Expert Systems with Applications 40 (2013) 3389–3397

Contents lists available at SciVerse ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Supply chain management with lean production and RFID application: A case study

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ARTICLE INFO

Keywords:
RFID
Lean production
Supply chain management

ABSTRACT

This study applies lean production and radio frequency identification (RFID) technologies to improve the efficiency and effectiveness of supply chain management. In this study, a three-tier spare parts supply chain with inefficient transportation, storage and retrieval operations is investigated. Value Stream Mapping (VSM) is used to draw current state mapping and future state mapping (with lean production and RFID) with material, information, and time flows. Preliminary experiments showed that the total operation time can be saved by 81% from current stage to future stage with the integration of RFID and lean. Moreover, the saving in total operation time can be enhanced to 89% with cross docking. In addition, utilizing RFID technology, the cost of labors can be significantly reduced while maintaining current service capacity at the members in the studied supply chain. Return-on-investment (ROI) analysis shows that the proposed method is both effective and feasible.

1. Introduction

Substantial competition force companies to ensure customers' demands can be satisfied as much as possible at the lowest cost. Therefore, companies attempt to develop new solutions to improve the quality of their supply chains and simultaneously reduce their operational costs. In the past decades, radio frequency identification (RFID) technologies have attracted considerable attentions (Sarac, Absi, & Dauzère-Pérès, 2008). Currently, RFID is emerging as an important technology for revolutionizing a wide range of applications including supply chain management. Numerous organizations are planning to, or have already adopted RFID in their operations in order to take advantage of a more automated and efficient business processes (Sheng, Zeadally, Mitrokotsa, & Maamar, 2011).

Lean production was introduced by Toyota under the names "Toyota production system (TPS)" or "just-in-time (JIT)" manufacturing in the 1960s (Bruun & Mefford, 2004; Reichhart & Holweg, 2007; Taj, 2008; Wu, 2003). JIT manufacturing aims to eliminate waste and to improve their productions by using a continuous improvement approach, including maintaining the only required inventory and reducing setup times to decrease lead times, queue lengths, and lot sizes to reach minimum cost. Lean production enables the integration of various tools in the production system and supply chain and focuses on waste elimination to reduce costs, improve quality, and decrease lead time, inventory, and equipment downtime. Numerous enterprises have applied lean production to improve their productivity and competitiveness over the past decades.

This study explores the application of lean production and RFID technology for improving the logistics efficiency in a three-tier spare parts supply chain. This supply chain consists of a head quarter (HQ), one central distribution center (CDC), 10 local distribution centers (LDCs), and repair shops (RSs). HQ and CDC are responsible for supplying spare parts to ten LDC on a daily basis, and these LDC in turn supply spare parts to more than 400 local RS. HQ has an Information System (IS) and each CDC, LDC, and RS has a Warehouse Management System (WMS). There exist space for improvement in current operations with both information flow and material flow among the members in the studies supply chain, and therefore this research adopts lean production and RFID to increase the effectiveness and efficiency.

Preliminary experiments show that about 99.5% average reading rate was achieved with a fixed Ultra-High Frequency (UHF) RFID reader and four antennas installed in CDC and LDC receiving/shipping docks and UHF passive tags mounted on cartons or pallets. The benefit and cost of using RFID in the supply chain management are analyzed and promoted, e.g., increasing the whole supply chain efficiency and decreasing labor cost. Furthermore, this study uses return-on-investment (ROI) analyses to show that RFID implementation is effective and feasible.

The remainder of the paper is organized as follows. Section 2 presents a review of relevant literature, and Section 3 analyses the supply chain operations without RFID. Section 4 redesigns a new supply chain process with lean and RFID, and Section 5

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http://dx.doi.org/10.1016/j.eswa.2012.12.047

evaluates the efficiency improvement and provides ROI analysis. Finally, Section 6 draws conclusions and proposes future research directions.

2. Literature review

In this section, literature related to RFID technology in supply chain applications, lean production and Value Stream Mapping (VSM), and ROI is reviewed.

2.1. RFID application in supply chain

RFID technologies offer several contributions to supply chain through their advanced properties such as unique identification of products, easiness of communication and real-time information (Michael & McCathie, 2005; Saygin, Sarangapani, & Grasman, 2007). The progress through RFID can be observed in different types of supply chains such as warehouse management, transportation management, production scheduling, order management, inventory management and asset management systems (Banks, Hanny, Pachano, & Thompson, 2007).

RFID can ameliorate the traceability of products and the visibility throughout the entire supply chain, and also can make reliable and speed up operational processes such as tracking, shipping, checkout and counting processes, leading to advanced inventory flows and more accurate information (Chow, Choy, Lee, & Lau, 2006; Sarac, Absi, & Dauzère-Pérès, 2010; Tajima, 2007). Companies can achieve better supply chain planning and management by integrating and storing more accurate data obtained through RFID technologies in their information technology systems (Whitaker, Mithas, & Krishnan, 2007). There is thus a strong link between IT applications and RFID technologies.

Bottani and Rizzi (2008) indicated that reengineering models increased possible benefits gained through RFID for all processes of distribution centers and retailers. Pigni and Ravarini (2008) analyzed the effects of RFID technologies in the fashion industry. They showed that RFID technology integration improved the system business process and provided an inter-organizational information system that promoted the efficiency and effectiveness of the entire supply chain. Ferrer, Dew, and Apte (2010) studied 21 RFID applications across a wide variety of industries. Their conclusion was that there were four common benefits: replacement of labor through automation, cycle time reduction, enabling self-service, and loss of prevention. Through these numerous benefits, RFID technologies can provide cost reduction, increased revenue, process improvement, service quality, etc. Lee, Ho, Ho, and Lau (2011) discussed demand and supply chain management and examined how RFID technology can enhance the responsiveness of the logistics workflow. They concluded that the synergy of using a combination of advanced technologies to form an integrated system can help achieve lean and agile logistics workflow. Lao et al. (2012) proposed an RFID-based system to help a distribution center to facilitate the food safety control activities. A real-time food management system was developed that integrated RFID technology and case-based reasoning technique for the distribution center operators in launching a food safety plan. The study concluded that the real time data capturing nature of RFID technology further improved the efficiency and timeframe requested for the actions.

An RFID-based system can provide real-time information to operators, manages, and supervisors in order to control actual situation in the supply chain. Therefore, they can manage customers' demands and timely adjust the production plan to improve the whole supply chain efficiency and effectiveness (Cheung, Cheung, & Kwok, 2012; Ko, Kwak, Cho, & Kim, 2011; Poon et al., 2011).

2.2. Lean production and VSM

Seth and Gupta (2005) presented that the goal of lean manufacturing is to reduce waste in human effort, inventory, time to market and manufacturing space to become highly responsive to customer demand while producing quality products in the most efficient and economical manner. This approach focused on the elimination of waste. Waste took many forms and can be found at any time and in any place. It may be found hidden in policies, procedures, process and product designs, and in operations. Waste consumes resources but does not add any value to the product.

Taj (2008) indicated lean thinking started off in manufacturing representing the meaning of 'manufacturing without waste', and waste can be anything other than the minimum amount of equipment, materials, parts, and working time that are essential to production. So and Sun (2010) emphasized that lean production was proved to be an effective tool for companies to improve continuously. Becoming a lean enterprise enabled manufacturers to improve throughput, reduce costs, and deliver shipment with shorter lead times.

Lasa, Castro, and Laburu (2009) pointed that one of the latest contributions of the lean production movement is the development of the VSM technique. It was introduced as a functional method to help practitioners rearrange manufacturing systems according to a lean perspective and was based on applying the different tools explained above in a systemic or holistic way (Pavnaskar, Gershenson, & Jambekar, 2003; Rother & Shook, 1998; Womack, Womack, & Jones, 2002). Abdulmalek and Rajgopal (2007) presented that a value stream is a collection of all actions (value added as well as non-value-added) that were required to bring a product (or a group of products that use the same resources) through the main flows, starting with raw material and ending with the customer. These actions considered the flow of both information and materials within the overall supply chain. As regards the real-world application of the technique, different practices have been developed and disseminated since VSM was created. Lasa et al. (2009) concluded that VSM was a suitable guide for the application of different lean techniques at a dock-to-dock level in serial production companies.

2.3. ROI analyses of RFID implementation in supply chains

Fleisch and Tellkamp (2005) indicated that there are several significant costs and benefits of RFID implementations. Thus, companies must decide whether to invest or not to acquire RFID technologies. Hence, ROI analyses are helpful to support decisions on the feasibility of RFID deployments. Sarac et al. (2008) showed RFID technologies can provide important benefits to companies. However, because of their high costs, integrating RFID technologies in companies still require important investigations. Furthermore, every company should perform its own ROI analysis, because an RFID technology can be more beneficial for a company than another technology and/or for another company's environment. In addition, the ROI analyses have often been studied through analytical models, simulations, case studies and experiments (Sarac et al., 2010).

Ustundag, Kılınç, and Cevikcan (2010) presented that for managers and professionals, it was very important to accurately measure the benefits of an RFID project in the planning phase. Using the most proper investment evaluation methods, the managers can take the accurate decisions on RFID implementation projects. Lee and Lee (2011) reported that net present value and ROI were commonly used to evaluate investment in new technologies. As there existed RFID technology uncertainties and risks such as global standardization, chip price, security and privacy and high investment costs, an accurate economic analysis prior to investment should be made.

3. The supply chain operations with neither lean nor RFID

3.1. Background

This three-tier spare parts supply chain is composed of HQ, 1 CDC, 10 LDCs, and more than 400 RS. HQ and CDC are responsible for supplying spare parts to ten LDC on a daily basis, and each LDC responsibly supplies spare parts to over forty local RS daily in its supported region.

As shown in Fig. 1, the order information flows from RS backward to the LDC and HQ, while the material flows in the reverse direction from the manufacturers forward to the CDC, LDC, and then to RS. If the inventory level is less than the reorder point (taking into account the safety stock and the average and variation of demands), the CDC will notify HQ to send purchase order (PO) to the manufacturers. One of the biggest challenges among these supply chain members is the long waiting time or delivery time of spare parts resulting in serious delay of the equipment repair at RS. The elimination or reduction of this long delivery time was one of the initial motivations for HQ to exam the potential benefit of lean production and RFID technologies.

3.1.1. HQ and CDC profile

HQ is responsible for controlling repair parts inventory level in CDC and processing procurement orders that can fulfill all LDC demands and in turn satisfy the requirement from RS. The HQ has an IS using traditional electronic data interchange (EDI) to communicate with CDC and data exchange to communicate with the local server of each of the ten LDC. When one LDC sends replenishment order (RO) to the HQ, the IS will issue the retrieval orders to CDC and this LDC, and then CDC will ship the spare parts to this LDC. HQ requires the feedback of information report from both CDC and LDC to track these parts and to confirm the supply process is completed.

The CDC owns eight warehouses and stores over 10 million parts of more than 10,000 types. Over 10,000 storage and retrieval operations are conducted for hundreds of part types daily. The CDC IS uses a barcode system to process and track cases and pallets. Manufacturers produce parts according to the PO from the HQ and deliver goods to the CDC for replenishment. The CDC operators are required to key in and transmit the receiving/retrieval information to update inventory level at both CDC WMS and HQ IS daily. Due to large amount of operations, the operators often have to work overtime to update status and feedback information.

3.1.2. LDC profile

Each LDC has a warehouse and is responsible for controlling repair parts inventory level and supplying repair parts to over forty local RS within their services region An LDC stores over 1 million parts of more than 6000 types. Over 1000 storage and retrieval operations for more than hundreds of part types are conducted daily. Each LDC has a WMS using barcode system to process and track cases and pallets.

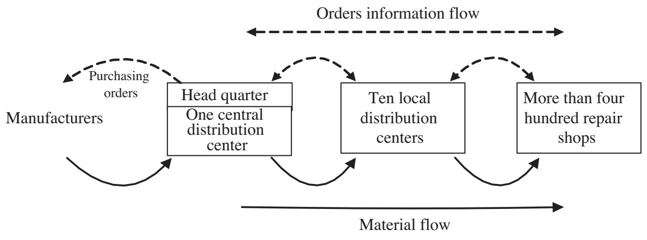


Fig. 1. The three-tier spare part supply chain with information and material flows.

Each request form RS is supplied from the inventory in the LDC warehouse. When the inventory level is lower than the reorder point, it triggers the placement of RO from LDC to the HQ. Once the replenishment goods are delivered by CDC to LDC, the goods information (order number, item, quantity, and receiving date) must be input to LDC WMS to update the inventory on hand. Additionally, the information must be transmitted to HQ as a report. Finally, the LDC needs to use the local server (with traditional EDI system) to communicate with each RS.

3.1.3. Repair shop profile

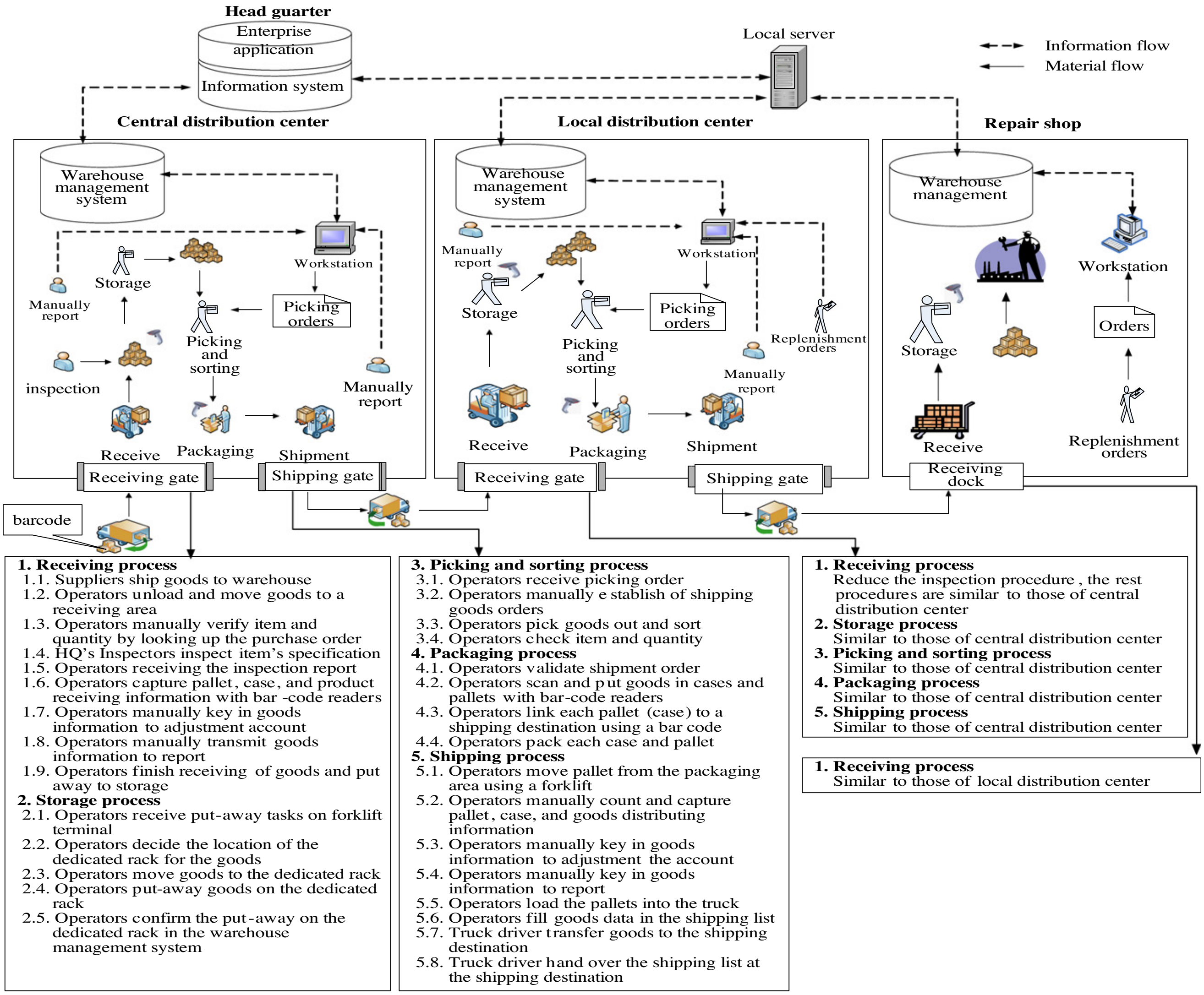
The RS is responsible for maintaining the local customers' equipment. Each of its warehouse stores over one thousand necessary repairs parts of about one hundred types. Repairers' demands are supplied from the inventory in RS local warehouses. When the inventory level is less than the reorder point, it triggers the RS to place RO to LDC. The LDC WMS will issue the retrieval order to supply RS based on the RO received and deliver parts to the RS for replenishment.

3.2. Current operation (as-is) analysis of the whole supply chain

Fig. 2 shows the typical functions performed by HQ, CDC, LDC, and RS with the flow of materials and information among these supply chain members. A series of operations are executed when a truck arrives in CDC and LDC receiving dock. First, operators unload the goods from the truck and manually verify the receiving of goods against PO/RO. HQ's inspector will inspect the specifications (only implemented in the CDC). Once the goods pass the inspection, operators will scan and key in goods information manually to update the inventory level and report. Second, operators sort and store goods to the warehouse. Third, operators pick and sort goods from the racks according to the pick list generated from the WMS. As there exist serious backlog of requests from RS in current operations, the spare parts do not stay long in the warehouse before they are retrieved for shipment. Fourth, operators validate, scan and pack the shipment goods. Fifth, operators manually verify of the shipping of goods against shipment order, and manually key in goods information to update the inventory level and report. Finally operators load the goods into a truck. It is observed in every warehouse the overall receiving, storage, picking and sorting, packaging, and shipping processes consist of 30 sub-processes, and most existing processes include numerous manual operations, such as data input (e.g., 1.7 and 1.8 in the receiving process and 5.3 and 5.4 in the shipping process), box/pallet scans (e.g., 1.6 in the receiving process and 4.2 in the packaging process), and count of boxes in each pallet (e.g., 1.3 in the receiving process and 5.2 in the shipping process).

In addition, the supply chain members communicate with each other via local servers which use a traditional EDI system for the data exchange. This batch-based model is executed (upload/download) only once per day, so the IS/WMS cannot provide timely and accurate information on a real-time basis. It is extremely time-consuming and inefficient in the operations of the silo-based legacy systems mode of information flow.

A VSM technique is used to draw current state mapping with material, information, and time flow, as shown in Fig. 3. It takes 1328.6 h (approximately 55.4 days) in total from the moment that goods are received by CDC to the moment that goods are shipped to RS. The waiting and transportation time in this process is about 1320.0 h. However the value-added time is only about 8.7 h. In current operation, it takes too long for both waiting and



1. Receiving process
1.1. Suppliers ship goods to warehouse
1.2. Operators unload and move goods to a receiving area
1.3. Operators manually verify item and quantity by looking up the purchase order
1.4. HQ's Inspectors inspect item's specification
1.5. Operators receiving the inspection report
1.6. Operators capture pallet, case, and product receiving information with bar-code readers
1.7. Operators manually key in goods information to adjustment account
1.8. Operators manually transmit goods information to report
1.9. Operators finish receiving of goods and put away to storage
2. Storage process
2.1. Operators receive put-away tasks on forklift terminal
2.2. Operators decide the location of the dedicated rack for the goods
2.3. Operators move goods to the dedicated rack
2.4. Operators put-away goods on the dedicated rack
2.5. Operators confirm the put-away on the dedicated rack in the warehouse management system

3. Picking and sorting process
3.1. Operators receive picking order
3.2. Operators manually establish of shipping goods orders
3.3. Operators pick goods out and sort
3.4. Operators check item and quantity
4. Packaging process
4.1. Operators validate shipment order
4.2. Operators scan and put goods in cases and pallets with bar-code readers
4.3. Operators link each pallet (case) to a shipping destination using a bar code
4.4. Operators pack each case and pallet
5. Shipping process
5.1. Operators move pallet from the packaging area using a forklift
5.2. Operators manually count and capture pallet, case, and goods distributing information
5.3. Operators manually key in goods information to adjustment the account
5.4. Operators manually key in goods information to report
5.5. Operators load the pallets into the truck
5.6. Operators fill goods data in the shipping list
5.7. Truck driver transfer goods to the shipping destination
5.8. Truck driver hand over the shipping list at the shipping destination

1. Receiving process
Reduce the inspection procedure, the rest procedures are similar to those of central distribution center
2. Storage process
Similar to those of central distribution center
3. Picking and sorting process
Similar to those of central distribution center
4. Packaging process
Similar to those of central distribution center
5. Shipping process
Similar to those of central distribution center

1. Receiving process
Similar to those of local distribution center

Fig. 2. Current supply chain operations (as-is model).

transportation. Two major wastes are thus identified and can be reduced or eliminated in following discussion.

After manufacturers deliver the goods according to the PO from HQ to CDC receiving dock, it takes an average of 42 days of waiting before the final acceptance. This includes about 24 days waiting for the specification inspection and about 18 days waiting for inspection report. The actual inspection time is less than 1 day. Furthermore, in both CDC and LDC the operators need to sequentially scan the barcode on each part in order to confirm the type and quantity in receiving, packaging, and shipping processes. They also need to key in the data into the local WMS to update the inventory on hand and transmit the information r report to HQ

The above processes directly lead to low efficiency in warehouse operations. Under time measurement by stop watch, it takes an average of 92.8 and 20 min to receive one type of goods and to store a part to the storage rack in CDC, 44 and 22 min in LDC, respectively. Moreover, it takes an average of 90, 35, and 90 min in CDC and 60, 30, and 30 min in LDC to pick, package, and ship goods, respectively. In summary, current warehouse operation in both CDC and LDC are inefficient as a result of poor management and slow manual operations which leads to low throughput, long lead time, and high labor cost.

4. Supply chain operations with lean and RFID

4.1. Reengineering the supply chain

In order to conduct reengineering to the process to a continuous flow with less congestion, waiting, and idleness, current waste on labor and time need to be eliminated. Three policies are adopted. First, HQ's inspector has to arrange the receiving schedule and delivery time according to the agreement with manufacturers. Since the manufacturers deliver the goods in accordance, the inspector can arrange the inspection schedule in advance and execute inspection on schedule. Besides, the HQ's executive can simplify the inspection document format and the approval procedure. After the inspector completes the inspection procedure and records the inspection result, the document can be approved and sent back to CDC on next day. Once the above operation processes are amended, the time for goods acceptance and storage to CDC can be shortened from 42 days to 2 days.

Second, the HQ changes the existing traditional proprietary EDI system to internet-based EDI system. Thus, the HQ and LDC as well as LDC and RS can directly communicate each other with real-time information flow in between, and the local server is no longer used to transmit information. Batch practices are also changed to a real-

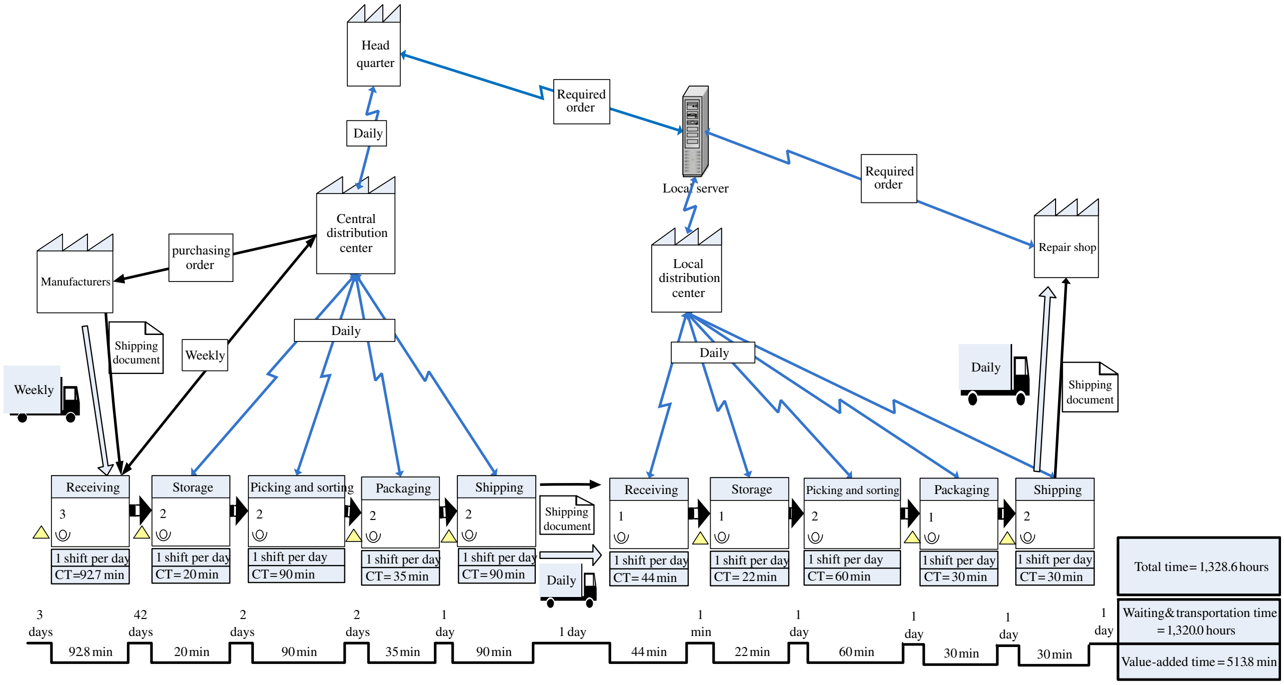


Fig. 3. VSM of current spare part supply chain.

time mode of operations. All information processing, including applications, replies, and receipts, are conducted on a real-time basis.

Third, HQ integrates RFID technology with information system and supply chain operation. In this study, an RFID reader is installed at the receiving and shipping dock to automatically capture the identities and data of RFID tags attached to the cartons and pallets. The reengineering operation process in CDC and LDC with pallet/case level tagging is shown in Fig. 4. The pallets/cases are identified through RFID reusable tags. Each receiving and shipping dock is equipped by an RFID reader that acts as a portal. Electronic Product Code (EPC) codes of pallets/cases can be read and the information is transmitted to WMS through Ethernet network on a real time basis. The data were manually collected by operators using traditional barcode, while it is automatically collected by the RFID system now. To compare the differences between "as-is" and "to-be" processes, the significant improvement are described in details as follows:

- The adoption of RFID technologies prompts CDC and LDC to change the way they conduct their activities by integrating activities, automating, or automatically performing some operation processes, such as changing from manual to automatic scanning of boxes and pallets (e.g., 1.4 in the receiving process and 5.2 in the shipping process), and cross-docking operation.
- The numbers of overall sub-processes are reduced from 30 to 22 in each warehouse. These include data entry, verification, and reporting in the receiving and shipping process. In addition, this automation provides accurate information, enabling efficiency measurements in real time and increasing the transparency of the flow of goods. This can have a significant impact on operational improvements by removing manual checks and eliminating mistakes caused by labor. The CDC and LDC could free their operators from non-value-added activities and allow them to concentrate on their core activities.
- RFID technologies can enable the HQ, CDC, and LDC to change their existing information system from a batch-based processing philosophy to a real-time execution and decision philosophy.

4.2. Assessment and deployment of RFID technology

In order to facilitate receiving and shipping process in the CDC and LDC, long RFID reading range of up to several meters is required. UHF RFID equipment operating between 922 MHz and 928 MHz ranges is adopted in this study, including fixed reader, handy reader, and passive tag. Fixed RFID reader and antennas are installed at receiving and shipping door, where two antennas are installed at each side of the door, 3 m in distance facing each other, and 3.45 m for lateral distance.

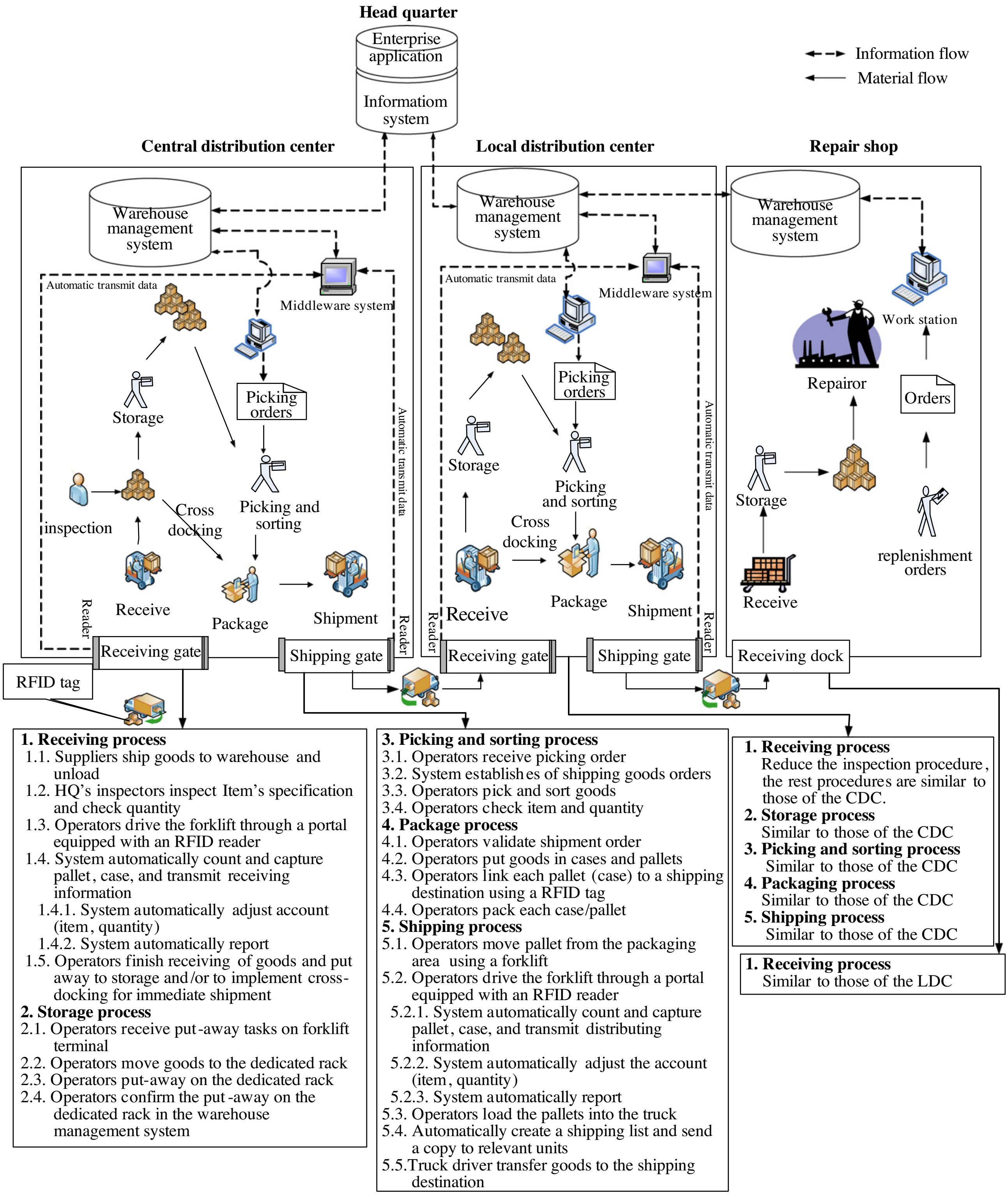
Passive tags are mounted on pallets or cartons. A tag consists of a chip used to store the identifying bit sequence and an antenna is used to communicate with the reader. The assembled chip and antenna of this passive tag sits on a 3 × 5 inch piece of material with a peel-and-stick adhesive backing. Multiple parts are stored in a carton which is packed on a pallet. One tag is used for one part of each type.

The information stored inside the tag is coding based on 16 bits of ASCII and each category can store 0–9 numbers and alphabetical A–F for English RFID. The RFID tag used in this study has a storage capacity of 12 bytes sufficient for storing 24 ASCII codes. The information stored in tag is a combination of part identification number, type, quantity, and adjustment date.

4.3. RFID reading rate test

One RFID reader can simultaneously read multiple tags mounted on cartons and pallets, and this is one of the major advantages of RFID application. However, this is also a major challenge in RFID application, as there is no guarantee of 100% reading rate due to radio frequency interference and metal shielding.

Having set up the RFID reader, the testing of reading rate of RFID reader is implemented. Different scenarios are planned and tested in CDC and LDC, respectively. For example, in one scenario, a total of 28 tags were tested for one pallet carrying four boxes with 2, 3, 4 and 19 different items, respectively. One tag is for one item and each item's tag is mounted outside the box with this item. As an-



1. Receiving process
- 1.1. Suppliers ship goods to warehouse and unload
- 1.2. HQ's inspectors inspect Item's specification and check quantity
- 1.3. Operators drive the forklift through a portal equipped with an RFID reader
- 1.4. System automatically count and capture pallet, case, and transmit receiving information
  - 1.4.1. System automatically adjust account (item, quantity)
  - 1.4.2. System automatically report
- 1.5. Operators finish receiving of goods and put away to storage and/or to implement cross-docking for immediate shipment

2. Storage process
- 2.1. Operators receive put-away tasks on forklift terminal
- 2.2. Operators move goods to the dedicated rack
- 2.3. Operators put-away on the dedicated rack
- 2.4. Operators confirm the put-away on the dedicated rack in the warehouse management system

3. Picking and sorting process
- 3.1. Operators receive picking order
- 3.2. System establishes of shipping goods orders
- 3.3. Operators pick and sort goods
- 3.4. Operators check item and quantity

4. Package process
- 4.1. Operators validate shipment order
- 4.2. Operators put goods in cases and pallets
- 4.3. Operators link each pallet (case) to a shipping destination using a RFID tag
- 4.4. Operators pack each case/pallet

5. Shipping process
- 5.1. Operators move pallet from the packaging area using a forklift
- 5.2. Operators drive the forklift through a portal equipped with an RFID reader
  - 5.2.1. System automatically count and capture pallet, case, and transmit distributing information
  - 5.2.2. System automatically adjust the account (item, quantity)
  - 5.2.3. System automatically report
- 5.3. Operators load the pallets into the truck
- 5.4. Automatically create a shipping list and send a copy to relevant units
- 5.5. Truck driver transfer goods to the shipping destination

1. Receiving process
Reduce the inspection procedure, the rest procedures are similar to those of the CDC.

2. Storage process
Similar to those of the CDC

3. Picking and sorting process
Similar to those of the CDC

4. Packaging process
Similar to those of the CDC

5. Shipping process
Similar to those of the CDC

1. Receiving process
Similar to those of the LDC

Fig. 4. Future supply chain operations (to-be model).

other example, an RFID tag is mounted on a pallet with multiple boxes of the same parts on it. Electric forklift and hydraulic cart are used to move the pallet for testing in the receiving/shipping process from manufacturers to CDC, and from CDC to LDC and also from LDC to RS. The tag's information including part identification number, types, reading antenna, and reading time. These are shown in the monitor screen while RFID tag is read by RFID reader. 30 and 15 tests are conducted for the reading rate in CDC and LDC, respectively. As a result, the average reading rate of CDC and LDC are 99.2% and 99.8%, respectively. 100% reading rate is achieved for tags mounted only on the pallets. The unread part can be done manually by handy reader to make up 100%.

4.4. Simulation with RFID system in CDC and LDC

The simulations with RFID system in receiving and shipping processes in CDC and LDC were conducted. Items with the high-demands, high-priority, and large quantity are first selected as the main objects for RFID implementation test. Through simulation, when RFID technology is used in the receiving and shipping process, manual activities such as counting or data input are omitted. Simulation test using RFID demonstrate that the average process time of receiving and shipping operation can be improved in both CDC and LDC.

Table 1 reveals significant increases in operation efficiency. The average time for goods receipt and check per operator per day is reduced from 88.9 to 16.2 min (with an improvement of 82%) and from 43.6 to 13.0 min (with an improvement of 70%) in CDC and LDC, respectively. In CDC, the average time for receipt and retrieval reporting (per order) is reduced from 10 s to 1 s and from 10.3 s to 1 s (both with an improvement of 90%), respectively. On the other hand, in LDC, the average time for receipt and retrieval reporting (per order) is reduced from 10.4 s to 1 s and from 10 s to 1 and 1 s (both with an improvement of 90%), respectively. With the above improvement, the operator headcount at each warehouse in CDC and LDC can be reduced by at least one while maintaining the original service capacity and level.

4.5. The future state (to-be) map

Fig. 5 shows the future state map with the integration of lean production and RFID technology in the new procedure. The original total operation time was 1328.6 h that can be reduced to 247.2 h by adopting lean production and RFID application with a saving of 1081.4 h. It can be observed that the average process time of receiving, storage, picking and sorting, packaging, and shipping were reduced from 92.8, 20, 90, 35, 90 to 18, 1, 80, 15, 0.5 and from 44, 22, 60, 30, 30 to 12.9, 0.1, 50, 12, 1.2 in CDC and LDC respectively. It is noted that with the application of RFID to facilitate the real-time data transmission to the WMS and the real-time reporting to HQ IS for quick approval, it becomes feasible to implement cross docking in CDC and LDC that was not possible before. With cross docking, after finishing the goods receiving in the inbound process, the operators can pick, pack and ship out the goods on the dock for the outbound process without moving them to the rack/storage area. Thus, the total operation time can be further reduced from 247.2 h to 147.7 h, with a further saving of 99.1 h. Fig. 6 presents the total time comparison. When CDC and LDC operators applied lean production and RFID technology, the total operation time can be reduced to 247.2 h (with an improvement of 81%). With cross docking operation on the basis of real-time data

Table 1
Operation time before and after the application of lean and RFID (without cross-docking) in CDC and LDC.

	Item	Unit	Time before lean and RFID adoption	Time after lean and RFID adoption	Improvement	Improvement percentage (%)
CDC	Average time for goods receipt and check (per operator per day)	min	88.9	16.2	−72.7	82
	Average time for receipt reporting (per order)	s	10.0	1.0	−9.0	90
	Average time for retrieval reporting (per order)	s	10.3	1.0	−9.3	90
LDC	Average time for goods receipt and check (per operator per day)	min	43.6	13.0	−30.6	70
	Average time for receipt reporting (per order)	s	10.4	1.0	−9.4	90
	Average time for retrieval reporting (per order)	s	10.0	1.0	−9.0	90

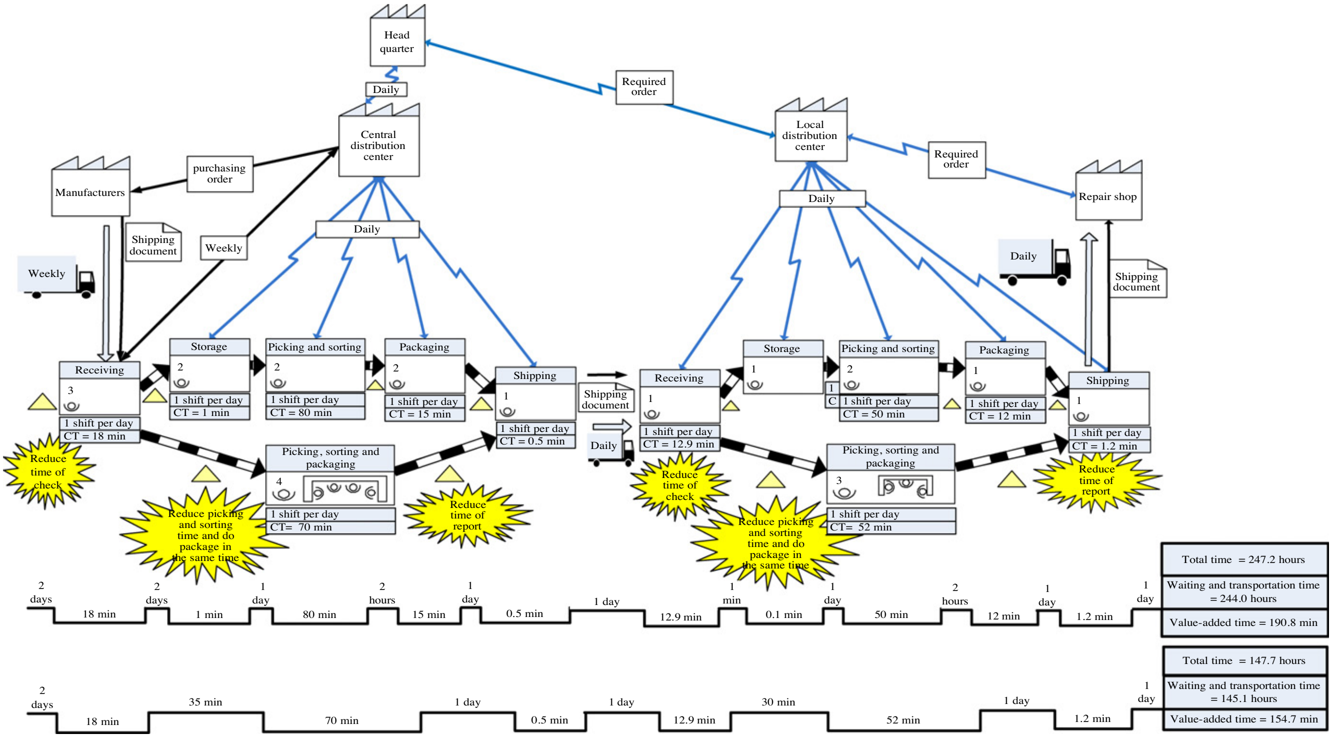


Fig. 5. VSM of future spare part supply chain.

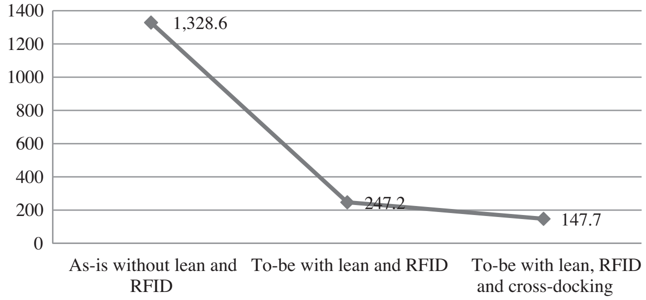


Fig. 6. Efficiency improvement of total operation time in three scenarios (in h).

communication with RFID, the total operation can be further reduced to 147.7 h (with an improvement of 89%).

5. Improvement evaluation and ROI analysis

5.1. Evaluation the efficiency improvement

In this study, RFID is integrated with lean production to improve warehouse operations. RFID systems are installed in eight CDC warehouses and 10 LDC warehouses and simulation of operations with RFID system is investigated. Table 2 illustrates the improvement of total supply chain operation time of three scenarios (i.e., as-is, to-be with lean and RFID, to-be with lean, RFID, and cross-docking), from the viewpoint of value-added as well as waiting and transportation time. The value-added time of CDC and LDC processes consists of receiving, storage, picking and sorting, packaging, shipping, and cross-docking, as shown in Figs. 2 and 4.

After the reengineering using lean production, the waiting and transportation time can be reduced from 1200 to 146 h and from 120 to 98 h (with improvement of 88% and 18%, respectively) from as-is scenario to to-be scenario with lean and RFID in CDC and LDC, respectively. Further improvement can be achieved to 72.6 and 72.5 h (with improvement of 94% and 40%, compared to as-is scenario) in the to-be scenario with lean, RFID, and cross-docking in CDC and LDC, respectively. The final waiting and transportation time is only 6% and 60% of the original version.

In addition to the saving of non-value added time such as waiting and transportation time majorly by the adoption of lean production, RFID can also significantly reduce the value-added time after reengineering. The value-added time can be reduced from 5.5 to 1.9 h and from 3.1 to 1.3 h (with improvement of 65% and 59%, respectively) from as-is scenario to to-be scenario with lean and RFID in CDC and LDC, respectively. Further improvement can be achieved to 1.5 and 1.1 h (with improvement of 73% and 65%, compared to as-is scenario) in the to-be scenario with lean, RFID, and cross-docking in CDC and LDC, respectively. The final value-added time is only 27% and 35% of the original version.

Summing up the above analysis of improvement in both CDC and LDC, the improvement in the entire supply chain is significant. After reengineering, the waiting and transportation time can be reduced from 1320 to 244, and finally to 145 h in the three scenarios (with an improvement of 82% and 89%, respectively). The final waiting and transportation time is only 11% of the original version. On the other hand, the value-added time can be reduced from 8.6 to 3.2, and finally to 2.6 h (with an improvement of 63% and 70%, respectively). The final value-added time is only 30% of the original version. In summary, saving of 89% and 70% on waiting and transportation time as well as value-added time can be achieved in to-be scenarios without and with cross-docking, respectively.

5.2. ROI analysis

ROI analysis is utilized to verify the investment of RFID technology and lean production application. Both hardware and software are assumed to be used for 5 years with straight-line depreciation policy. As interest rate is very low in these years, the discount rate is set as 0 to simplify the analysis. The total cost of RFID technology and lean production application consists of hardware (including PC, RFID reader, antenna, printer, label, and maintenance) as well as software, system integration, and training. Table 3 shows a rough estimation of the cost at HQ, CDC and LDC. The supply chain has one HQ, 1 CDC with 8 warehouses and 10 LDC, each with one warehouse. The average annual total cost of HQ, CDC and LDC is about USD 158,800.

The average annual cost of a typical operator working at HQ or in the warehouses of CDC and LDC is about USD 30,000, including salary, bonus, and overhead. As discussed in Section 4.4 and Table 1, each warehouse of CDC and LDC can reduce at least one operator due to the efficiency increase and elimination of the waste in waiting and transportation time. HQ can save at least one headcount due to the implementation of new IS. The annual saving is 30,000 multiplied by 19 = 570,000 considering the reduction of one operator in HQ and one operator in each of the eight CDC warehouses and ten LDC warehouses.

Eq. (1) presents the ROI formula considering the time value of money

$$\mathrm{ROI} = \frac{\sum_{t=0}^{n} \frac{B_t - C_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{C_t}{(1+i)^t}} \tag{1}$$

where t is the time period, C_t is the required average annual cost for time t, B_t is the average annual benefit, and i is the discount rate for the time value of money set to 0 reflecting the very low interest rate recently. According above the above analysis, these parameters become

$B_t = 570{,}000.$
$C_t = 158{,}800.$
$B_t - C_t = 411{,}200.$

Table 2
The comparison of supply chain operation time (with respect to waiting and transportation time as well as value-added time) of three scenarios: as-is with neither lean nor RFID, to-be with lean and RFID, and to-be with lean, RFID, and cross docking. Time is in hours and improvement percentage is shown in the parenthesis.

Item		As-is without lean and RFID	To-be with lean and RFID	To-be with lean, RFID and cross-docking
CDC	Total time	1205.5	147.9 (88%)	74.1 (94%)
	Waiting and transportation time	1200.0	146.0 (88%)	72.6 (94%)
	Value-added time	5.5	1.9 (65%)	1.5 (73%)
LDC	Total time	123.1	99.3 (19%)	73.6 (40%)
	Waiting and transportation time	120.0	98.0 (18%)	72.5 (40%)
	Value-added time	3.1	1.3 (59%)	1.1 (65%)
Supply chain	Total time	1328.6	247.2 (81%)	147.7 (89%)
	Waiting and transportation time	1320.0	244.0 (82%)	145.1 (89%)
	Value-added time	8.6	3.2 (63%)	2.6 (70%)

Table 3
Rough estimation of the cost at HQ, CDC and LDC (in USD). The supply chain has 1 CDC with 8 warehouses and 10 LDC, each with one warehouse.

Unit	Item	Unit price	Total price
HQ	IS (PC, software, system integration, training)	200,000	200,000
CDC	Hardware (PC, RFID reader, antenna, printer, label)	18,000	144,000
	Software, system integration, and training	15,000	120,000
LDC	Hardware (PC, RFID reader, antenna, printer, label)	18,000	180,000
	Software, system integration, and training	15,000	150,000
Total cost			794,000
Average annual total cost (5-year average)			158,800

$i = 0.$
$n = 5.$

The analysis results in ROI of 2.6 indicating a worthwhile investment of lean and RFID to this spare part supply chain.

6. Conclusion and future research

This research uses VSM to analyze the factors leading to insufficient supply chain operations and applies both lean production and RFID technology to improve supply chain efficiency and effectiveness. The preliminary results in a case study (with 1 CDC, 10 LDC, and more than 400 repair shops) demonstrate that the total operation time, from current stage to future stage with integration of lean and RFID, can be saved by 81% (with 82% saving in waiting and transportation time and 63% saving in value-added time). The saving can be further enhanced to 89% (with 89% saving in waiting and transportation time and 70% saving in value-added time) with the adoption of cross-docking. Furthermore, each warehouse can reduce at least one operator while maintaining current service capacity and level in both CDC and LDC. ROI analysis with a value of 2.6 justifies the effectiveness of lean production and RFID application. The result of this study is a good reference for further improvements in supply chain and logistics system through the use of better management philosophy and modern technology.

This study can be extended in several directions. With the spirit of lean production, the warehouses should conduct continuous improvement to further increase operational efficiency. It is of interest to apply RFID to transportation system to increase the traceability of deliveries. Moreover, it is important to further improve the reading rate of UHF RFID readers by adjusting the location and position of tags and the distance between tags and readers, as current 99.5% is still with space of improvement.

Acknowledgements

The authors would like to express their thanks to Mr. Ti-Chen Ting and Mr. Chien-Jung Huang for their work in the simulation and experiments of RFID technology implementation in distribution centers.

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