varepsilon_{mazx} = (1-\delta^{-1})(\alpha k_\ell^{-1})^{1/2} + 1. \tag{C.3}$$

As a remark, since n_ℓ must be an integer and the optimal integer valued n_ℓ must be on the neighborhood of n_ℓ^*, one can simply compare the expected profit $EP_{1,H}^\ell(n_\ell)$ at each one of these two neighbors to find the globally optimal integer valued n_ℓ. The optimal (integer valued) n_ℓ for the RFID system and bar-coding system cases is represented by n_R^* and n_B^*, respectively.

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