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Warehousing and Inventory Management in Dual Channel and Global Supply Chains

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Warehousing and Inventory Management in Dual Channel and Global Supply Chains

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Warehousing and Inventory Management in Dual Channel and Global Supply Chains

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DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

I. Co-Authorship Declaration

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

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

II. Declaration of Previous Publication

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

Thesis Chapter	Publication title/full citation	Publication status
Chapter 3	Alawneh, F., Zhang, G., 2018. Dual-channel warehouse and inventory management with stochastic demand. Transportation Research Part E, April 2018, Vol.112, pp.84-106.	Published
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ABSTRACT

More firms are adopting the dual-channel supply chain business model where firms offer their products to customers using dual-channel sales (to offer the item to customers online and offline). The development periods of innovative products have been shortened, especially for high-tech companies, which leads to products with short life cycles. This means that companies need to put their new products on the market as soon as possible. The dual-channel supply chain is a perfect tool to increase the customer's awareness of new products and to keep customers' loyalty; firms can offer new products online to the customer faster compared to the traditional retail sales channel. The emergence of dual-channel firms was mainly driven by the expansion in internet use and the advances in information and manufacturing technologies. No existing research has examined inventory strategies, warehouse structure, operations, and capacity in a dual-channel context.

Additionally, firms are in need to integrate their global suppliers base; where the lower parts costs compensate for the much higher procurement and cross-border costs; in their supply chain operations. The most common method used to integrate the global supplier base is the use of cross-dock, also known as Third Party Logistic (3PL). This study is motivated by real-world problem, no existing research has considered the optimization of cross-dock operations in terms of dock assignment, storage locations, inventory strategies, and lead time uncertainty in the context of a cross-docking system.

In this dissertation, we first study the dual-channel warehouse in the dual-channel supply chain. One of the challenges in running the dual-channel warehouse is how to organize the warehouse and manage inventory to fulfill both online and offline (retailer) orders, where the orders from different channels have different features. A model for a dual-channel warehouse in a dual-channel supply chain is proposed, and a solution approach is developed in the case of deterministic and stochastic lead times. Ending up with numerical examples to highlight the model's validity and its usefulness as a decision support tool.

Second, we extend the first problem to include the global supplier and the cross-border time. The impact of global suppliers and the effect of the cross-border time on the dual-channel warehouse are studied. A cross-border dual-channel warehouse model in a dual-channel supply chain context is proposed. In addition to demand and lead time uncertainty, the cross-border time

is included as stochastic parameter. Numerical results and managerial insights are also presented for this problem.

Third, motivated by a real-world cross-dock problem, we perform a study at one of the big 3 automotive companies in the USA. The company faces the challenges of optimizing their operations and managing the items in the 3PL when introducing new products. Thus, we investigate a dock assignment problem that considers the dock capacity and storage space and a cross-dock layout. We propose an integrated model to combine the cross-dock assignment problem with cross-dock layout problem so that cross-dock operations can be coordinated effectively. In addition to lead time uncertainty, the cross-border time is included as stochastic parameter. Real case study and numerical results and managerial insights are also presented for this problem highlighting the cross-border effect.

Solution methodologies, managerial insights, numerical analysis as well as conclusions and potential future study topics are also provided in this dissertation.

DEDICATION

To the soul of my parent. To my brothers, sisters, and my entire family especially my brother Arafat for their help through my Ph.D. journey. To my extraordinary wife Ahlam for her support, love, and patience. My purest love to my baby Amr.

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LIST OF ABBREVIATIONS/SYMBOLS

CFIA: Canadian Food Inspection Agency

COI: Cube-per Order Index

DC: Distribution center

EDI: Enhanced Driving License

EPC: Electronic Product Code

ERP: Enterprise Resource Planning

FAST: Free and Secure Trade

FDA: U.S. Food and Drug Administration

GAMS: General Algebraic Modeling System

GPS: Global positional system

IT: Information Technology

LTL: Less-than-truckload

MIP: Mixed-integer programming

NAFTA: North American Free Trade Agreement

NEXUS: Trusted Traveler Program

NFC: Near Field Communication

3PL: Third Party Logistic Provider

RFID: Radio Frequency Identification

R,Q: Continuous Review Policy

R,T: Periodic Review Policy

UCR: Unique Consignment Reference

USDA: U.S. Department of Agriculture

CHAPTER 1: INTRODUCTION

There is an enormous and urgent need to adapt the current supply chain strategies and operations to the new digital era. The development periods of innovative products have been shortened, especially for high-tech companies, which leads to products with short life cycles. This means that companies need to put their new products on the market as soon as possible. The dual-channel supply chain (to offer the item to customers online and offline) is a perfect tool to increase the customer's awareness of new products and to keep customers' loyalty; firms can offer new products online to the customer faster compared to the traditional retail sales channel. The emergence of dual-channel firms was mainly driven by the expansion in internet use and the advances in information and manufacturing technologies providing a competitive advantage to the supply chain (Gunasekaran et al., 2017).

Consequently, supply chain processes must be designed to be able to operate in the new digital world by taking into consideration customer expectations, for example, the possibility of ordering products online, and a volatile demand market. All components, such as products, machines, raw material, and handling equipment are connected via Radio Frequency Identification (RFID) or sensors to other components and display an increasing degree of intelligence and autonomy. Every link of the supply chain, including purchasing, production, transportation, warehouse storage, distribution centers, sales, after sales, and returns items is controlled and monitored using real-time data provided by advanced identification technologies such as RFID and near-field communication (NFC). This enables us to extract real-time information and accurate data about the performance of the supply chain at any moment. Even more, having real-time access to an enterprise resource planning program (ERP) can help sales personnel to obtain accurate information regarding product availability and features (He et al., 2010). One of the most used technologies in the supply chain is RFID which enhances supply chain visibility; supply chain performance that can be deeply analyzed and allows more easily the enablement of continuous improvement to make the supply chain more cost-effective and environment-friendly (Green and sustainable supply chain) (Geerts and O'Leary, 2014). RFID also can enhance the warehouse operations-order picking, storage assignment, and production planning which can expedite the customs clearance of cargo and cross-border supply chain. A smart and autonomous warehousing system has emerged to adapt the warehouse operations to the new digital era. This has lead to the urgent need to develop business models and decision making supporting tools that are more adaptable to the new era (Chui et al.,2010).

1.1 Dual Channel Supply Chain

Online sales have experienced a significant growth in recent years (Wu, 2015). The total e-commerce sales in the United States reached $341.8 billion in 2015, which is a 14.8% increase from 2014 (U.S. Department of Commerce). It is believed that this increase was because many firms upgraded their single-channel, offline sales business models to dual-channel clicks-and-mortar models, which integrate both online and offline sales, during that time. Moreover, it has been predicted that such growth in online sales will continue: web-influenced sales are expected to grow annually by 6% between 2015 and 2020 (Wu, 2015). Studies have shown that in 2008, 94% of the best financially performing firms were dual-channel sales firms (Kilcourse and Rowen, 2008). The emergence of dual-channel firms was mainly driven by the expansion in internet use and the advances in information and manufacturing technologies providing a competitive advantage to the supply chain (Gunasekaran et al., 2017). Additionally, the multi-sales channel is an effective strategy for sales expansion especially with increased competition from international trade agreements. Much research highlights the importance of these economic factors in offering different customer segments with different channels (Moriarty and Moran, 1990; Rangan et al., 1992; Anderson et al., 1997; Gabrielsson et al., 2002). Customers are usually heterogeneous when it comes to sales-channel preference; multiple channels sales may lead to new customer segments that might not be reached by a single sales channel (Kacen et al., 2002). Finally, the online sales channel is a perfect tool to increase the customer's loyalty and awareness of new products, where the firms can offer new products online to the customer faster compared to the traditional retail sales channel (Keeney, 1999).

Firms introducing online sales are facing many challenges in terms of logistics and delivery processes, such as large volumes of very small orders; short delivery lead times; flexible delivery for example, nighttime and even 24-hr shipping; and the picking and packing process for single unit orders, in addition to the usual challenges of the conventional business. Warehouses or distribution centers must be ready to prepare orders coming from both offline stores and online shoppers. The conventional warehouse designed for physical stores and delivery does not work under a dual-channel business environment. For example, warehouse workers cannot use the same picking patterns for online orders as for physical shoppers (Master, 2015). Warehouses operating in the current digital era of e-commerce must have the all-purpose infrastructure, which is capable of sharing information, being interconnected, and handling different orders from different customer segments with different features such as diverse order sizes and delivery lead times (McCrea, 2017; Graves, 2012).

Two common strategies for the fulfillment process in the dual-channel business environment are the decentralized and centralized policies. A firm with a decentralized warehouse policy establishes a dedicated e-fulfillment warehouse and has separate warehouses where each sales channel has separate inventory, operation, and commercial teams. In many situations, using a decentralized policy for all channels in dual-channel strategies results in inefficiency (Bendoly, 2004; Zhang et al., 2010; Hübner et al., 2015). Despite the current profits of these firms, they lack inter-channel coordination, which leads to long-term inefficiency and consumer confusion (Zhang et al., 2010).

The strategy of using a centralized warehouse, i.e., one integrated warehouse or several warehouses clustered in the same location, to serve both online and offline orders for a region has recently gained popularity and is the most common organizational structure for dual-channel markets (Agatz et al., 2008; Hübner et al., 2015; Hübner et al., 2016). The strategy's growth in popularity is owing to the advantages that have been perceived by the firms adopting it. Such firms include the International Business Machines Corporation, Hewlett-Packard, Whirlpool Corporation, Pioneer Corporation, Hamilton Beach, and Nike (Huang et al., 2012; Zhang and Tian, 2014; Li et al., 2015; Panda et al., 2015; Xiao and Shi, 2016). The advantages of this structure include reducing the facility cost by building an integrated warehouse, reducing warehouse space and inventory required for both channels, increasing the coordinating ability and flexibility of fulfilling both online and offline orders, and increasing the service levels.

One of the challenges in running the dual-channel warehouse is how to organize the warehouse and manage inventory to fulfill both online and offline (retailer) orders, where the orders from different channels have different features. Two important differences are the order size and order time. Typical online orders are placed at random times and are usually of small sizes, while typical offline orders are placed at scheduled times and are usually of large sizes (Agatz et al., 2008). Those differences affect the warehouse structure and operation. Many firms with dual-channel distribution systems have difficulty developing an effective inventory policy to reach an optimal channel performance. One of the key issues they face is deciding on the optimal order quantity and reorder point when a new sales channel is introduced. Moreover, they need to consider both capacity constraints and uncertain demands of both offline and online channels.

Figure 1.1 shows the difference between a dual-channel warehouse and a conventional retailer warehouse or an e-commerce warehouse. As shown, the dual-channel warehouse has two areas that fulfill the online and retailer orders. The focus of our study is to analyze the structure of the dual-channel warehouse and determine multi-item inventory policy (Q, R) for both areas, taking into account the warehouse capacity, demand, and lead time uncertainty so that the total cost of the dual-channel warehouse would be minimized.

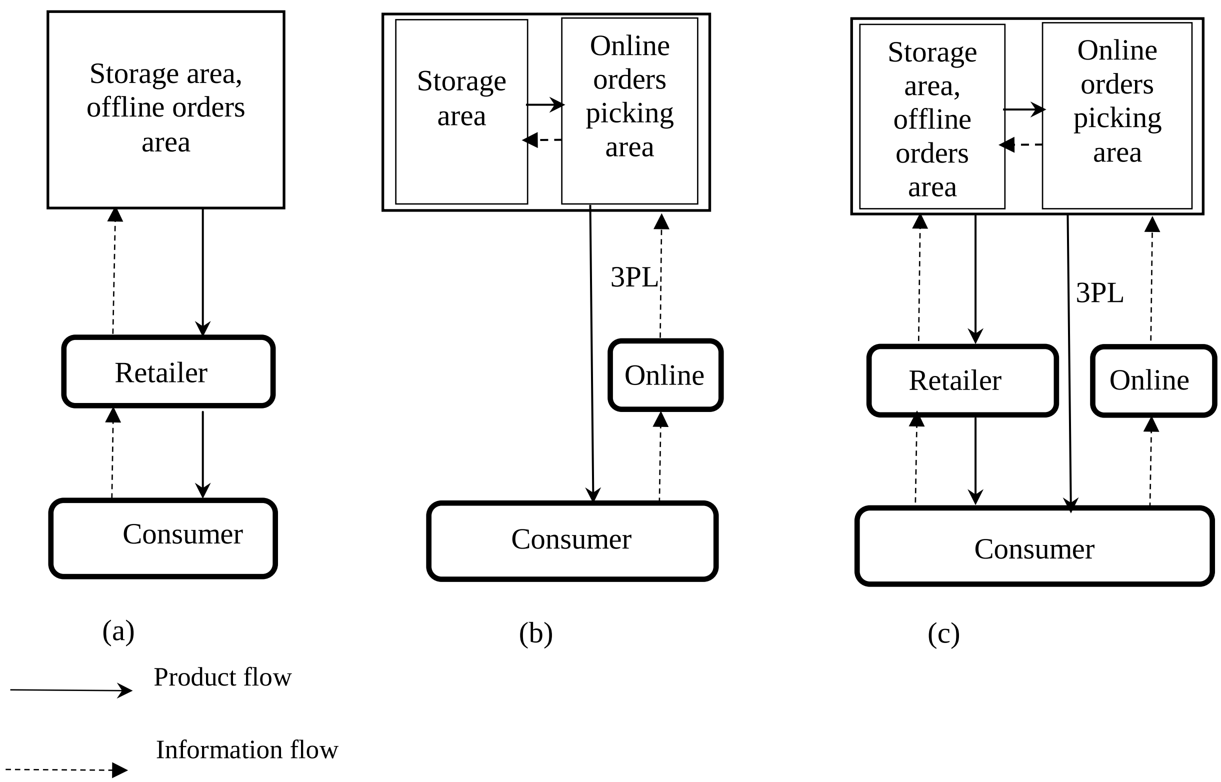

Figure 1.1 (a)–(b) Single-channel warehouses and (c) dual-channel warehouse

Designing a suitable warehouse structure for a centralized warehouse policy is critical for warehouse operations to prepare orders from both online and offline shoppers. The logistics viewpoint indicates that it is common to find modern warehouse layouts divided into different areas for each customer platform (Webb, 2002; Master, 2015). One of the best warehouse practices for 2017 is to develop all-purpose facilities that can "talk" to one another, handle small orders, medium orders, and large orders, and perform all functions in a very accurate manner (McCrea, 2017). A dual-channel warehouse that introduces a new area for e-fulfillment process provides an efficient and practical structure to connect two warehouse areas for centralized warehouse policy. Usually, for heavy or bulky items such as refrigerators and large furniture, a dedicated e-fulfillment warehouse is a better choice because it has a low-cost efficiency in moving those items frequently in different areas of a warehouse. For most items in electronics, department stores, and even grocery stores, a dual-channel warehouse can be a good option because the added dedicated e-fulfillment area can be designed to provide an efficient and flexible solution for a high volume of small orders, such as low-density warehouse, low inventory, special equipment or structure, and long operation time (De Koster, 2003).

1.2 Warehousing and Storage Policies

Warehousing is one of the main important factors to consider in supply chain operations analysis and product planning. An efficient warehouse can dramatically reduce operational costs as the handling cost is decreased. “Warehouse” is defined as the place to store goods and support the variation in product demand between the production plants before product delivery to the final consumers. In a warehouse, the products, components, and parts are received, stored and are retrieved when needed. The warehouse could be used as well to prepare customer orders, or assemble, test, label, and pack products and items, which adds value for the customers (Larson et al., 1997; Heragu et al., 2005; De Koster et al., 2007; Gu et al., 2007; Gutierrez et al., 2007). Additionally, the warehouse role in the supply chain includes the support of the demand variations as well due to seasonality or production and transportation requirements.

There are three categories of warehouses according to their use. The first type is a distribution warehouse where various products from different suppliers are stored. The second type of warehouse is a production warehouse where the finished or semi-finished products are stored. The third type is a contract warehouse operated by third-party logistics provider “3PL” (Van den Berg and Zijm, 1999). Depending on the warehouse type, different operations, and internal and external designs are required.

There are various storage policies used within the warehouse which includes:

1. Random storage policy which is based on storing the items randomly within the warehouse based on a first-come-first-served concept. The main advantage is the maximization of space

utilization while increasing the picking order and travel times. The emergence of new technologies such as RFID gave a significant push to a randomized policy, as the operator can easily locate the item through the active RFID tag. For more information regarding this policy, please refer to (Hausman et al., 1976; Larson et al., 1997; De Koster et al., 2007).

2. Dedicated policy which is based on assigning fixed locations to each product for the duration of the planning period. The main advantage is that the picker will be familiar with an item's storage location, even when the space utilization is not optimum. For more details refer to (Goetschalckx and Ratliff, 1990; Cormier and Gunn, 1992; Larson et al., 1997; De Koster et al., 2007; Zhang et al., 2017).

3. Class-based policy is based on set criteria, for example, Cube-per Order Index (COI), demand, or size. A class is defined, whereby a block in the warehouse is assigned to each class while the items are stored randomly within each block. For more details, refer to (Heskett, 163; Heskett, 1964; Hausman et al., 1976; Cormier and Gunn, 1992; Francis et al., 1992; Larson et al., 1997; Caron et al., 1998; De Koster et al., 2007; Muppani and Adil, 2008)

4. Turnover based policy is where the items with the highest turnover rates are stored close to the shipping area. It is, in fact, a combination of randomized and dedicated assignment policies. The assignment rule should be kept up to date as the demand varies. For more details, please refer to (De Koster et al., 2007)

5. Volume-based policy is based on storing the items with the highest volume close to the Inbound /Outbound (I/O) area. For more details, please refer to (Peterson and Schmenner, 1999; Peterson and Aase, 2004).

6. Shared storage policy allows different products to be successively stored in the same location. The advantage of this policy is the possibility to share the same location with various items, however, the storage requirement varies over time and needs to be updated. For more details, please refer to (Goetschalckx and Ratliff, 1990; Cormier and Gunn, 1992; Francis et al., 1992).

7. Activity-based/ duration of stay policy is based on criteria where the ABC activity index is developed, and the items are stored based on their activity function. For more details, please refer to (Hausman et al., 1976; Goetschalckx and Ratliff, 1990; Zeng et al., 2002; Li at al., 2016).

Based on the warehouse use, we could have front and reserved areas within the warehouse. The reserved area consists of storage locations where the items are usually kept for a longer time, while the front area is where the items are stored for shorter periods or cross-docked before being shipped to customers (Rouwenhorst et al., 2000; Heragu et al., 2005).

With the highly competitive, fast-paced, and dynamic business market, having correct and updated inventory records is a vital factor for effective warehouse operation which affects the safety stock levels and ordered quantities. RFID technologies are a key factor and have a considerable impact on the performance of the supply chain operations (warehouse operations) by reducing the inventory losses, increasing process speeds, and enhancing information accuracy (Sarac at al., 2010; Daduna, 2012; Chen et al., 2013). In conclusion, for each item, there is a need to determine the safety inventory, replenishment, and inventory policy as well as where to store and move each item within the warehouse.

1.3 Border Crossing Time and RFID Application in Cross-Border Supply Chain

1.3.1 Border Crossing Time

It is widely known that Canada and the USA enjoy a unique commercial relationship, and they are very close trading partners; the import and export sales between the two countries has reached more than 600 billion (Office of the United States Trade Representative). A noteworthy percentage of this bilateral trade is the use of land/ bridge crossings-primarily trucks- as a principal means of transportation (Anderson and Coates, 2010). Table 1.1 highlights the busiest crossings between Canada and the USA using the monetary value of goods exported and imported under the North American Free Trade Agreement (NAFTA) region.

The border crossing time is often unpredictable due to various reasons such as the increased security concerns which translate into more and longer inspection times, understaffing which means fewer open lanes, and the lack of specialized agents to deal with controlled items such as drugs and agricultural products (Thompson, 2014). The variability of border crossing times is extremely costly, especially for firms that rely totally on their global suppliers.

After 9/11 events, the US government launched the Free and Secure Trade program, or FAST, which is a commercial clearance program for low-risk shipments coming to the U.S. from Canada and Mexico. The FAST program permits expedited shipping processing for commercial shipper after going through strict security and background checks and fulfill certain eligibility requirements. Every link in the supply chain of the FAST member must be certified under the Customs-Trade Partnership Against Terrorism program or C-TPAT. C-TPAT is voluntary partnership program between the government and the private sector. It provides expedited shipping processing for the participated members who meet supply chain security criteria (US Customs and Border Protection).

Some researchers have investigated the border crossing time problem, for example, Goodchild et al. (2007) studied the border time uncertainty and proposed different strategies to minimize its negative impact. Some of the measures they proposed include increasing the buffer time by scheduling earlier arrival times to the border crossings; using alternative routes, or border crossing with fewer delays; and considering border peak conjunction hours in shipment scheduling then adjusting transport according to periods with low border activity. In addition to considering the border delays in the planning stages, they considered changing the transportation mode taking into account uncertainty levels and the probability of delays.

Table 1.1 The value of US-Canada International Trade by Transport Mode (in Millions of US $). US Department of Transportation

Border Crossing	Exports to Canada	Exports to Mexico	Total Exports	Imports from Canada	Imports from Mexico	Total Imports	Total North American Trade
Laredo, TX	0	72364	72364	0	82870	82870	155233
Detroit, Mi	65398	5	65404	44076	311	44387	109790
Buffalo-Niagara Falls, NY	38085	8	38092	27785	134	27919	66011
El Paso, TX	0	27214	27214	0	27868	27868	55082
Port Huron, MI	29293	0	29294	21196	124	21320	50613

Anderson and Coates (2010) examined the freight movements between the US and Canada. The study's main finding was that the observed border crossing time was lower than the expected average border crossing time, this means that firms overestimated the delay times by arriving excessively earlier, meanwhile the critical factor was the variability of the border crossing times, not its mean time.

1.3.2 RFID Application in Cross-Border Supply Chain

RFID is a data collecting technology where items can be automatically identified in real time from certain distances without any contact or direct sight. RFID has many advantages such as increased efficiency and process operations faster, reduced storage space and handling costs, and increased profit and customer satisfaction as the number of stock-outs decreases (Li et al., 2006). An excellent example of the benefit of RFID technology is its use by Procter & Gamble and Wal-Mart, where their inventory levels dropped by 70%, increasing the fill rate to 99%, and the reducing administrative costs by modifying their supply chain (Thonemann, 2002). RFID growth increased from $1 billion in 2003 to $4 billion in 2008 to $20 billion in 2013 (Bagchi et al., 2007). The main RFID application fields in the supply chain currently are inventory management, logistics and environmental sensors (Gaukler and Seifert, 2007). There is more opportunity to gain from RFID applications, such as the use of RFID to reduce the cross-border transportation time, in this case between the US and Canada (Sarac et al., 2010).

Implementing an RFID supply chain network between Canada and the USA can improve the whole supply chain efficiency in many ways, such as:

1. Forecasting a real-time dynamic border crossing time by analyzing the big data captured by the RFID, Bluetooth, GPS, Radar, and Vehicle Waveform Identification Devices. It is important to classify the expected wait times in functions of the type of user and according to shipment type. The expected wait times for a passenger vehicle are not the same as the wait times for a truck driver, and the wait times for a driver carrying hazards material is not the same as a truck carrying low-risk material. It is important, as well, to take into consideration the different departmental personnel availability from different agencies such as the Canadian Food Inspection Agency (CFIA), the U.S. Food and Drug Administration (FDA), and the U.S. Department of Agriculture (USDA). Shipments involving those agencies can be scheduled around their staff availability.
2. Enhance the “Trust Shipper Program” by using the RFID technology, electronic seals, or GPS, which allow shipments to be tracked from the time they leave the trusted shipper’s yard until the border crossing. Trucks could go through fast-tracking gates if the truck arrives within the normal time, using a specific route without any suspicious stops and with its electronic seals intact.

3. RFID Solution to Less-than-truckload (LTL): Carriers cannot participate in trusted shipper programs unless all shipments are from trusted importers. Using the RFID technology will reduce the inspection times as we can identify shipment source and destination.

4. Electronic Reporting of Imports and Exports: it is mandatory to collect data electronically from the receiver and the shipper for risk assessment purposes. RFID is an excellent tool to facilitate this process.

5. Using the RFID and other relevant technologies in establishing preclearance zones; the border is no longer simply a physical line between the two countries. This zone could be the manufacturing facilities or warehouses.

6. Staffing Scheduling and Training: Based on the data obtained about the volume of users and type of shipment, a better staff scheduling could be arranged specifically for the government departments that inspect those shipments, such as CFIA, FDA, and USDA.

7. Extend the use of RFID Technology in Cross-Border Travel Documentation, such as FAST and NEXUS, and Enhanced Driving License (EDI).

8. Use the benefit of RFID and relevant technologies in enhancing the Border Contingency Plan. Not all shipments are of the same type and origin; shutting down the whole crossing is not an option anymore. Safe shipments can continue while efforts will be focused on suspicious shipments, to balance security and trade concerns.

1.4 Global Cross-Docking System

Original Equipment Manufacturers (OEMs) are in need of integrating their global supplier base where the lower parts costs compensate for the much higher procurement cost in the Just in Time (JIT) concept. Production scheduling is usually established for three to four days; however, last-minute rework needed in the Paint Shop due to paint defects usually shortens the known and fixed production schedule to a couple of hours. Suppliers’ locations must be within the assembly plant area to deliver JIT or Just in Sequence (JIS) parts.

The most common method used by OEM to integrate their global supplier in the JIT concept is the use of cross-dock, also known as Third Party Logistic (3PL), terminal which is normally located in the assembly plant perimeter (Serrano et al., 2017; Schwerdfeger et al., 2018) as the storage space inside the assembly plant is limited (Boysen et al., 2015). Note; cross-dock and 3PL are used interchangeably in this work. Global suppliers deliver parts to the cross-dock which is used as intermediate storage and they are metered in (delivered) to the assembly plant by trucks when required, usually every two hours (Figure 1.2). Additionally, it is possible to supply multiple assembly plants from the same cross dock which leads to transportation economy of scale as well as reducing the safety stocks due to risk pooling (Schwarz, 1989; Boysen and Fliedner, 2010). It is worth mentioning that the cross-docking strategy is not exclusively used in the automotive industry. It is also currently used by many firms in different industries such as in retail, the postal service and the food industry (Werners and Wülfing, 2010; Agustina et al., 2014; Martins et al., 2017; Goodarzi et al., 2018; Zenker and Boysen, 2018).

Firms are facing challenges and need to make decisions when adopting the cross-dock strategy on all levels. On the strategic level, decisions need to be made on the location of the cross-dock as well as the optimal layout. Once the cross-dock center location is known, decisions need to be made regarding the optimal material flow between suppliers to cross-dock and from cross-dock to assembly plants to satisfy the end demand with minimal cost. Additionally, managers are faced with operational decisions such as optimal vehicle routing between cross-dock and assembly plants, shipment scheduling and dock assignment.

One of the challenges in adopting the cross-dock is how to assign trucks to inbound and outbound docks, determine the optimal inventory policy to satisfy the demand but at the same time minimize the holding costs without compromising the service level, and consider some real case constraints such as the dock capacity and the available storage space.

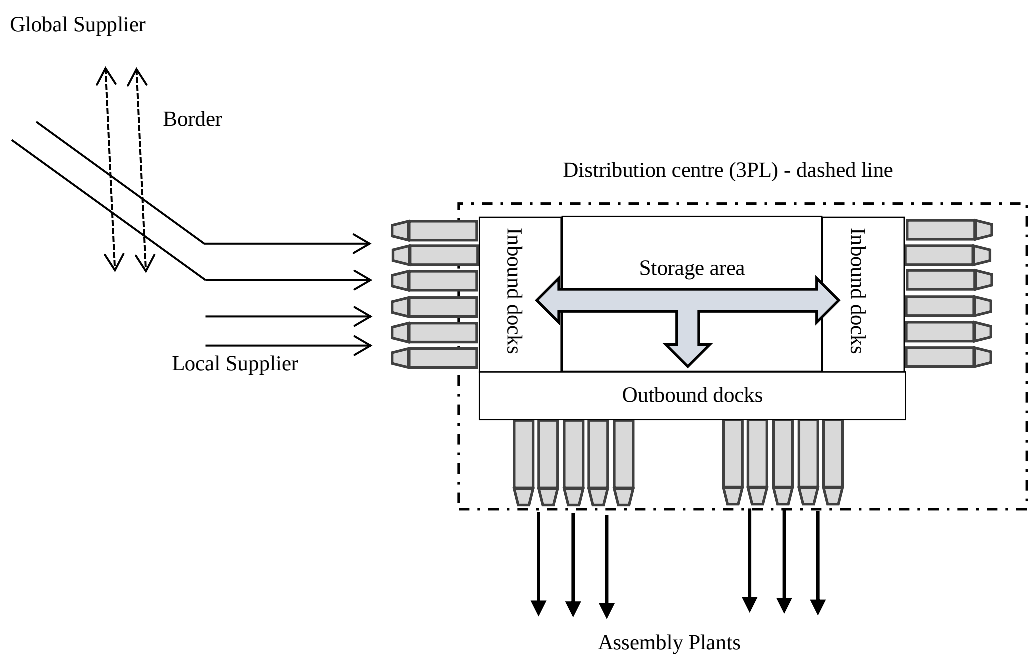

Figure. 1.2 Cross-docking system (3PL)

There is an important difference between local and global suppliers; global suppliers have less shipping frequency and bigger shipment size to reduce the procurement cost per unit. This leads to the need for intermediate storage in the 3PL.

One of the key decisions the firms need to make when adopting the cross-dock strategy is to determine the optimal dock assignment, safety stock, and storage locations for all parts, especially global supplier parts. Moreover, they need to consider dock and storage capacities as well as uncertain delivery time from suppliers to 3PL.

1.5. Research Objectives

The research objectives are to develop decision methods/tools to support the warehouse operations, inventory management, multi-channel warehouse layout design, and capacity management in the dual-channel supply chain, and the use of RFID and product identification in the inventory management of the cross-border global supply chain as well as dock assignment in the global cross-docking system. In the decision support tools (mathematical models), there is a continuous need to study the impact of the following issues in the supply chain:

Uncertainty: There are various sources of uncertainty to be considered in the mathematical model such as demand and lead time.

Cross-border supply chain: Investigate the impact of cross-border time variability on the performance of the supply chain and suggest new approaches to enhance its performance.

Environmental factors: The growing complexity and the dynamic nature of the supply chain has led to the need for a flexible supply chain. This would result in optimizing not only the supply chain costs (ordering, holding, and operational), but also it is necessary for taking other factors into consideration when optimizing the supply chain network such as environmental and cross-border costs. Therefore, multi-criteria mathematical support decision models should be developed with appropriate solution methodologies.

1.6 Solution Methodologies

Unconstrained nonlinear programming: Unconstrained Nonlinear programming is the process of optimizing a nonlinear function, where we maximize or minimize a non-linear objective function without considering any constraint. The problem might be unbounded or have several critical points if the function is positive semi-definite, negative semi-definite or indefinite. We can obtain the optimal solution if the functions are either positive definite (i.e. there exists one global minima) or negative definite (i.e. there exists one global maxima) such that the first derivative =0. We use the second derivative test to check the concavity or convexity of the objective function.

Constrained nonlinear programming: Constrained Nonlinear programming is the process of optimizing nonlinear function, where we maximize or minimize a non-linear objective function subject of set of constraints. The problem might be unbounded or have several critical points if the function is positive semi-definite, negative semi-definite or indefinite. We can obtain the optimal solution, if the functions are either positive definite (i.e. there exist one global minima) or negative definite (i.e. there exist one global maxima) such that the first derivative =0. We use the second derivative test to check the concavity or convexity of the objective function.

Lagrange multiplier: In mathematical optimization, the method of Lagrange multipliers is a strategy for finding the local maxima and minima of a function subject to equality constraints. The great advantage of this method is that it allows the optimization to be solved without explicit parameterization in terms of the constraints. As a result, the method of Lagrange multipliers is widely used to solve challenging constrained optimization problems. For the case of only one constraint and only two choice variables, consider the optimization problem

maximize f(x, y)

subject to g(x, y) = c

We assume that both f(x, y) and g(x, y) have continuous first partial derivatives. We introduce a new variable (λ) called a Lagrange multiplier and study the Lagrange function defined by

$$L(x, y, \lambda) = f(x, y) - \lambda \cdot g(x, y)$$

where the λ term may be either added or subtracted. If $f(x_0, y_0)$ is a maximum of f(x,y) for the original constrained problem, then there exists λ_0 such that (x_0, y_0, λ_0) is a stationary point for the Lagrange function (stationary points are those points where the partial derivatives of L are zero). However, not all stationary points yield a solution of the original problem. Thus, the method of Lagrange multipliers yields a necessary condition for optimality in constrained problems (Chiang 1984; Bertsekas 1999; Heath 2005).

Stochastic programming: Stochastic programming is one of the main approaches when dealing with random and uncertain parameters. The main objective of the stochastic programming is to find an optimal solution which performs well, under any possible value of the random parameters. In the stochastic programming, the expected value is usually used to model the objective function where the main goal of the objective function is to minimize expected cost or maximize expected profit (Snyder 2006).

Mixed-integer programming (MIP): Mixed-integer programming is an optimization problem (maximization or minimization) where the optimal decision variables must be non-negative and have an integer value. When the integer variables must be 0 or 1, it is called a binary variable. Integer constraints make an optimization problem harder to solve.

1.7 Contributions

This study contributes to the existing literature in several ways. Problem 1 is the is the first work to analyze the structure of the emerging dual-channel warehouses and develop a structure related to the inventory policy for such warehouses. Second, it develops a mathematical model that determines the multi-item product inventory policy for the two areas in integrated dual-channel warehouses, minimizing their total expected cost. The constraints of warehouse space and uncertain demands are also considered. Third, it provides closed-form solutions for instances without a warehouse space constraint as well as a solution algorithm for the case with the warehouse space constraint. Furthermore, the proposed solution can be used to evaluate the performance of two-echelon dual-channel warehouse systems by comparing the total system costs for different warehouse structures and evaluating the effects of adding a new sales channel.

Problem 2 is considered an extension to Problem 1 where we analyzed the structure of the cross-border dual-channel global supply distribution centers, taking into account the border crossing lead times and the development of an inventory policy for the distribution center. Second, we developed a mathematical model that jointly determines multi-item products order quantities of the cross-border distribution center thereby minimizing the total expected cost taking into account the border crossing uncertainty, stochastic lead times and the uncertain demands. Finally, this model evaluates the impact of cross-border delays and assists in the decision-making process as it is a very effective tool that converts the delays' impacts into cost impacts as necessary.

Problem 3 is the first study to analyze the inventory policy of the cross dock and develop an integrated model of the 3PL center including the dock door assignment, safety stock, and intermediate storage locations inside the 3PL center. Second, the developed model considers real case constraints such as dock and storage capacities and stochastic lead time. Third, the proposed model identifies the cross-border cost and highlights its impact on the 3PL inventory level. Forth, the proposed model can be used as an analytical tool to help optimize the cross-border supply chain considering border crossing time variability and its associated delays. Fifth, a real-world industrial cross-dock and layout problem is solved, and the results obtained could be applied to optimize the cross-dock and layout at other similar cross-dock facilities. Sixth, the proposed model can be used as a decision support system when setting up new 3PL center for new programs when launching new products or building new plants. To the best of our knowledge, this paper is the first study to integrate the inventory management and storage layout along with dock door assignment in the global 3PL center, although, there have been some papers addressing these decisions individually.

1.8 Organization of the Dissertation

This dissertation is structured as follows: Chapter 2 presents reviews of the literature. In Chapter 3, a model for dual-channel warehouse and inventory management in the dual-channel supply chain is proposed. Chapter 4 presents a model for a dual-channel warehouse with inventory management in a global channel supply chain considering the cross-border costs and uncertainty in demand and lead-times. Chapter 5 presents a model for a cross-docking warehouse with inventory management considering the dock assignment problem as well as the cross-border costs and uncertainty in demand and lead-times. Finally, Chapter 6 presents conclusions and future related topics for this dissertation. Figure 1.3 below demonstrates the relationship between the 3 problems that we present in this dissertation.

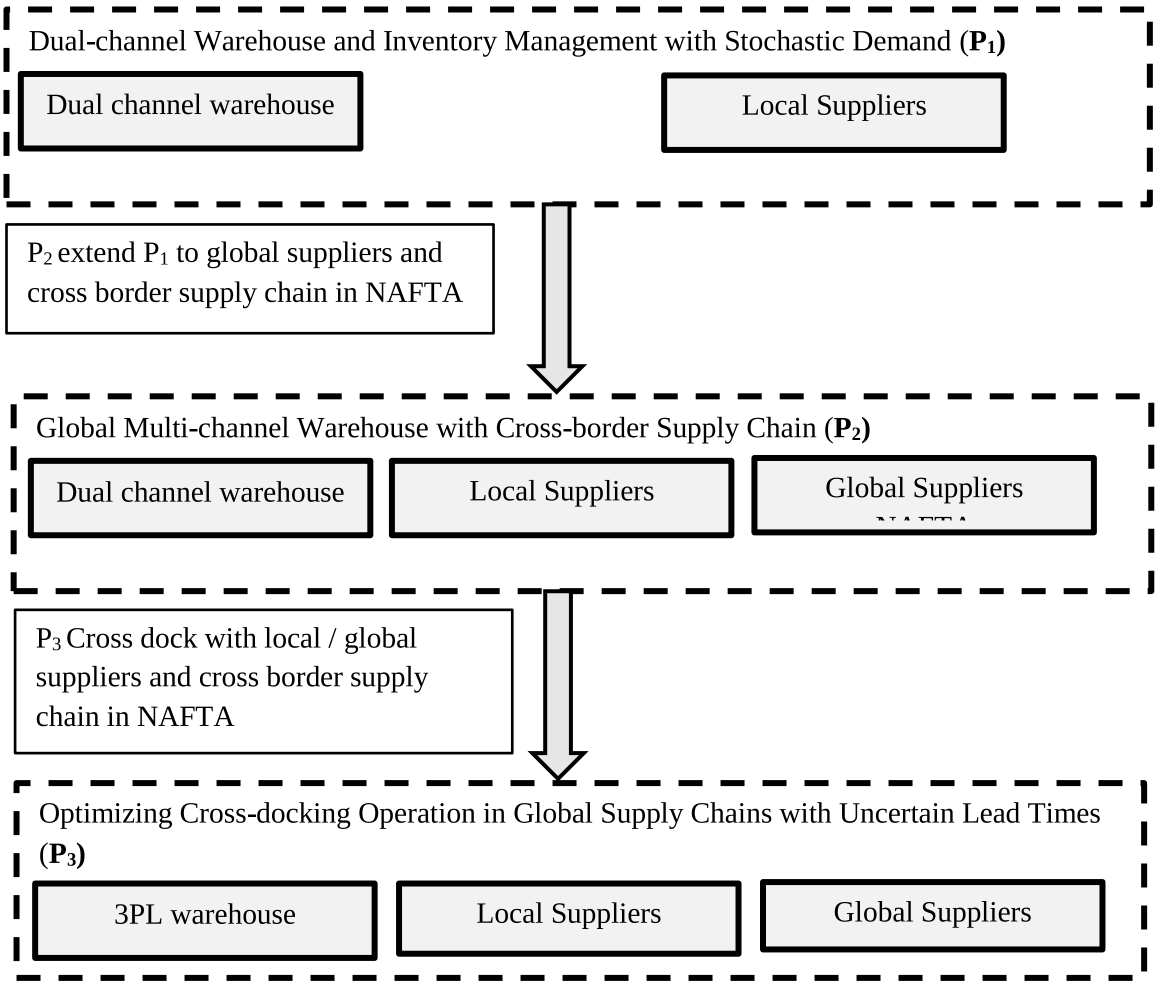

Figure. 1.3 Problems flow chart

CHAPTER 2: LITERATURE REVIEW

In this chapter, we will conduct a comprehensive literature review related to warehouse and inventory management in dual-channel supply chain, border crossing time and RFID application in cross-border supply chain, and dock assignment problem in global cross-docking system. A detailed review of each of the mentioned topics is presented in the following sections.

2.1 Warehouse and Inventory Management in Dual-Channel Supply Chain

This study is related to two streams of literature that have examined dual-channel supply chains: inventory management in dual-channel supply chains; and warehouse operations, layout designs, and capacity management in dual-channel warehouses. A literature review of each of these topics can be found below.

2.1.1 Inventory Management in Dual-Channel Supply Chains

Various forms of inventory management have been studied in the dual-channel supply chain literature. Chiang and Monahan (2005) proposed what may be described as one of the first models that studied inventory policy in a two-echelon dual-channel supply chain that receives demands from different customer segments. They assumed that the inventory was stored in both the manufacturer’s warehouse to satisfy online demand and in retail stores to satisfy offline demand. They developed a stock-based inventory control strategy to minimize the system’s operating cost by considering the inventory holding and lost sales costs. The model developed by Teimoury et al. (2008) is considered an extension to that by Chiang and Monahan (2005). The former’s main contributions include the separation of both channels’ lost sale costs and the development of two solution algorithms. One algorithm was based on the simulated annealing method, and the other algorithm was based on the best neighborhood concept. Takahashi et al. (2011) considered setup costs for both order production and order delivery. They proposed an inventory control strategy with the objective of minimizing inventory holding costs, lost sales costs, as well as production and delivery costs. They calculated the total cost using Markov analysis to highlight the performance of their proposed inventory control policy.

Boyaci (2005) also furthered research on dual-channel supply chains inventory management when he investigated the inventory levels of a retailer and a manufacturer with double-marginalization. The author found that as double marginalization increased, the manufacturer tended to overstock while the retailer tended to be out of stock. Additionally, Geng and Mallik (2007) studied inventory competition between a direct online channel owned by a manufacturer and an offline retail channel. They claimed that the profit of a dual-channel supply chain would increase as the capacity increases. Furthermore, Hoseininia et al. (2013) investigated the competition that arose between channels; they based their system on a Stackelberg game. They analyzed the inventory level and its relationship to production costs and wholesale prices. Moreover, Schneider and Klabjan (2013) studied dual-channel revenue management by analyzing the conditions and effects of offering channel-specific prices. They also inspected the necessary conditions for optimal inventory control policies of dual-channel sales with channel-dependent sale prices.

Swaminathan and Tayur (2003) described the major adjustments necessary for a conventional supply chain to cope with e-commerce fulfillment processes. After a comprehensive literature review, they concluded that channel integration in a dual-channel supply chain increases profit, reduces inventory, and enhances customer service. However, the models studied in their paper primarily focused on electronic commerce. Hence, dual-channel operations and their interdependencies have not been discussed. Another significant review of supply chain management in an electronic commerce environment was conducted by Agatz et al. (2008). They focused on the distribution network design, warehouse layout, inventory, and capacity management topics. The authors divided the dual-channel fulfillment process into integrated fulfillment (using one warehouse to fulfill the demand of different sales channels) and dedicated fulfillment (using a dedicated warehouse for different channels). This division was based on their literature survey. Integrated fulfillment is the most common network among dual-channel firms.

Zhao et al. (2016) suggested a new inventory strategy called online-to-offline strategy. They considered a dual-channel supply chain with one manufacturer and one retailer. They also proposed a centralized and decentralized inventory model with and without lateral transshipment. The decision variables in their model were the inventory level for the store and transshipment price; however, no ordering or holding costs were considered. They demonstrated the existence of a unique Nash equilibrium of the inventory order levels in the dual channel and an optimal transshipment price to maximize the profit of the entire supply chain. However, they neither considered the dual-channel warehouse nor the ordering and holding costs. Zhang and Tian (2014) studied a dual-channel supply chain with one manufacturer, which sells products through a direct channel and a retailer. They constructed a single-period profit-sharing model between the manufacturers and retailers. The decision variables were the inventory levels of the direct and retailer's channel with a retailer service constraint. Nonetheless, they neither considered the dual-channel warehouse nor the operational costs. Yao et al. (2009) studied a dual-channel supply chain comprising one manufacturer and one retailer. They studied a centralized inventory strategy, the Stackelberg inventory strategy, and 3PL e-tail operation strategy. They proposed a single-period model to obtain the inventory level for the manufacturer and for the retailer that maximizes the expected profit. However, they did not deal with the dual-channel warehouse in terms of structure or at the operational level. Khouja (2003) proposed a 3-stage supplier–manufacturer–customer supply chain model. They employed a periodic review inventory policy and defined inventory coordination mechanisms such as cycle time and number of orders. Nonetheless, they did not consider the dual-channel warehouse, its structure, or operations.

Reviewing the inventory management research stream, we found that the (Q, R) policy is extensively used in the literature. Many of the recently published articles have considered the (Q, R) policy (Sarkara et al., 2015). The advanced inventory management systems and the reduced cost of radio frequency identification technology have made the continuous review inventory control policy (Q, R) a very attractive approach. In the modeling process, the annual ordering cost, annual holding cost, annual back ordering cost, or annual lost sales cost are considered subject to some service constraint, which is typically the fill rate. Generally, it is difficult to obtain a closed-form solution, and a well-known iterative algorithm is used to obtain the optimal order quantities. This has led to the use of many heuristics or approximation approaches in solving the model.

As observed, all the reviewed studies above did not consider the dual-channel supply chain inventory strategies in the context of a dual-channel distribution system. They allocated online demand to the manufacturer warehouse without studying the implications that online fulfillment capability has for the dual-channel warehouse structure and operations. Additionally, they did not consider the dual-channel warehouse structure, operations, or capacities. Finally, they considered deterministic lead times. This study fills these research gaps by examining the inventory strategies for a dual-channel supply chain while considering the dual-channel warehouse structure, operations, space constraint, stochastic demand, and lead time. It combines the research fields of dual-channel warehouse operations, structure designs, and capacity management as well.

2.1.2 Warehouse Operations and Management in Dual-Channel Supply Chains

The literature on dual-channel warehouse operations demonstrates the importance of picking processes, particularly with regard to direct channel fulfillment processes. Hübner et al. (2015) reviewed the operation structures of multi-channel retailing, including network design, inventory management, warehouse operations, and capacity management. They discussed the structures and challenges in multi-channel warehouse operations. They concluded that the main driver in multi-channel operations was an efficient integration of warehouse operations. They provided interesting insights on multi-channel operations. However, their findings were based on a literature survey, and the analysis they presented was not based on an application of the model to a real case study or numerical analysis.

Allgor et al. (2003) studied e-retailing settings and the effects they had on conventional inventory models. The authors divided warehouses into two areas: a deep storage area and a low storage picking area. They proposed a multi-item, two-stage periodic review model (R, T). A heuristic-based algorithm was proposed as a solution approach. Xu (2005) presented a periodic review inventory model for a single-channel e-tailer order fulfillment process considering warehouse space. To optimize warehouse operations, the warehouse was divided into two areas. One of these areas had a low density for order picking and the other had a high density for stocking items and replenishing the center's picking area using a periodic review inventory control policy. They considered a stochastic demand; however, they assumed a deterministic lead time. This study differs from that of Allgor et al. (2003) and Xu (2005) in the following two aspects: first, this study considers the dual-channel supply chain with both online and offline demands while the references dealt with a single channel only, i.e., e-tailer supply chain; second, the proposed model in this study is based on a continuous review inventory policy (Q, R) and specifically considers warehouse structure, operations, and capacities, while the references proposed a periodic review model (R, T). The similarity between our studies and those in the references is the division of the warehouse into two stage areas.

Related to the dual-channel warehouse in terms of division of space, the forward-reserve problem has already been modeled in previous studies. Hackman and Rosenblatt (1990) developed a model to determine which items to assign to the automated storage and retrieval system (AS/RS), where the warehouse was divided into two areas: AS/RS area and the area for manual or semi-automated material handling system. Instead of deciding into which area each item should be placed, this study decides the inventory policy for each item, and both areas have all items to serve online and offline orders. Bartholdi and Hackman (2008) investigated how to allocate a forward pick area in a distribution center. The dual-channel warehouse in this study offers delivery operations in both areas. The previous works investigated the forward-reserve problem with a single-channel and deterministic demand, while no ordering and backorder costs were considered. It is noted that the e-commerce industry has been using the "dual-channel warehouse" for several years, but only a couple of articles discussing such a warehouse can be found in the literature, such as that by Hübner et al. (2015). Furthermore, none of those articles provided quantitative analysis for the dual-channel warehouse.

A comprehensive literature review indicates that some mathematical inventory management models have been proposed for dual-channel supply chains; however, there is a lack of research that investigates the warehouse structure, operations, and capacity in a dual-channel context as we can see in Table 2.1 below. Some articles have addressed the warehouse operations and capacity management of single-channel warehouses, but they have not addressed these in a dual-channel context. Therefore, to the best of our knowledge, inventory management, warehouse structure, operations, and capacity management have not been harmonized for an integrated model in a dual-channel context.

Table 2.1 Problem 1 literature review

Reference	Inventory Management	MC warehouse	Layout & operations	Capacity management
Allgor et al. 2003	✓		✓	✓
Swaminathan and Tayur 2003			✓	
Boycai 2005	✓			
Chiang and Monahan 2005	✓			
Xu 2005	✓		✓	✓
Geng and Mallik 2007	✓			

Agatz et al. 2008		✓	✓		
Teimoury et al. 2008	✓				
Takahashi et al. 2011	✓				
Hoseininia et al. 2013	✓				
Hübner et al. 2015	✓		✓		✓
Problem 1	✓	✓	✓	✓	

2.2 Border Crossing Time and RFID Application in Cross-Border Supply Chain

2.2.1 Border Crossing Time

Some researchers have investigated the border crossing time problem, for example, Goodchild et al., (2007) studied the border time uncertainty and proposed different strategies to minimize its negative impact. Some of the measures they proposed include increasing the buffer time by scheduling earlier arrival times to the border crossings; using alternative routes, or border crossing with less delay time; and considering border peak conjunction hours in shipment scheduling then adjusting transport according to periods with low border activity. In addition to considering the border delays in the planning stages, and changing the transportation mode, they did consider uncertainty levels and the probability of delays.

Anderson and Coates (2010) examined the freight movements between the US and Canada. Their study main finding was that the observed border crossing time was lower than the expected average border crossing time, this means that firms overestimated the delay times by arriving excessively earlier, meanwhile the critical factor was the variability of the border crossing times, not its mean time.

Cedillo-Campos et al. (2014) modeled the US-Mexico border crossing using a dynamic system approach to investigate uncertainty caused by delays, and variabilities in border crossing times. They identified the variable of interest on the sides of the border used in their model development input such as daily shipments, primary and secondary inspection time, and transit time from the border to the customer location. They concluded that as the cross-border time increased, the volume of items crossing the border also increased; however, if the safety stock on either side of the border is considered, the number of products ordered and moved through the border decreased.

Lee and Lim (2014) studied the border crossing procedure between Hong Kong and mainland China and how the use of RFID technologies would impact the cross-border supply chain regarding enhancing the efficiency of the cross-border procedure. They proposed a new border crossing process based on advanced technologies such as RFID. They modeled the process and used simulation to demonstrate the effectiveness of the proposed model. They showed that the implementation of the proposed border crossing process would minimize the variability of the average border crossing time, including the inspection process. They argued that enhancing the cross-border supply chain between Hong Kong and mainland China would increase the flow of products from heavy manufacturing regions in mainland China to a logistic hub such as Hong Kong due to the reduction of cross-border uncertainty, shorter lead times, thereby enabling production planning and just in time manufacturing.

Hedaoo, (2015) developed a Binary Integer Linear Programming (BILP) mathematical model for the facility location-allocation problem between the USA and Canada. They considered capacitated, single commodity, multiple time-periods (dynamic) and multi-facility location-allocation problem. Simulated annealing based Meta-heuristic is developed to solve the problem to near optimality.

Sardar and Lee (2015) investigated the cross-border complexity issue and developed a mathematical model to quantify its effects on the global supply chain disruption risk. They considered many factors in defining cross-border complexity such as operational procedures that the products must go through at the border and the number of borders that the goods cross.
They used in their model development a basic principle of probability and reliability and applied it to a real case study from Toyota Motor Corporation. Numerical analysis was performed to highlight the effects of crossing borders on the risk of disruption in Toyota's supply chain.

Chung et al., (2018) examine the effects of transportation risk and different buffer inventory strategies on the performance of JIT border crossing supply chain. They used simulation to model several risks to show the effect of border crossing uncertainty on service level and lead time. However, the simulation model is for a single item with one supplier; they did not consider any capacity constraints such as production and storage capacities. Finally, the proposed simulation model did not consider the cost element. These elements should be added to the model to reflect more complex real-life scenarios. As we can see, some articles have studied the border crossing time; however, none have considered the effect of the cross-border time on 3PL center in terms of storage capacity and inventory levels. Firms are in urgent need to quantify the cost of the cross-border process. Additionally, there is a need for analytical tools to help optimize the cross-border supply chain considering border crossing time variability and its associated delays.

2.2.2 RFID Application in Cross-Border Supply Chain

Peru (2008) investigated the use, benefit, and limitations of advanced identification technologies such as RFID, Unique Consignment Reference (UCR), and tracking technologies to enhance the cross-border supply chain. They concluded that such use of these technologies would increase the cross-border supply chain due to the information sharing between shippers and the Customs staff as they would both have access to the same database where the shipment information is saved.

Sarac et al. (2010) summarized after intensive literature review the advantage and benefit of the RFID application to the field of the supply chain. The benefits obtained included but were not limited to, the reduction of inventory levels, increase of overall efficiency, the speeding up of the processes, and the growth of information accuracy.

Daduna (2012) highlighted the increasing importance of the RFID in the retail industry due to the growing complexity of the logistics process and uncertainty in the supply chain and the need for real-time data where the RFID provides a reliable solution approach.

Zhu et al. (2012) presented a comprehensive study of RFID benefit and application in different industries; one of the main field applications is in the warehouse industry as a mean of tracking technology. Based on a comprehensive literature review, they developed a framework for the future of the RFID and its application in different fields.

Chen et al. (2013) developed a case study that integrated the lean supply with the use of the RFID; their results have shown a total time saving of 81% basically due to the saving in total operational time, being enhanced by 89%.

Hardgrave et al. (2013) performed two studies to highlight the importance of accurate inventory on the retail’s business performance and the vital role of RFID in achieving the reduction of inventory record inaccuracy by 81%.

Laosirihongthonga et al. (2013) performed a comprehensive study regarding the main effects of implementing the RFID in Thai industry. They concluded with listing soft and hard factors facing the implementation of RFID. Bhero and Hoffman (2014) studied the use of RFID technologies in optimizing cargo clearance processes. They identified inefficiencies in the clearance processes, especially in the manual operations handled by customs officers, and proposed RFID based solutions to automate these processes. The proposed solution goals are the enhancement of cargo clearance integrity while reducing the human involvement, thereby smoothening the flow of goods clearance processes. They concluded that the delays in the cargo clearance process are in fact due to sub-optimal systems and to the operations where human interaction is required. As we can see in Table 2.2, there is a gap in literature to address the dual channel warehouse with cross-border supply chain.

Table 2.2 Problem 2 literature review

Reference	Border crossing time/safety stock	FAST	RFID
Goodchild et al. 2007	✓		
Peru 2008	✓		✓
Anderson and Coates 2010	✓		
Sarac et al. 2010			✓
Daduna 2012			✓
Chen et al. 2013			✓
Cedillo-Campos et al. 2014	✓	✓	
Lee and Lim 2014	✓		✓
Sardar and Lee 2015	✓		
Chung et al. 2018	✓	✓	
Problem 2	✓	✓	✓

2.3 Dock Assignment Problem in Global Cross-Docking System

Extensive literature review on the cross-docking has been reviewed. For a detailed review, we refer to the recent literature review conducted by Van Belle et al., (2012) and Ladier and Alpan, (2016). According to Van Belle et al., (2012), the cross-docking literature is lacking real-world applicability; for instance, they highlighted the assumption of infinite storage capacity assumption, as well as the use of travel distance to measure the travel time without considering the congestion in the dock door assignment problem. Lastly, they recommended the integration of several problems in one model such as, in real life, the cross-docking problems are very independent. For instance, the scheduling and routing problems are interrelated. Ladier and Alpan, (2016) compared the literature dealing with the operational cross-docking system with the industry practice. One of the main gaps they highlighted is the need to remove simplification assumption to make the problem close to real life. They concluded that considering the storage capacity in the cross-dock models would be an important step toward narrowing the gap between literature and industry needs.

Tusi and Chang, (1992) studied the cross-dock assignment problem where each inbound is assigned to one origin and each outbound dock is assigned to only one destination. They proposed a branch and bound algorithm to solve the problem. Zhu et al. (2009) extended the model presented by Tusi and Chang, (1992) to the case where the number of origin and number of destination is much greater than the number of the inbound docks and the number of outbound docks respectively. Moreover, they considered the dock capacity constraints. They solved the nonlinear integer model using a branch and bound algorithm. Guignard et al., (2012) extended the work proposed by Zhu et al., (2009) and used a heuristic algorithm to solve the model. However, no storage capacity, nor inventory level were considered in the aforementioned papers.

Kuo, (2013) investigated the truck sequencing and truck dock assignment in a cross-docking system, the objective is to minimize the makespan. They used four simulated annealing algorithms as a solution approach and compare the experimental results showing improvement over the solution obtained randomly. Enderer et al., (2017) integrated the dock door assignment problem and the vehicle routing problem to minimize the material handling costs and the transportation costs between outbound docks and final point of use. They proposed two formulations and use column generation and heuristic algorithm as a solution approaches. However, no capacity nor inventory levels are considered in both papers.

Nassief et al., (2018) presented two new mixed integer programming models of the dock assignment problem. They used a column generation algorithm to solve the linear relaxation of one of the formulations and to compare obtained results with benchmark instances. They also performed a sensitivity analysis of several input parameters. They did not consider dock and storage capacity constraints nor safety stock level.

As observed, all the reviewed papers above did not consider the dock assignment problem along with inventory strategies in the context of a cross-docking system. They assigned the inbound and outbound docks without considering the dock and storage capacity. Additionally, they did not consider the supplier lead time uncertainty. As shown in Table 2.3 below, this paper fills this gap by examining the inventory policy, storage layout along with dock assignment problem, considering real-life constraints such as dock utilization, storage capacity, and supplier lead time. It integrates the research fields of dock assignment, storage layout, and capacity management as well.

Table 2.3 Problem 3 literature review

Reference	Dock assignment	Storage - Layout	Inventory management	Global suppliers	Storage & dock
Enderer et al. 2017	✓				✓
Zuluaga et al. 2017	✓				
Chung et al. 2018			✓	✓	
Goodarzi et al. 2018	✓	✓			
Nasiri et al. 2018	✓	✓			
Schwerdfeger et al. 2018	✓			✓	
Zenker and Boysen 2018	✓		✓	✓	
Smith et al. 2018			✓	✓	
Zenker and Boysen 2018	✓		✓	✓	
Problem 3	✓	✓	✓	✓	✓

2.4 Research Gaps

The research gaps (based on literature survey) are as follows:

1. Some mathematical models were proposed to address the subject of serial echelon warehouse and inventory management in supply chain; they proposed a two-serial echelon mathematical model for the warehouse inventory control policy to satisfy demand but not for the dual-channel warehouse in dual-channel supply chain context. No authors to our knowledge have considered dual-channel warehousing and inventory management for the dual-channel supply chain.

2. Some mathematical models were proposed to address the topic of multi-echelon inventory management in dual supply chain; they proposed a mathematical model by allocating online demand to a central warehouse, with the off-line demand satisfied from the store level inventory. They do not consider the warehouse layout design and capacity management of the dual-channel warehouse to fulfill the online demand.

3. Some articles have addressed the warehouse operations and capacity management for single channel warehouse (mainly online channel fulfillment), but not in the dual-channel context. To the best of our knowledge, the case of inventory management and warehouse operations and capacity management in the dual-channel context have not been harmonized in an integrated model.

4. In the mathematical models, there are several parameters such as demand, lead time, and cross-border times which are not deterministic. As a result, several sources of uncertainty should be considered. To this aim, some techniques such as stochastic programming can be applied.

5. There is a need for analytical tools to help optimize cross-border supply chain considering border crossing time variability and its associated delays.

6. In the global supply chain optimization, it is not only preferred to minimize the total operational cost (including operation, transportation, and holding costs) but also it is necessary to optimize other factors such as border crossing costs, environmental considerations, CO_2 emissions, truck idle time, and pollution. Many firms are looking to adopt the concept of green supply chain. Therefore, multi-criteria models should be developed, and appropriate solution approaches should be utilized including the environmental cost.

7. The dock assignment problem has been explored individually or integrated with vehicle routing and truck sequencing problems in the relevant literature. However, none of the research papers investigate the dock assignment problem along with inventory management and storage layout

considering real case constraints such as dock utilization, storage capacity and uncertain lead time including the cross-border time.

8. The study on the integration of the cross-dock assignment and layout considering cross-border time problems is motivated by a real-world case where there is a need to optimize the cross-dock operations considering local and global supplier's base.

9. Some researchers have investigated the border crossing time problem and tried to quantify the cross-border cost. However, none have considered the effect of the cross-border time on 3PL center in terms of storage capacity and inventory levels.

CHAPTER 3: DUAL-CHANNEL WAREHOUSE AND INVENTORY MANAGEMENT WITH STOCHASTIC DEMAND

3.1. Introduction and Motivation

New streams of research have recently commenced studying dual-channel supply chains. One stream has focused on the competition and coordination that arise between sales channels (Hua and Li, 2008; Lu and Liu, 2015; Lin, 2016; Matsui, 2016; Wang et al., 2016; Chen and Chen, 2017). Another stream has studied the challenging logistics and processes of fulfilling online orders once they have been placed (De Koster, 2003; Tetteh and Xu, 2014). Research has also been centered on price and service interaction between channels (Tango and Xing, 2001; Yao and Liu, 2005; Lu and Liu, 2013; Ryan et al., 2013; Panda et al., 2015; Rodríguez and Aydin, 2015; Liu et al., 2016; Xiao and Shi, 2016; Yan et al., 2016; Giri et al., 2017; Matsui, 2017), and online order fulfillment processes (Agatz et al., 2008; Mahar et al., 2009). Inventory management in dual-channel supply chains has also been explored (Khouja, 2003; Yao et al., 2009; Zhang and Tian, 2014; Zhao et al., 2016). However, none of the emerging research streams has examined inventory management in a joint warehouse while considering the operations and capacity of the warehouse.

This study contributes to the existing literature on warehouse management in several ways. First, it is the first work to analyze the structure of the emerging dual-channel warehouses and develop a structure related to the inventory policy for such warehouses. Second, it develops a mathematical model that determines the multi-item product inventory policy for the two areas in integrated dual-channel warehouses, minimizing their total expected cost. The constraints of warehouse space and uncertain demands are also considered. Third, it provides closed-form solutions for instances without a warehouse space constraint as well as a solution algorithm for the case with the warehouse space constraint. Furthermore, the proposed solution can be used to evaluate the performance of two-echelon dual-channel warehouse systems by comparing the total system costs for different warehouse structures and evaluating the effects of adding a new sales channel. To the best of our knowledge, this study is the first work to address the inventory policies of the emerging dual-channel warehouses with a unique structure, although, there have been several studies on inventory policies of a dual-channel supply chain.

The remainder of the chapter is structured as following: In Section 3.2, the problem is defined. Furthermore, in Section 3.3 a new mathematical model is proposed. Section 3.4 presents the solution methodology. Additionally, a numerical result is presented in Section 3.5. To end up with the conclusions in Section 3.6.

3.2. Problem Statement

The main objectives of a manufacturer's warehouse are to increase space utilization, reduce operation cost, and fulfill orders quickly and reliably. These objectives are usually conflicting. To obtain high space utilization, we need to store items in a high-density storage area such as pallets or high beam storage systems. Meanwhile, efficient order picking for online orders, which are usually of small sizes, requires the picker to have full access to the stored items, which means that they need to be displayed in low-density storage areas such as racks or stands. At the same time, to provide a high level of service, the warehouse needs to have an optimal inventory level for each item.

We consider the emerging dual-channel warehouse to fulfill both online and offline orders. To optimize the operation, the structure design of the dual-channel warehouse reflects the different features of the two different orders: the warehouse is divided into two storage areas with different inventory levels. One area, called Stage 1 area, is usually for picking items that are displayed on shelves or stands, packing, and shipping small size online customer orders, while the other area, called Stage 2 area, is for deep storage, to store inventory, replenish Stage 1, and fulfill offline retailer's large size orders. Orders from the supplier or the manufacturer will usually come in pallets and be stored first in Stage 2 area. Together, the areas form a two-echelon serial inventory control system, which is shown in Figure 3.1.

Our goal is to develop a decision support tool for the operational and strategic decision related to the dual-channel warehouse with both online and offline fulfillment capability. On the operational level, we intend to assist in determining the optimal inventory level, item flow between the deep storage area and online picking area, as well as the replenishment frequency of both areas. On the strategic level, we will analyze the effect of the warehouse structure and space reserved for the online picking area on the total operating cost.

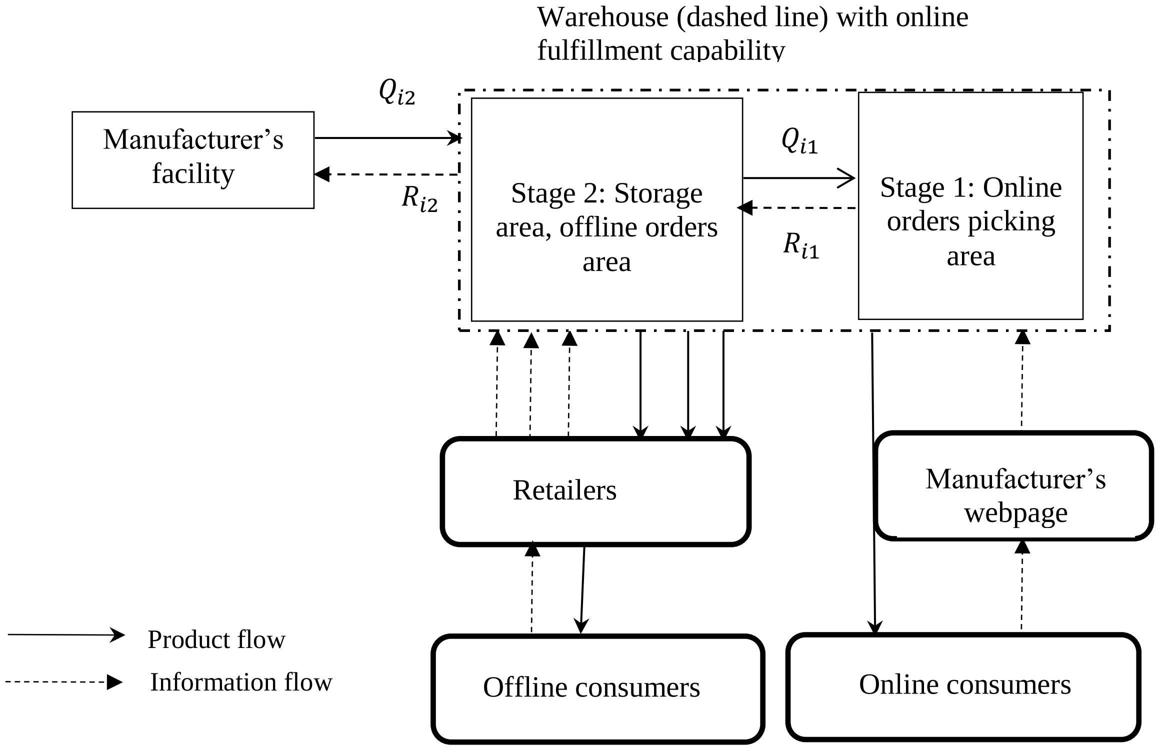

Figure 3.1 Dual-channel warehouse with online fulfillment capability

3.3 Model Formulation

3.3.1 Notations and Assumptions

The notations used in developing the mathematical model are given as follows:

i: Item index

j: Stage index, where *j* = 1 for warehouse area dedicated to satisfying online demand (online picking area), and *j* = 2 for warehouse area dedicated to satisfying both retail and dedicated online area demands

L_{ij}: Length of lead time for item *i* in stage *j* (random variable)

D_{ij}: Expected annual demand for item *i* in stage *j*

h_{ij}: Holding cost per unit time for item *i* at stage *j*

b_{ij}: Backorder cost per unit for item *i* at stage *j*

A_{ij}: Ordering cost per order for item *i* at stage *j*

x_{ij}: Demand during lead time (DDLT, random variable) for item *i* in stage *j*

$f(x_{ij})$: Probability density function of lead-time demand for item *i* at stage *j*

γ_{ij}: Storage space required by a stock keeping unit in stage *j*

α: Minimum required probability that total order quantities will be within warehouse space

S: Available space of the entire warehouse

Decision variables

Q_{i2}: Order quantity for item *i* in Stage 2

Q_{i1}: Order quantity for item *i* in Stage 1

R_{i2}: Reorder point when new order is placed for item *i* in Stage 2

R_{i1}: Reorder point when new order is placed for item *i* in Stage 1

Assumptions and preliminary analysis

1) The demand rate per unit time (day or week) during lead time is a random variable with a mean of $\mu_{d_{ij}}$ and standard deviation of $\sigma_{d_{ij}}$. We assumed that the demand standard deviation is very small relative to the mean demand; therefore, the probability of negative demand is negligible (Lee, 2005; Zhang et al., 2006).

2) The lead time L_{ij} is a random variable with a mean of $\mu_{L_{ij}}$ and a standard deviation of $\sigma_{L_{ij}}$.

3) If the DDLT for item *i* in stage *j* is in a situation where the demand and lead time are normally distributed and statistically independent, then the mean and standard deviation of the DDLT are

$$\mu_{x_{ij}} = \mu_{L_{ij}} \times \mu_{d_{ij}} \text{ and } \sigma_{x_{ij}} = \sqrt{\mu_{L_{ij}} \times \sigma_{d_{ij}}^2 + \mu_{d_{ij}}^2 \times \sigma_{L_{ij}}^2}. \tag{3.1}$$

In the situation where there is a fixed lead time,

$$\mu_{x_{ij}} = L_{ij} \times \mu_{d_{ij}} \text{ and } \sigma_{x_{ij}} = \sqrt{L_{ij} \times \sigma_{d_{ij}}^2}. \tag{3.2}$$

In the situation where there is a uniform distribution of the demand and lead time, the demand joint distribution function is defined as

$$f(x_{ij}) = \frac{1}{(d_{M_{ij}} - d_{m_{ij}})(t_{M_{ij}} - t_{m_{ij}})}. \tag{3.3}$$

Moreover, the mean of the DDLT is

$$\mu_{x_{ij}} = \frac{(d_{M_{ij}} + d_{m_{ij}})(t_{M_{ij}} + t_{m_{ij}})}{4}, \tag{3.4}$$

and the standard deviation of the DDLT is

$$\sigma_{x_{ij}} = \sqrt{\frac{(d_{M_{ij}} - d_{m_{ij}})^2 (t_{Mij} - t_{m_{ij}})^2 + 3(d_{M_{ij}} + d_{m_{ij}})^2 (t_{M_{ij}} - t_{m_{ij}})^2 + 3(d_{M_{ij}} - d_{m_{ij}})^2 (t_{M_{ij}} + t_{m_{ij}})^2}{144}}, \tag{3.5}$$

where $\left(t_{m_{ij}}, t_{M_{ij}}\right)$ are respectively the lower and upper limits of the uniform lead time demand distribution, and $(d_{m_{ij}}, d_{M_{ij}})$ are the lower and upper limits of the uniform demand distribution respectively (Das and Hanaoka, 2014). In the retail environment, where the demand per period is normally large, the normal distribution is an appropriate modeling choice (Hadley and Whitin, 1963; Silver and Peterson, 1985), particularly if we have sufficient historical data from which the mean and the standard deviation can be drawn. However, a uniform distribution is commonly used for new items in situations where such historical data is not available (Wanke, 2008). Usually, the warehouse serves many retailers via the offline channel. The integrated offline demand is large and thus, it can be assumed to reasonably follow the normal distribution or the uniform distribution.

The uniform and normal distributions are both typically used to describe uncertain demands/lead time. Our model proposed in the next section is independent of the probability distribution unless it is continuous and works for other probability distributions such as the exponential distribution. However, solving the problem, particularly those with closed-form solutions, depends on the different distributions.

4) After conducting a literature review on the dual-channel demand structure, we found that the demand is categorized within two streams. In the first stream, the demand of each channel is treated as an independent random variable. The total system demand is the aggregation of both channel demands (Alptekinoglu and Tang, 2005; Lee, 2005; Abdul-Jalbar et al., 2006; Seifert et al., 2006; Zhang et al., 2006; Bichescu and Fry, 2009). In the second stream, the demand is correlated, and the total system demand, which follows a specific distribution, is known. Then it is split between the individual channels (Lippman and McCardle, 2004; Tsay and Agrawal, 2004; Chiang and Monahan, 2005; Yao et al., 2005).

In our proposed model, we considered both cases of independent and correlated demand. Additionally, regardless of the demand structure, we have assumed that customer channel loyalty β_j ranges between 0–100%. This means that with 100% channel loyalty, sales are lost in situations where there is a sales channel absence. We assumed that online and retailer demand is independent (the assumption is relaxed in Section 5). Consequently, as an illustrative example, the single-item (we dropped the *i* index for simplicity) system demand is given as follows:

Stage 2 demand will be the aggregation of the online and offline demand, i.e., $D_2 = D_r + D_d$ and the demand at Stage 1 is $D_1 = D_d$. In the case where we have a single-retailer channel, Stage 2 demand will be the retailer demand plus the percentage of customers willing to switch from the online channel, i.e., $D_2 = D_r + \beta_1 D_d$. In cases where there is only an online channel, Stage 2 demand will be the aggregation of the online demand plus the percentage of customers willing to switch from the retailer channel: $D_2 = D_d + \beta_2 D_r$.

Stage 1 demand is given by the following:

$D_1 = D_d$ where there is a dual sales channel,

$D_1 = 0$ where there is only a retailer channel,

$D_1 = D_d + \beta_2 D_r$ where there is only an online channel.

5) This study employs a continuous review inventory control policy, also known as the (Q, R) policy. Such a policy is also used extensively in the existing literature, such as in articles by Khouj and Stylianou (2009), Yang et al. (2011), Qadikolaei et al. (2012) and Sarkara et al. (2015).

6) A demand that cannot be immediately satisfied by the inventory is backordered with a penalty cost (Hadley and Whitin, 1963; Nahmias, 2013). This is more common when dealing with online demand as online orders have more flexible delivery times than offline orders.

7) Each stage (each area in the warehouse) has a reorder point that corresponds to an installation inventory for that stage. The reorder point is equal to the expected DDLT plus the safety stock, which is a function of stock-out probability during lead time. Stage 1 receives internal shipments from Stage 2, while Stage 2 receives shipments from the supplier.

8) The orders do not cross, because a single supplier is used, or one outstanding order is assumed.

3.3.2 Mathematical Model

The problem is to determine the inventory policy for both stages in the dual-channel warehouse so that the total expected cost is minimized, subject to the warehouse capacity limit. The formulation of the problem is given as follows.

The objective of the problem is to minimize the annual total expected cost, denoted as C(Q_{i2}, R_{i2}, Q_{i1}, R_{i1}), which comprises ordering, holding, and shortage costs. For a given inventory policy (Q_{ij}, R_{ij}), the average inventory level for Stage 1 is the average cycle inventory plus the safety inventory, approximately expressed as $Q_{i1}/2 + R_{i1} - \mu_{x_{i1}}$, where $R_{i1} - \mu_{x_{i1}}$ is the safety stock. The approximation on the average inventory is reasonable for many real cases and is widely used in textbooks and in the literature (De Bodt and Graves, 1985; Yano, 1985; Zipkin, 1986; Ghalebsaz-Jeddi et al., 2004; Khouja and Stylianou, 2009; Nahmias, 2013; Fattahi et al., 2015). Similarly, the average inventory level for Stage 2 is approximately expressed as $Q_{i2}/2 + R_{i2} - \mu_{x_{i2}}$. Thus, the annual total expected cost is formulated as follows with respect to the decision variables $Q_{i2}, R_{i2}, Q_{i1}, R_{i1}$.

Objective: Min the total expect cost

$$
\begin{aligned}
\mathrm{C}(\mathrm{Q}_{i2}, \mathrm{R}_{i2}, \mathrm{Q}_{i1}, \mathrm{R}_{i1})
&= \sum_i \frac{A_{i2}\mathrm{D}_{i2}}{\mathrm{Q}_{i2}} + \sum_i \frac{A_{i1}\mathrm{D}_{i1}}{\mathrm{Q}_{i1}} + \sum_i \mathrm{h}_{i2}\left[\left(\frac{\mathrm{Q}_{i2}}{2}\right) + \left(\mathrm{R}_{i2} - \mu_{x_{i2}}\right)\right] \\
&+ \sum_i \mathrm{h}_{i1}\left[\left(\frac{\mathrm{Q}_{i1}}{2}\right) + \left(\mathrm{R}_{i1} - \mu_{x_{i1}}\right)\right] + \sum_i \frac{\mathrm{b}_{i2}\mathrm{D}_{i2}}{\mathrm{Q}_{i2}}\left[\int_{\mathrm{R}_{i2}}^{\infty} (x_{i2} - \mathrm{R}_{i2})\, f(x_{i2})\, \mathrm{d}x_{i2}\right] \\
&+ \sum_i \frac{\mathrm{b}_{i1}\mathrm{D}_{i1}}{\mathrm{Q}_{i1}}\left[\int_{\mathrm{R}_{i1}}^{\infty} (x_{i1} - \mathrm{R}_{i1})\, f(x_{i1})\, \mathrm{d}x_{i1}\right]. \qquad (3.6)
\end{aligned}
$$

The first and second terms of the objective function (3.6) refer to the annual ordering cost, which is the order cost multiplied by the number of cycles. The third and fourth terms refer to the annual approximated holding cost. The fifth and sixth terms represent the annual backorder cost, which is equal to the backorder cost multiplied by the expected number of shortages per cycle.

We consider the warehouse capacity constraint. Because of uncertain demand, we set the probability that the total simultaneous items inventory within the warehouse space when the order is received will not be smaller than α. Then we have the following constraints:

$$P\left[\left(\sum_i \gamma_{i2}(Q_{i2} + R_{i2} - x_{i2}) + \gamma_{i1}(Q_{i1} + R_{i1} - x_{i1})\right) \le S\right] \ge \alpha, \qquad (3.7)$$

$$R_{ij}, Q_{ij} \ge 0 \;\forall\; i, j. \qquad (3.8)$$

The space constraint (3.7) can be written as

$$P\left[\sum_i \gamma_{i2}x_{i2} + \gamma_{i1}x_{i1} \ge \sum_i \left(\gamma_{i2}(Q_{i2} + R_{i2}) + \gamma_{i1}(Q_{i1} + R_{i1})\right) - S\right] \ge \alpha, \qquad (3.9)$$

which can be reformulated as

$$\sum_i \left(\gamma_{i2}(Q_{i2} + R_{i2}) + \gamma_{i1}(Q_{i1} + R_{i1})\right) \leq S + \mu_Y + z_{1-\alpha}\sigma_{Y,} \tag{3.10}$$

where

$$Y = \sum_i \sum_j \gamma_{ij} x_{ij}, \mu_Y = \sum_i \sum_j \gamma_{ij}\mu_{ij}, and\ \sigma_Y^2 = \sum_i \sum_j {\gamma_{ij}}^2 \sigma_{ij}, \tag{3.11}$$

and $z_{1-\alpha}$ is the value of the cumulative probability distribution of the demand at point $1 - \alpha$ (Ghalebsaz-Jeddi et al., 2004).

A variant of the above constraint can be applied to either Stage 1 or Stage 2 in case we have a separate warehouse space limit. If the warehouse space constraint is applied to either area, we obtain the following:

For Stage 1, the constraint will be

$$\sum_i \gamma_{i1}(Q_{i1} + R_{i1}) \leq S_1 + \mu_{Y1} + z_{1-\alpha}\sigma_{Y1}, \tag{3.12}$$

where $\mu_{Y1} = \sum_i \gamma_{i1}\mu_{i1}, \sigma_{Y1}^2 = \sum_i {\gamma_{i1}}^2 \sigma_{i1}$, and S_1 is the area dedicated for Stage 1.

Meanwhile, if the space constraint is applied to Stage 2, we obtain

$$\sum_i \gamma_{i2}(Q_{i2} + R_{i2}) \leq S_2 + \mu_{Y2} + z_{1-\alpha}\sigma_{Y2}, \tag{3.13}$$

where $\mu_{Y2} = \sum_i \gamma_{i2}\mu_{i2}, \sigma_{Y2}^2 = \sum_i {\gamma_{i2}}^2 \sigma_{i2}$, and S_2 is the area dedicated for Stage 2.

The model formulated using (3.6), (3.8), and (3.10), denoted as problem *(P)*, is a constrained nonlinear program, where it is difficult to find a closed-form solution. A detailed solution approach is discussed in the next section.

3.4 Solution Methodology

Before introducing the solution approach, we define the expected shortage per cycle (ESC) and cycle service level (CSL). Silver and Peterson (1985) defined the ESC for the single-stage case. We extended the ESC to the dual-stage case as follows:

$$ESC(R_{ij}) = \int_{R_{ij}}^{\infty} (x_{ij} - R_{ij})\, f(x_{ij})dx_{ij}, \tag{3.14}$$

$$CSL: \int_0^{R_{ij}} f(x_{ij})dx_{ij}. \tag{3.15}$$

The constrained nonlinear problem given is a convex problem, which is described by the following theorem.

Theorem 1: The nonlinear programming problem *(P)* is convex.

Proof. Please see Appendix A.

Because problem *P* is a convex nonlinear program, this implies that the solution of the problem *(P)* is unique and satisfies the necessary Karush–Kuhn–Tucker (KKT) conditions. We consider a Lagrange function

$$\begin{aligned} L(Q_{i2}, R_{i2}, Q_{i1}, R_{i1}, \theta) &= \sum_i \frac{A_{i2}D_{i2}}{Q_{i2}} + \sum_i \frac{A_{i1}D_{i1}}{Q_{i1}} + \sum_i h_{i2}\left[\left(\frac{Q_{i2}}{2}\right) + \left(R_{i2} - \mu_{x_{i2}}\right)\right] \\ &+ \sum_i h_{i1}\left[\left(\frac{Q_{i1}}{2}\right) + \left(R_{i1} - \mu_{x_{i1}}\right)\right] + \sum_i \frac{b_{i2}D_{i2}}{Q_{i2}}\left[\int_{R_{i2}}^{\infty} (x_{i2} - R_{i2})\, f(x_{i2}) dx_{i2}\right] \\ &+ \sum_i \frac{b_{i1}D_{i1}}{Q_{i1}}\left[\int_{R_{i1}}^{\infty} (x_{i1} - R_{i1})\, f(x_{i1}) dx_{i1}\right] \\ &+ \theta\left[\sum_i \left(\gamma_{i2}(Q_{i2} + R_{i2}) + \gamma_{i1}(Q_{i1} + R_{i1})\right) - S - \mu_Y - z_{1-\alpha}\right], \end{aligned} \tag{3.16}$$

where θ is the Lagrange multiplier for the space constraint. Then we can find the optimal solution via the following KKT first-order conditions:

From $\frac{\partial L}{\partial Q_{ij}} = 0$, we obtain

$$-\frac{A_{ij}D_{ij}}{{Q_{ij}}^2} + \frac{h_{ij}}{2} - \frac{b_{i1}D_{i1}}{{Q_{ij}}^2}\left[\int_{R_{i1}}^{\infty} (x_{i1} - R_{i1})\, f(x_{i1}) dx_{i1}\right] + \gamma_{ij}\theta = 0. \tag{3.17}$$

Rearrange to obtain

$$Q_{ij} = \sqrt{\frac{2D_{ij}\left(A_{ij} + b_{ij}ESC(R_{ij})\right)}{h_{ij} + 2\gamma_{ij}\theta}}. \tag{3.18}$$

From $\frac{\partial L}{\partial R_{ij}} = 0$, we obtain

$$h_{ij} + \frac{b_{ij}D_{ij}}{Q_{ij}}\left[f(x_{ij})dx_{ij}\right] + \gamma_{ij}\theta = 0. \tag{3.19}$$

Rearrange to obtain

$$\int_{R_{ij}}^{\infty} f(x_{ij})dx_{ij} = \frac{(h_{ij} + \gamma_{ij}\theta)Q_{ij}}{b_{ij}D_{ij}}. \tag{3.20}$$

We also have

$$\frac{\partial L}{\partial \theta} = \sum_i \sum_j \gamma_{ij}(Q_{ij} + R_{ij}) - S - \mu_Y - z_{1-\alpha}\sigma_y \leq 0 \text{ and} \tag{3.21}$$

$$R_{ij}, Q_{ij}, \theta \geq 0 \; \forall \; i, j. \tag{3.22}$$

If (3.18) is substituted into (3.20), we obtain

$$\int_{R_{ij}}^{\infty} f(x_{ij})dx_{ij}$$

$$= \frac{(h_{ij} + \gamma_{ij}\theta)\sqrt{\frac{2D_{ij}(A_{ij} + b_{ij}ESC(R_{ij}))}{h_{ij} + 2\gamma_{ij}\theta}}}{b_{ij}D_{ij}}. \tag{3.23}$$

Squaring both sides and arranging, we obtain

$$\left[\int_{R_{ij}}^{\infty} f(x_{ij})dx_{ij}^{\;2}\right] b_{ij}^2 D_{ij}^2 = (h_{ij} + \gamma_{ij}\theta)^2 \left[\frac{2D_{ij}(A_{ij} + b_{ij}ESC(R_{ij}))}{h_{ij} + 2\gamma_{ij}\theta}\right]. \tag{3.24}$$

Rearranging the above equation, we obtain

$$b_{ij}D_{ij}\left(1 - CSL(R_{ij})\right)^2 - 2\left(h_{ij} + (h_{ij} + 1)\gamma_{ij}\theta\right)ESC(R_{ij}) - \frac{2\left(h_{ij} + (h_{ij} + 1)\gamma_{ij}\theta\right)A_{ij}}{b_{ij}}$$

$$= 0. \tag{3.25}$$

We will discuss the solution approaches for both uniform and normal demand distributions. For each distribution, we also investigate two situations: with and without warehouse space constraints (or inactive constraint). We discuss the problem without constraint because we can develop closed-form solutions for the situation, which may occur in practice.

3.4.1 Uniform Distribution Presentation of Demand and Lead- Time

This section provides the solution when the demand and lead time follow a uniform distribution. The use of uniform demand is a common approach in the case of new products whenever one does not have sufficient historical data to obtain the parameters of the probability density function of the demand or lead time (e.g., the normal distribution mean and standard deviation) (Wanke, 2008; Das and Hanaoka, 2014).

3.4.1.1 Uniform distribution and deterministic lead time without space constraint

Assume that the demand follows the uniform distribution $(0, U_{ij})$; then

$$\int_{R_{ij}}^{\infty} f(x_{ij})dx_{ij} = \left(1 - \frac{R_{ij}}{U_{ij}}\right), \tag{3.26}$$

and

$$\int_{R_{ij}}^{\infty} (x_{ij} - R_{ij}) f(x_{ij})dx_{ij} = \frac{U_{ij}}{2} - R_{ij} + \frac{R_{ij}^2}{2U_{ij}}. \tag{3.27}$$

If (3.26) and (3.27) are substituted into (3.25), then

$$b_{ij}D_{ij}\left(1 - \frac{2R_{ij}}{U_{ij}} + \frac{{R_{ij}}^2}{U_{ij}^2}\right) - 2h_{ij}\left(\frac{U_{ij}}{2} - R_{ij} + \frac{{R_{ij}}^2}{2U_{ij}}\right) - \left(\frac{2h_{ij}A_{ij}}{b_{ij}}\right) = 0. \tag{3.28}$$

Rearranging the above equation, we obtain

$$\left(\frac{b_{ij}}{U_{ij}^2} - \frac{h_{ij}}{U_{ij}}\right)R_{ij}^2 - \left(2h_{ij} - \frac{2b_{ij}D_{ij}}{U_{ij}}\right)R_{ij} + \left(b_{ij}D_{ij} - h_{ij}U_{ij} - \frac{2h_{ij}A_{ij}}{b_{ij}}\right) = 0. \tag{3.29}$$

The result is a quadratic equation with one unknown, R_{ij}. Then we can determine the optimal reorder point for each stage:

$$R_{ij} = \frac{-\left(2h_{ij} - \frac{2b_{ij}D_{ij}}{U_{ij}}\right) \pm \sqrt{\left(2h_{ij} - \frac{2b_{ij}D_{ij}}{U_{ij}}\right)^2 - 4\left(\frac{b_{ij}}{U_{ij}^2} - \frac{h_{ij}}{U_{ij}}\right)\left(b_{ij}D_{ij} - h_{ij}U_{ij} - \frac{2h_{ij}A_{ij}}{b_{ij}}\right)}}{2\left(\frac{b_{ij}}{U_{ij}^2} - \frac{h_{ij}}{U_{ij}}\right)}. \tag{3.30}$$

With R_{ij} calculated above, we can determine the optimal order quantity Q_{ij} using (3.18).

3.4.1.2 Uniform distribution and stochastic lead time without space constraint

In the case of a stochastic demand and stochastic lead time, an integration should be obtained using the joint distribution function of two random variables. If the demand by unit time follows the uniform distribution U~ (0, d_M) and the lead time U~ (0, t_M), then

$$\int_{R_{ij}}^{\infty} f(x_{ij})dx_{ij} = = 1 - \left[\frac{R_{ij}}{(d_{M_{ij}}t_{M_{ij}})}\left(1 + ln\left(\frac{d_{M_{ij}}t_{M_{ij}}}{R_{ij}}\right)\right)\right], \tag{3.31}$$

and

$$\int_{R_{ij}}^{\infty}(x_{ij}-R_{ij})f(x_{ij})dx = \frac{1}{(2d_{M_{ij}}t_{M_{ij}})}\left[\frac{t_{M_{ij}}^2}{2}\left(d_{M_{ij}}^2-\frac{{R_{ij}}^2}{t_{M_{ij}}^2}\right)-{R_{ij}}^2 ln\left(\frac{d_{M_{ij}}t_{M_{ij}}}{R_{ij}}\right)\right]-$$

$$R_{ij}\left[1-\left(\frac{R_{ij}}{(d_{M_{ij}}t_{M_{ij}})}(1+\ln\left(\frac{d_{M_{ij}}t_{M_{ij}}}{R_{ij}}\right)\right)\right]. \quad (3.32)$$

When (3.31) and (3.32) are substituted into (3.25), then

$$b_{ij}D_{ij}\left[\left(1-\left(\frac{R_{ij}}{(d_{M_{ij}}t_{M_{ij}})}\left(1+ln\left(\frac{d_{M_{ij}}t_{M_{ij}}}{R_{ij}}\right)\right)\right)\right)\right]^2$$

$$-2h_{ij}\left[\left(\frac{1}{(2d_{M_{ij}}t_{M_{ij}})}\right)\left(\frac{t_{M_{ij}}^2}{2}\left(d_{M_{ij}}^2-\frac{{R_{ij}}^2}{t_{M_{ij}}^2}\right)-{R_{ij}}^2 ln\left(\frac{d_{M_{ij}}t_{M_{ij}}}{R_{ij}}\right)\right)\right.$$

$$\left.-R_{ij}\left(1-\left(\frac{R_{ij}}{(d_{M_{ij}}t_{M_{ij}})}(1+\ln\left(\frac{d_{M_{ij}}t_{M_{ij}}}{R_{ij}}\right)\right)\right)\right]-\frac{2h_{ij}A_{ij}}{b_{ij}}=0. \quad (3.33)$$

Equation (3.33) is nonlinear with the single variable of reorder point R_{ij}, which can be solved using an Excel spreadsheet, or using an advanced math program, such as Matlab. With the calculated optimal reorder point, we can determine the optimal order quantity Q_{ij} using (3.18) for this case.

3.4.1.3 Uniform Distribution with Space Constraint

When there is a warehouse space constraint, we can determine the optimal solution by solving the dual problem of the Lagrangian function given in (3.16):

$Max_{\theta}\ Min\ L(Q_{i2}, R_{i2}, Q_{i1}, R_{i1}, \theta)$.

Actually, we can solve the problem first without considering the warehouse constraint through equations (3.30) or (3.33), and then check the constraint (3.10). If the constraint is satisfied, then we determine the optimal solution for the original problem. Otherwise, we can use either a subgradient method or bisection search to solve the Lagrangian dual problem. Because the problem is convex, there is a unique solution. In this case, based on (3.21), we have

$$\sum_i\sum_j\gamma_{ij}(Q_{ij}+R_{ij})-S-\mu_Y-z_{1-\alpha}\sigma_y=0. \quad (3.34)$$

For a given value of θ, Q_{ij} and R_{ij} can be calculated using (3.30) or (3.33); then they can be substituted into equation (3.34). This reduces the problem to a solution for one equation with one unknown θ:

$$g(\theta) = \sum_{i} \sum_{j} \gamma_{ij} \left(Q^{\sim}{}_{ij} + R^{\sim}{}_{ij} \right) - S - \mu_Y - z_{1-\alpha} = 0. \tag{3.35}$$

As there is one variable and solution uniqueness, we can use the bisection search method to determine the solution. Therefore, if there are two distinct values of $\theta_1$and θ_2, such that $g(\theta_1)$ and $g(\theta_2) < 0$, satisfying this condition is sufficient to allow using any one-dimensional search technique to solve (4.30). The following algorithm is thus proposed.

1. Let $\theta_1 = 0$ and let θ_2 be the smallest number, such that $g(\theta_2) < 0$.
2. Let $Q_1^{\sim}, R_1^{\sim}$ be the solution when $\theta = \theta_1$, and let $Q_2^{\sim}, R_2^{\sim}$be the solution when $\theta = \theta_2$.
3. Let $\theta = \frac{\theta_1 + \theta_1}{2}$ and solve for $Q^{\sim}$ and $R^{\sim}$; find $g(\theta)$.
4. If $g(\theta) > 0$, then $\theta_1 = \theta, Q_1^{\sim} = Q^{\sim}$, and $R_1^{\sim} = R^{\sim}$; if $g(\theta) < 0$, then $\theta_2 = \theta, Q_2^{\sim} = Q^{\sim}$, and $R_2^{\sim} = R^{\sim}$.
5. If $\left(g(\theta_1) - g(\theta_2)\right) < \varepsilon_g$, then stop. Otherwise, go to 3.

3.4.2 Normal Distribution Demand and Lead Time

In situations where sufficient historical data are available, the normal probability distribution for the demand and lead time can be generally estimated. Using the formulas presented in assumption 3, we can calculate the mean and standard deviation of the DDLT for deterministic or stochastic lead time. In the next sections, we will discuss the solution methodology when space constraint is active or inactive.

3.4.2.1 Normal Distribution Without Space Constraint

Given that $R_{ij} = \mu_{x_{ij}} + k\sigma_{x_{ij}}$, the expected shortage per cycle can be formulated as a function of the safety factor *k*, as presented by Kundu and Chakrabarti (2012). In situations where there is a single channel, the proposed formula may be extended to consider two-echelon dual-channel situations. If

$$ESC(R_{ij}) = \frac{\sigma_{x_{ij}}}{2} \left(\sqrt{1 + k_{ij}^2} - k_{ij} \right), \tag{3.36}$$

then the Lagrange function for the independent demand is

$$L\left(Q_{ij},k_{ij},\theta\right)=\sum_i\sum_j\frac{A_{ij}D_{ij}}{Q_{ij}}+h_{ij}\left(\left(\frac{Q_{ij}}{2}\right)+k_{ij}\sigma_{x_{ij}}\right)+\frac{b_{ij}D_{ij}}{Q_{ij}}\left(\frac{\sigma_{x_{ij}}}{2}\left(\sqrt{1+k_{ij}^2}-k_{ij}\right)\right)$$

$$+\theta\left[\sum_i\sum_j\gamma_{ij}\left(Q_{ij}+\mu_{x_{ij}}+k_{ij}\sigma_{x_{ij}}\right)-S-\mu_Y-z_{1-\alpha}\right]. \quad (3.37)$$

Using the necessary KKT conditions for minimization problems, we obtain

$$\frac{\partial L}{\partial Q_{ij}}=0,-\frac{A_{ij}D_{ij}}{{Q_{ij}}^2}+\frac{h_{ij}}{2}-\frac{b_{ij}T_{ij}\left(\frac{\sigma_{x_{ij}}}{2}\left(\sqrt{1+k_{ij}^2}-k_{ij}\right)\right)}{{Q_{ij}}^2}+\theta\gamma_{ij}$$

$$=0. \quad (3.38)$$

This leads to

$$Q_{ij}=\sqrt{\frac{2D_{ij}\left[A_{ij}+b_{ij}\left(\frac{\sigma_{x_{ij}}}{2}\left(\sqrt{1+k_{ij}^2}-k_{ij}\right)\right)\right]}{h_{ij}+2\gamma_{ij}\theta}}, \quad (3.39)$$

$$\frac{\partial L}{\partial k_{ij}}=0,h_{ij}\sigma_{x_{ij}}+\frac{b_{ij}D_{ij}}{2Q_{ij}}\left[\sigma_{x_{ij}}\left(\frac{k_{ij}}{\sqrt{1+k_{ij}^2}}-1\right)\right]+\theta\gamma_{ij}\sigma(x)_{ij}=0. \quad (3.40)$$

If we substitute (3.39) into (3.40), we have

$$\frac{b_{ij}D_{ij}}{2\sqrt{\frac{2D_{ij}\left[A_{ij}+b_{ij}\left(\frac{\sigma_{x_{ij}}}{2}\left(\sqrt{1+k_{ij}^2}-k_{ij}\right)\right)\right]}{h_{ij}+2\gamma_{ij}\theta}}}\left(\sigma_{xij}\left(\frac{k_{ij}}{\sqrt{1+k_{ij}^2}}-1\right)\right)+h_{ij}\sigma_{x_{ij}}+\gamma_{ij}\sigma_{x_{ij}}\theta$$

$$=0. \quad (3.41)$$

As the warehouse space constraint is not active, $\theta=0$; the remainder is one equation with one unknown. We may solve for k_{ij} and consequently find $Q_{ij}$and R_{ij}.

3.4.2.2 Normal Distribution with Space Constraint

When the warehouse space constraint is active, we can apply the solution approach presented for the uniform distribution. Similar to the KKT conditions on Lagrangian multiplier with a uniform distribution, we have

$$\frac{\partial L}{\partial \theta} = \sum_i \left(\gamma_{i2}\left(Q_{i2} + \sigma_{x_{i2}} k_{i2}\right) + \gamma_{i1}\left(Q_{i1} + \sigma_{x_{i1}} k_{i1}\right)\right) - S - \mu_Y - z_{1-\alpha} \leq 0. \quad (3.42)$$

With the bisection search method in Section 3.4.1.3, we can obtain the solution.

3.5 Extension to Correlated Demands

In this section, we extend the model to the situation where the demands from the two stages are correlated. We assume that the total demand D is known and follows a specific distribution. To determine the Stage 2 and Stage 1 demand, we define a channel demand split factor φ, where the online demand = φD and retailer demand = (1− φ)D (Yao et al., 2009). In this case, Stage 2 demand will be as follows:

$D_2 = D$ where there is a dual sales channel;

$D_2 = (1 - \varphi D) + \beta_1 (\varphi D)$ where there is only a retailer channel;

$D_2 = \varphi D + \beta_2 (1 - \varphi) D$ where there is only an online channel.

Stage 1 demand will be

$D_1 = \varphi D$ where there is a dual sales channel;

$D_1 = 0$ where there is only a retailer channel;

$D_1 = \varphi D + \beta_2 (1 - \varphi) D$ where there is only an online channel.

The model given by (3.6) and (3.10) is changed with the following new objective function:

$$\begin{aligned} C(Q_{i2}, R_{i2}, Q_{i1}, R_{i1}) &= \sum_i \frac{A_{i2} D_i}{Q_{i2}} + \sum_i \frac{A_{i1} \varphi_i D_i}{Q_{i1}} + \sum_i h_{i2} \left[\left(\frac{Q_{i2}}{2}\right) + \left(R_{i2} - \mu_{x_{i2}}\right)\right] \\ &+ \sum_i h_{i1} \left[\left(\frac{Q_{i1}}{2}\right) + \left(R_{i1} - \mu_{x_{i1}}\right)\right] + \sum_i \frac{b_{i2} D_{i2}}{Q_{i2}} \left[\int_{R_{i2}}^{\infty} (x_{i2} - R_{i2})\, f(x_{i2})\, dx_{i2}\right] \\ &+ \sum_i \frac{b_{i1} D_{i1}}{Q_{i1}} \left[\int_{R_{i1}}^{\infty} (x_{i1} - R_{i1})\, f(x_{i1})\, dx_{i1}\right]. \end{aligned} \quad (3.43)$$

S.T.

$$\sum_i \left(\gamma_{i2}(Q_{i2} + R_{i2}) + \gamma_{i1}(Q_{i1} + R_{i1})\right) \leq S + \mu_Y + z_{1-\alpha}\sigma_Y. \quad (3.44)$$

Applying the solution approach presented in Section 3.4, we obtain

$$L(Q_{i2}, R_{i2}, Q_{i1}, R_{i1}, \theta)$$
$$= \sum_i \frac{A_{i2}D_i}{Q_{i2}} + \sum_i \frac{A_{i1}\varphi_i D_i}{Q_{i1}} + \sum_i h_{i2}\left[\left(\frac{Q_{i2}}{2}\right) + \left(R_{i2} - \mu_{x_{i2}}\right)\right]$$
$$+ \sum_i h_{i1}\left[\left(\frac{Q_{i1}}{2}\right) + \left(R_{i1} - \mu_{x_{i1}}\right)\right] + \sum_i \frac{b_{i2}D_{i2}}{Q_{i2}}\left[\int_{R_{i2}}^{\infty} (x_{i2} - R_{i2})\, f(x_{i2})\, dx_{i2}\right]$$
$$+ \sum_i \frac{b_{i1}D_{i1}}{Q_{i1}}\left[\int_{R_{i1}}^{\infty} (x_{i1} - R_{i1})\, f(x_{i1})\, dx_{i1}\right]$$
$$+ \theta\left[\sum_i \left(\gamma_{i2}(Q_{i2} + R_{i2}) + \gamma_{i1}(Q_{i1} + R_{i1})\right) - S - \mu_Y - z_{1-\alpha}\right]. \quad (3.45)$$

Using the necessary KKT conditions for minimization problems, we obtain

$$b_{i2}D_i\left(1 - CSL(R_{i2})\right)^2 - 2(h_{i2} + (h_{i2} + 1)\gamma_{i2}\theta)ESC(R_{i2}) - \frac{2(h_{i2} + (h_{i2} + 1)\gamma_{i2}\theta)A_{i2}}{b_{i2}}$$
$$= 0, \quad (3.46)$$

and

$$b_{i1}\varphi_i D_i\left(1 - CSL(R_{i1})\right)^2 - 2(h_{i1} + (h_{i1} + 1)\gamma_{i1}\theta)ESC(R_{i1}) - \frac{2(h_{i1} + (h_{i1} + 1)\gamma_{i1}\theta)A_{i1}}{b_{i1}} = 0, \quad (3.47)$$

$$\frac{\partial L}{\partial \theta} = \sum_i \left(\gamma_{i2}(Q_{i2} + R_{i2}) + \gamma_{i1}(Q_{i1} + R_{i1})\right) - S - \mu_Y - z_{1-\alpha}\sigma_y \leq 0. \quad (3.48)$$

The solution methodology discussed for the independent demand model can be used to solve the correlated demand model for uniform and normal demands.

3.6. Numerical Examples and Results

In this section, we present numerical examples to verify the model and solution methods and to show the results for different demand distributions and the effects of demand features, warehouse space, and channel preference.

3.6.1 Model Parameters

The parameters used for the experiment are based on the following observations:

$\gamma_1 > \gamma_2$: γ represents the storage requirements in the warehouse per item. The assumption is based on the fact that the space required for each unit stored on pallets in Stage 2 is less than that in Stage 1, where items are usually stored in low-density storage systems such as stands or racks to facilitate the individual item picking process.

$D_2 > D_1$: *D* represents the demand. Offline demand is usually higher than online demand and the order size for an offline channel demand is larger than that for an online channel.

$A_2 > A_1$: *A* represents the ordering cost. The ordering process for Stage 1 aims to replenish items for Stage 2, while the replenishment for Stage 2 requires ordering items from the supplier. Thus, the ordering cost for Stage 2 from the external supplier is higher.

$b_2 > b_1$: *b* represents the backorder cost. The backorder cost for the online channel is set to be less than that of the offline channel. The size of an online order is usually smaller than that of an offline order, and online orders have more flexible delivery times than offline orders (Agatz et al., 2008). Having a shortage in offline orders usually results in a higher penalty based on the contract signed between the manufacturers and retailers, while shortage in an online order has a lesser economic effect on the manufacturers; therefore, it is reasonable to have a shortage cost for Stage 2 that is higher than that for Stage 1.

$h_1 > h_2$: *h* represents the holding cost per item. The holding cost for the online channel is higher than that for the offline channel as the required space to store a unit in the online low-density area is greater than that in the offline high-density area.

3.6.2 Numerical Examples for Independent Demands

We testes seven examples with different demand distributions and lead times for the case where the demands are independent. The input parameters used are given in Appendix B.

3.6.2.1 Uniform Distribution Demand

The first example is the dual-channel warehouse with independent demands that follow the uniform distribution, while the lead time is deterministic. Table 3.1 presents the obtained solution for two items with a uniform distribution demand. For instance, the order size for item 1 is 19,010 units, while the reorder point is 1003 units. Stage 2 replenishes Stage 1 with a batch of 335 units at a reorder point of 131 units. The total system cost is $33,566.

Table 3.1 Inventory policy (Q, R) and cost for Example 1

Order Quantity		Reorder point		Total Cost
Q_{11}	335	R_{11}	131	$33,566
Q_{12}	19010	R_{12}	1003	
Q_{21}	142	R_{21}	51	
Q_{22}	7663	R_{22}	401	

Example 2 is the same as Example 1 but without the warehouse constraint. In addition, both deterministic and stochastic lead times are considered. Table 3.2 presents the main parameters and results. The reorder point with a stochastic lead time (more safety stock) has increased to cope with higher uncertainty.

Table 3.2 Results for Example 2 with uniform demand and stochastic lead time

	Input parameters						Results (Q, R)		
	d_M	t_M	D	A	B	h	R	Q	Total Cost
Deterministic	60	0	60000	500	60	10	30	2388	\$29,809
lead time	50	0	45000	500	60	10	25	1985	
Stochastic lead	60	15	60000	500	60	10	2135	18457	\$35,964
time	50	18	45000	500	60	10	2111	15753	

3.6.2.2 Normal Distribution Demand

Table 3.3 presents the solution for Example 3, which has a normal distribution demand and deterministic lead time, but no space constraint. Example 4 is the same as Example 3 except that it has a stochastic lead time for Stage 2 (note that the lead time for Stage 1 remains deterministic). As we can observe, the reorder point for the stochastic case is higher than that of the deterministic case, and the total cost is increased from \$5,561 to \$6,030 as the inventory holding cost increases because we have to keep more safety stock to cope with higher demand variation (see Table 3.4).

Table 3.3 Results for Example 3 with normal distribution demand and deterministic lead time

Order Quantity		Reorder Point		Safety Factor		Total Cost
Q_{11}	155	R_{11}	4	k_{11}	1.517	\$5,561
Q_{12}	246	R_{12}	128	k_{12}	2.117	
Q_{21}	238	R_{21}	3	k_{21}	1.494	
Q_{22}	336	R_{22}	106	k_{22}	1.979	

Table 3.4 Results for Example 4 with normal distribution demand and stochastic lead time

Order Quantity		Reorder Point		Safety Factor		Total Cost
Q_{11}	155	R_{11}	4	k_{11}	1.517	\$6,030

Q_{12}	250	R_{12}	154	k_{12}	2.117
Q_{21}	238	R_{21}	3	k_{21}	1.494
Q_{22}	340	R_{22}	124	k_{22}	1.979

To observe the effect of warehouse space, Example 5 illustrates the optimal inventory policy for the situation with normal distribution demand and deterministic lead time with warehouse capacity constraint. Table 3.5 presents the obtained results.

Table 3.5 Results for Example 5 with normal distribution and space constraint

θ	J	Q_j	R_j	$g(\theta)$
0.5	1	43	13	
0.5	2	879	472	−310

As we can observe in Table 4.5, the order quantity for Stage 2 is in batches of 879 items and an order is placed when the inventory position drops to 472 units. Stage 2 replenishes Stage 1 in batches of 43 units each time area one inventory level drops to 13 units. The order size and the reorder point decrease until the warehouse space constraint is not active.

3.6.2.3 Online and Offline Demands with Different Distributions

In some scenarios, the demands of the two stages do not follow the same distribution. Examples 6 and 7 are provided to observe the solutions under the situation with different demand distributions. Example 6 assumes that the demands of Stage 1 and Stage 2 follow the uniform distribution and normal distribution respectively, while Example 7 shows the opposite case. Table 3.6 and Table 3.7 present the parameters and the inventory policies for Examples 6 and 7 respectively. This demonstrates the flexibility of our model to capture the demand nature in the dual-channel supply chain.

Figure 3.2 illustrates the effect of different switch rates of the offline demand to the online demand on the online inventory policy, for the normal independent demand and deterministic lead time without space constraint. This scenario usually occurs when a certain percentage of customers switch from the physical store shopping to the online. As shown, the higher the switch rate, the higher is the order size and the reorder point. When more customers switch from offline to online shopping, the online demands increase. To reduce ordering cost, the order size increases if the warehouse has enough space. The reorder point increases because the DDLT also increases a little. The effect on order size is higher than that on the reorder point.

Table 3.6 Parameters and results for Example 6 with different demand distributions

Input parameters				Results (Q, R)			
D_{11}	3000	U_{21}	10	R_{11}	131	Q_{11}	335
D_{21}	1200	U_{31}	28	R_{21}	51	Q_{21}	142
D_{31}	4500	μ_{12}	2000	R_{31}	198	Q_{31}	350
D_{12}	24000	μ_{22}	1200	R_{12}	790	Q_{12}	2125
D_{22}	9600	μ_{32}	3500	R_{22}	645	Q_{22}	1756
D_{32}	45000	σ_{12}	150			Q_{32}	3660
U_{11}	25	σ_{22}	110			Total Cost	$5,315
		σ_{32}	165				

Table 3.7 Parameters and results for Example 7 with different demand distributions

Input parameters				Results (Q, R)			
D_{11}	3500	μ_{21}	100	R_{11}	340	Q_{11}	360
D_{21}	1400	μ_{31}	320	R_{21}	145	Q_{21}	162
D_{31}	5000	U_{12}	2000	R_{31}	470	Q_{31}	395
D_{12}	24500	U_{22}	1200	R_{12}	880	Q_{12}	2300
D_{22}	10000	U_{32}	3500	R_{22}	665	Q_{22}	1955
D_{32}	47000	σ_{11}	20			Q_{32}	3690
μ_{11}	250	σ_{21}	12			Total Cost	$6,015
S	2400	σ_{31}	67				

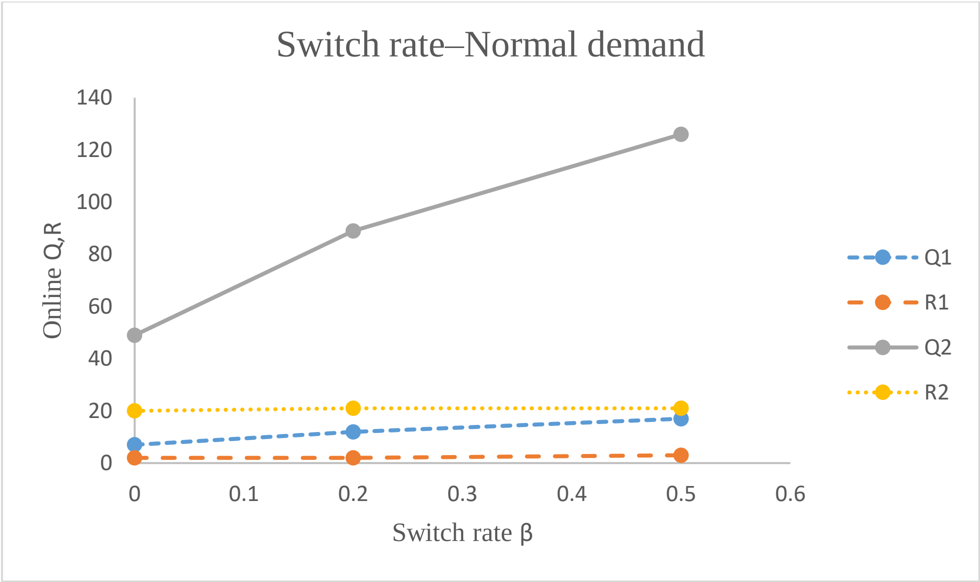

Figure 3.2 Inventory policy as a function of the switch rate

We perform a sensitivity analysis on the demand, mean of the DDLT, and standard deviation of the DDLT for different switch rates (0, 0.2, and 0.5). The results for 17 scenarios are listed in Table 3.8.

Table 3.8 Effect of switch rates on optimal inventory policies

	$\beta = 0$				$\beta = 0.2$				$\beta = 0.5$			
	Q_1	R_1	Q_2	R_2	Q_1	R_1	Q_2	R_2	Q_1	R_1	Q_2	R_2
D	7	2	49	20	12	2	89	21	17	3	126	21
D + 10%	7	2	52	20	12	2	90	21	17	3	127	21
D + 20%	7	2	54	20	13	2	91	21	18	3	128	21
D + 30%	8	2	56	20	13	2	92	21	18	3	129	21
D − 10%	6	2	47	19	12	2	87	21	17	3	125	21
D − 20%	6	2	44	19	12	2	86	21	17	3	125	21
D − 30%	6	2	42	19	12	2	85	21	17	3	124	21
μ + 10%	7	2	49	21	12	3	89	22	17	3	126	23
μ + 20%	7	3	49	22	12	3	89	24	17	3	127	24
μ + 30%	7	3	49	24	12	3	89	25	17	3	126	26
μ − 10%	7	2	49	18	12	2	89	19	17	2	126	20
μ − 20%	7	2	49	17	12	2	89	18	17	2	126	19
μ − 30%	7	2	49	15	12	2	89	17	17	2	126	17

σ + 20%	7	2	50	20	12	3	89	22	17	3	127	23
σ − 20%	7	2	49	18	12	2	88	19	17	2	126	20
All + 20%	7	3	50	23	12	3	89	25	17	3	127	26
All − 20%	7	2	49	16	12	2	88	17	17	2	126	17

As indicated in Table 3.8, the order sizes increase when switch rates increase for all scenarios, and the reorder points increase for most situations, which means that the result is robust. Moreover, Table 3.8 indicates that the total expected demand has a major effect on the order size. As the total expected demand increases, the order size logically increases as well.

3.6.3 Results for Correlated Demand

In this section, we illustrate the solution for the correlated demand model with normal demand. Figure 3.3 shows the solution of the model with different split factors (φ). As we can observe, as the split factor increases, the online demand increases and the offline demand decreases, and consequently the order sizes and the reorder point of Stage 1 are increasing as well. The changes in the online demand affect the offline demand considerably compared to that of the independent demand model.

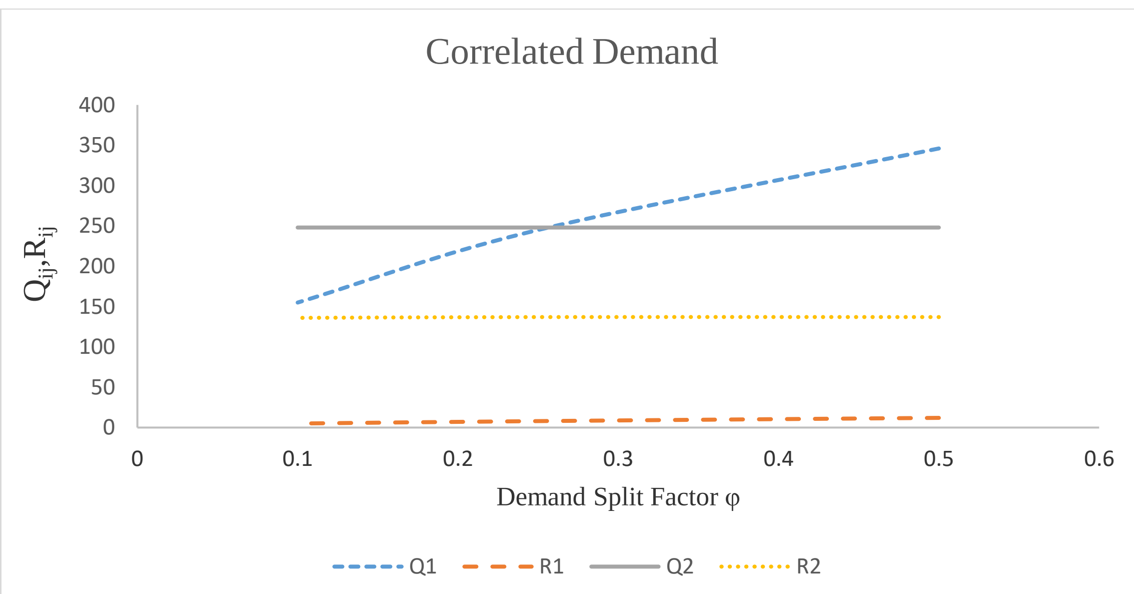

Figure 3.3 Effect of the demand split factor on inventory policy

Furthermore, as shown in Figure 3.3, the split factor has more effect on the order size than on the reorder point. The order size is linearly increased as the split factor increases while the reorder point is almost unaffected. This demonstrates the flexibility of the proposed model and how it can be used as a support tool for independent and correlated demands.

3.6.4 Sensitivity Analysis and Model Robustness

To demonstrate the robustness of the proposed solutions, we perform a numerical analysis involving the main model parameters including the demand (total expected demand, and the mean of DDLT), backorder cost, and available warehouse space. We solve the base problem and the scenarios when each input parameter is increased or decreased by 10%. The obtained solution of the base model and the solution of all scenarios are presented in Table 3.9.

Based on the results given in Table 3.9, we can calculate the relative changes in the solution making different changes to the model parameters: increasing the expected annual demand by 20% would increase the order sizes, reorder points, and total cost by an average of 5.7%, 4.0%, and 9.9% respectively. The order sizes and reorder points would increase by an average of 9.7% and 7.70%, respectively should the average DDLT increase by 20%, while the total cost does not change.

Table 3.9 Effect of model parameters on the optimal solutions

Scenario	R_{11}	R_{12}	R_{21}	R_{22}	Q_{11}	Q_{12}	Q_{21}	Q_{22}	TC
D	6	17	8	21	96	114	191	203	$3,686
D + 10%	6	18	8	22	96	114	200	213	$3,855
D − 10%	6	17	8	20	95	113	181	193	$3,508
μ + 10%	7	17	8	21	104	124	191	203	$3,686
μ − 10%	6	17	7	21	87	104	191	203	$3,686
b + 10%	6	17	8	21	96	114	191	203	$3,693
b − 10%	6	17	8	21	95	113	191	203	$3,677
S − 10%	5	16	7	19	94	112	189	201	$3,687
S − 20%	4	12	6	14	92	110	182	193	$3,708

Because the space constraint for the base case is not active, we observe the effect of space by decreasing the space by 10% and 20% to make the constraint active. Increasing the space by 10% (from −20% to −10%) would increase the order sizes and reorder points by an average of 3.0% and 27.7% respectively. It is interesting to note that the warehouse space has a significant effect on the reorder point. This is because the system will reduce the safety inventory if it encounters a space issue.

3.6.5 Cost Comparison between Dual-Channel Warehouse and Decentralized Warehouse

This experiment demonstrates how the proposed model is used as a decision support tool when deciding whether to have two decentralized warehouses or one dual-channel warehouse when adding a new sales channel. A company with an offline channel typically investigates the possibility of adding an online channel when considering expanding to a dual-channel business, or vice versa. Note that for an online channel only, the warehouse usually needs to be divided into two areas: deep storage area and front picking area (Xu, 2005). However, for an offline channel only, the warehouse is not divided, but instead, the entire warehouse is used as a deep storage area as retailer orders are sent in pallets; hence, a small picking area is not required.

Figure 3.4 shows the total operating costs for a decentralized warehouse system with two single warehouses (one for online fulfillment and the other for the offline channel) and the cost of the dual-channel warehouse for different demands. For a single online channel only, the warehouse is segregated into high- and low-density areas. There are ordering costs from area one to area two and ordering costs from area two to an external supplier. There are backorder costs for area one and area two in addition to holding costs. Moreover, for a single offline channel only, the warehouse would not be divided into two areas. The total cost comprises ordering costs from an external supplier, holding costs, and backorder costs. Finally, the dual-channel warehouse is a centralized warehouse fulfilling the demand of both channels. In conclusion, the cost of operating the dual-channel warehouse is significantly lower than the cost of operating an online channel or an offline channel separately, which means that the dual-channel warehouse is cost effective.

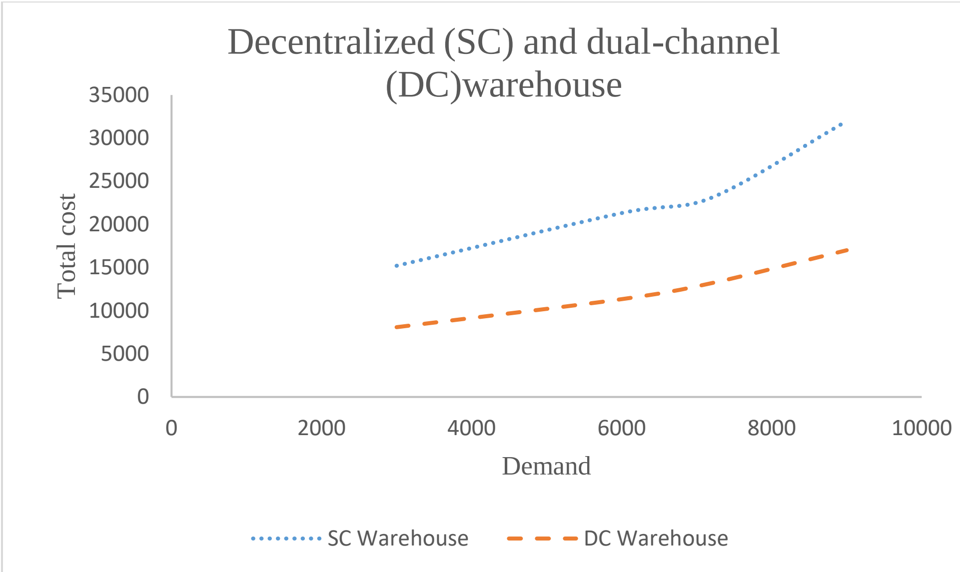

Figure 3.4 Cost comparison of decentralized and dual-channel warehouse with different demands

3.6.6 Sales Channel Decision Insights

One of the major decisions faced by a management team of the dual-channel business is to decide what items to sell offline, online, or in both channels and to analyze the effect of online and offline sales on the cost. The proposed model is a useful decision support tool with regard to calculating the incurred inventory related cost in such a dilemma. Table 3.10 presents the results obtained for an item with different offline demand increments for three scenarios of online demand, namely unchanged, increased, and decreased, owing to the addition of the offline demand. We can observe that with a 200-unit offline demand, the cost of the system is increased from $4,208 to $4,915, which is approximately $3.5 per unit of additional demand in the case where the online demand is unchanged, and $3.3 per unit if the online demand decreases when the item is also offered offline. If the offline demand is 600 units, the total cost of the system is increased to $5,425, which is approximately $2 per unit of additional demand. Based on the cost increment, decision makers can make an informed decision on which channel to offer the items. The obtained results support the idea that low-demand items should be sold online while fast-moving items should be sold both online and offline.

Table 3.10 Cost and inventory policy with different sales channel demands

Input parameters		Results (Q, R)				
Online demand	Offline demand	Q_1	Q_2	R_1	R_2	*Total Cost*

1200	0	96	174	12	12	$4,208
1200	200	96	190	12	34	$4,915
1200	400	96	204	12	34	$5,178
1200	600	96	216	12	35	$5,425
1100	200	88	195	11	32	$4,881
1100	400	88	202	11	33	$5,022
1300	200	89	202	11.5	33	$5,022
1300	400	105	215	11.5	35	$5,328
1300	600	105	220	14	36	$5,549

3.6.7 Channel Preference and Backorder Cost

In some cases, owing to the business nature, we need to decide on channel preference in terms of which channel will be prioritized to fulfill the demand. Channel preference can be easily incorporated into our model by modifying the backorder cost. Figure 3.5 illustrates an example of backorder cost and its effect on the channel preference.

As we can observe in Figure 3.5, we keep the backorder cost constant for the offline channel and increase the backorder cost for the online channel. The offline fill rate decreases, and the online fill rate increases as the online backorder cost increases. The higher the online backorder cost is, the higher the online service level will be. One of the interesting findings is that the fill rate of the offline channel keeps decreasing although the fill rate of the online channel reaches almost 99%. This is because the backorder cost affects the fill rate directly. As the online backorder cost increases, the optimal solution will tend to minimize the expected shortages and consequently increases the fill rate by keeping a higher level of safety stock in the online fulfillment area, which increases the possibility of stock out in Stage 2.

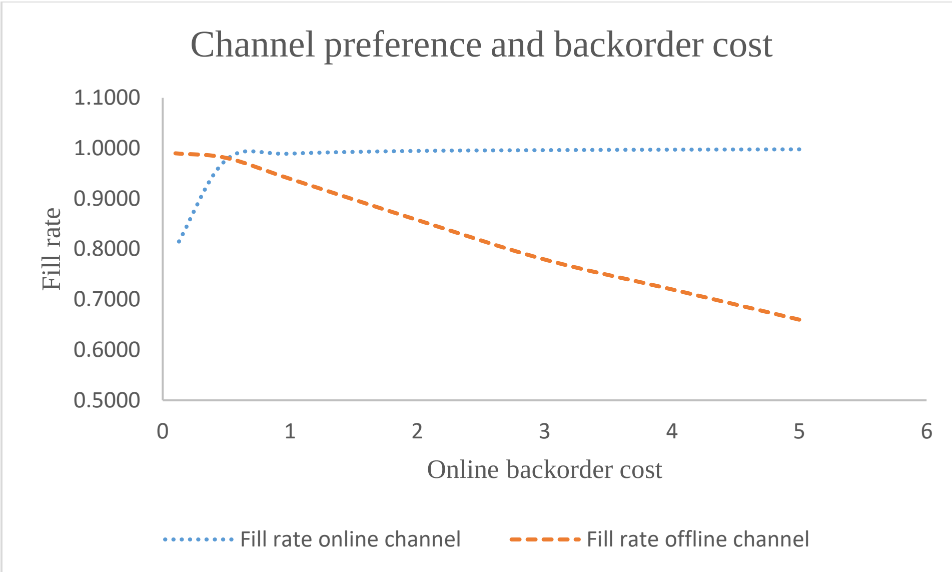

Figure 3.5 Backorder cost and channel preference

3.6.8 Dual-Channel Warehouse Space Effects

This section highlights the importance of having an appropriate warehouse space assigned to both offline and online areas and demonstrates how the proposed model can be used as a support tool for analyzing the effect of space and the effectiveness of the proposed warehouse management. The model has been run for two different cases: one case considers total warehouse space as a constraint, while the other case considers individual warehouse space constraint per area.

Table 3.11 presents the obtained results when a total warehouse space of S = 1000 m^2 is considered. The total system cost is $3,693.00. The corresponding order quantities and reorder points for the online and offline warehouse areas are within a safety factor of approximately 1.35. If the warehouse space constraint is considered individually per area and the online fulfillment area is limited to 300 m^2, the cost of the system is increased to $3,739.00, as indicated in Table 3.12. The safety factor for the offline area remained the same, while the safety factor for the online area decreased to approximately 1.28 owing to the space limitation.

Table 3.11 Inventory policy and cost with warehouse space constraint (S = 1000 m^2)

Order Quantity		Reorder Point		Safety Factor		Total Cost
Q_{11}	18	R_{11}	8	k_{11}	1.379	$3,693.00
Q_{12}	192	R_{12}	97	k_{12}	1.324	

Q_{21}	21	R_{21}	6	k_{21}	1.348
Q_{22}	203	R_{22}	114	k_{22}	1.355

Table 3.12 Inventory policy and cost with dedicated area for online fulfillment (S_1= 300 m^2)

Order Quantity		Reorder Point		Safety Factor		Total Cost
Q_{11}	11	R_{11}	7.6	k_{11}	1.296	$3,739.00
Q_{12}	192	R_{12}	97	k_{12}	1.324	
Q_{21}	12	R_{21}	5.9	k_{21}	1.267	
Q_{22}	203	R_{22}	114	k_{22}	1.355	

Table 3.13 Inventory policy and cost with dedicated area for online fulfillment (S_1= 500 m^2)

Order Quantity		Reorder Point		Safety Factor		Total Cost
Q_{11}	18	R_{11}	8	k_{11}	1.379	$3,693.00
Q_{12}	192	R_{12}	97	k_{12}	1.324	
Q_{21}	21	R_{21}	6	k_{21}	1.348	
Q_{22}	203	R_{22}	114	k_{22}	1.355	

If the area dedicated to the online fulfillment process is increased to 500 m^2, the results are given in Table 3.13. The results demonstrate that the system cost is decreased to $3,693.00. The safety factors are increased to their original values (rounding the value to 1.35) owing to the optimal dedicated warehouse space for the online fulfillment process. A 1.23% cost decrease is obtained by setting a suitable space for the online fulfillment process.

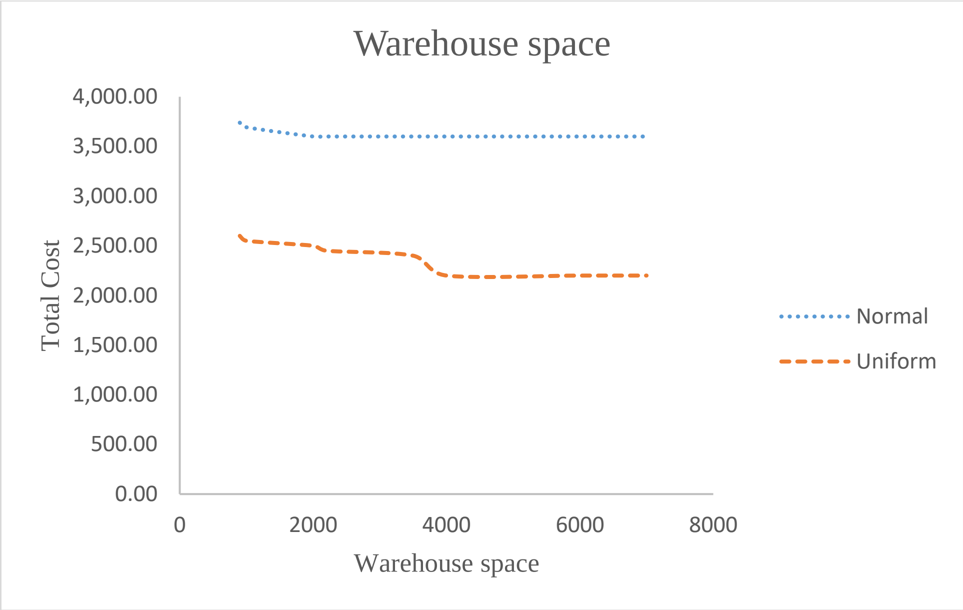

Figure 3.6 Total cost as a function of warehouse space

Figure 3.6 illustrates a numerical example of the warehouse space constraint analysis for both normal and uniform demand distributions. We can observe that for the normal distribution case, the warehouse space constraint is inactive with a warehouse space greater than 2000 m^2, while for the uniform demand distribution example, the warehouse space limit is approximately 4000 m^2. The analysis provides insights regarding the warehouse space and effects on the system total cost. Thus, the firm can adjust the space of the areas of the two stages when the demands or operation costs change to increase the flexibility of the dual-channel warehouse.

3.6.9 Effects of Demand Uncertainty

To observe the effect of demand uncertainty on the total system cost, problems with different levels of demand uncertainty are solved, for both uniform and normal distribution cases. As we can observe in Figure 3.7, the total cost increases when the demand variation increases owing to uncertainty. In the case of normal demand distribution, an almost linear increase is observed, while in the case of uniform demand distribution, the increase becomes steep. As uncertainty levels increase, preventive measures such as an increase in safety stock are necessary, but such measures consequently increase the system cost.

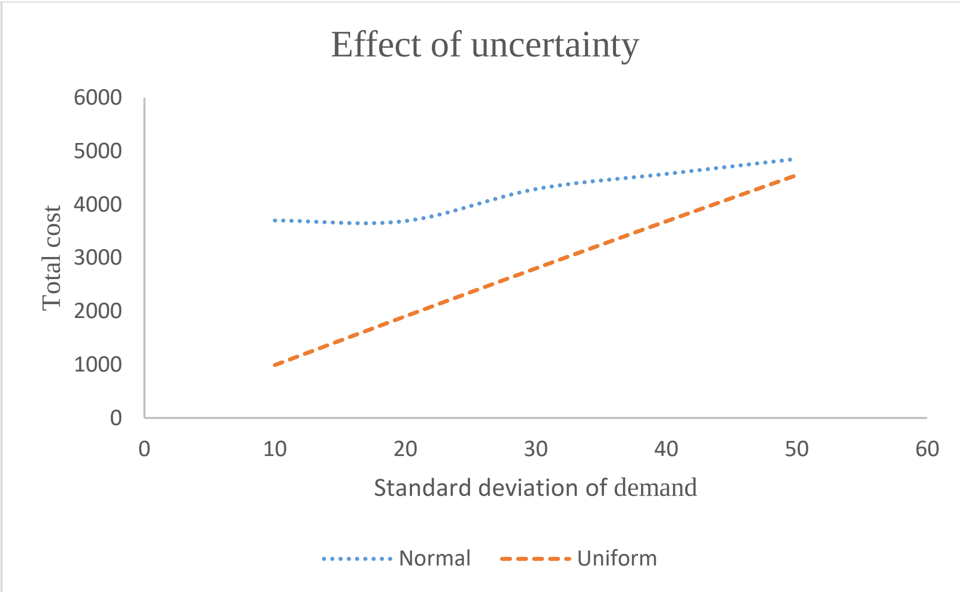

Figure 3.7 Effect of demand uncertainty on total cost

3.7 Conclusion

In this chapter examines the structure of the emerging dual-channel warehouse and presents an inventory control model for the dual-channel warehouse to determine the ordering quantities and reordering points for both offline and online channels. The proposed model takes into account the warehouse structure and capacity, online fulfillment operation, ordering costs, holding costs, and backorder costs. Moreover, it considers the demand and lead time uncertainty. Closed-form solutions are developed for both uniform and normal distributions without a warehouse space constraint, and an iterative algorithm for cases with a space constraint.

Numerical examples demonstrate that the proposed model could be used to evaluate the performance of dual-channel warehouse systems. The performances of online, offline, and dual-channel warehouse strategies are also compared. Adopting the proposed inventory policy for the dual-channel warehouse inventory system considering an online sales channel alongside an offline sales channel will enhance supply chain flexibility. Moreover, it could lead to an overall reduction in ordering, inventory holding, and backorder costs. The numerical example shows that a 1.23% decrease in operational costs is obtained by allocating a suitable space for the online fulfillment process.

In addition to determining the optimal inventory policy for a dual-channel warehouse, our sensitivity analyses illustrate that the proposed model yields a robust solution and provides a tool to support some strategic decisions made by companies operating in a dual-channel context. For example, it can analyze the effect of the warehouse structure and space reserved for online and offline areas on the total operating cost and service levels, and it can provide a guide or at least an option for redesigning the conventional warehouse structure to adapt to the new features of the dual-channel business.

This research makes contributions in the following three aspects. First, we analyze the structure of dual-channel distribution centers and develop inventory policy for the distribution center. Second, we develop a mathematical model that jointly determines multi-item products order quantities to the areas in the integrated dual-channel distribution center minimizing the total expected cost considering the distribution center space constraints and the uncertain of demands, all while using deterministic and stochastic lead-times. Third, we provide a closed form solution for instances of uniform distribution demand, and a solution algorithm for the normally distributed demand. Our proposed model is also an effective performance evaluation tool of any two-echelon dual-channel warehouse systems. Finally, this model evaluates online, offline, and dual-channel warehouse strategies, (shown in Figure 3.1) and assists in deciding between either randomized or dedicated online fulfillment areas as necessary.

CHAPTER 4: GLOBAL DUAL-CHANNEL WAREHOUSE WITH CROSS-BORDER SUPPLY CHAIN

4.1 Introduction and Motivation

Efficient and flexible supply chains are a vital survival factor for business success nowadays. The logistics industry must keep up with the efficiency level, visibility, and control over the uncertainty sources in the supply chain, such as demand forecasting or delivery times. As we discussed previously, the supply chain optimization and visibility are a key objective in the new digital era. We live in a very competitive world; manufacturers need to optimize their operations to remain competitive. One key aspect is to have mitigation strategies for many sources of uncertainty in the dynamic world we are living in, and the cross-border delay is a very essential source of uncertainty especially now that more firms extend globally. Uncertainty of the border crossing time impacts the viability of supply chains. Hence, it is of extreme importance to have the correct response to the uncertainty of lead times in global supply chain networks.

Some governmental agencies such as the Canada Border Services Agency usually publish some data about the expected border crossing times. Nonetheless, these studies do not consider the variability of border crossing times. However, the cost of uncertainty and delay in border crossings is a major problem for global supply networks. The delay cost might include penalties imposed by buyers, the cost of inventory holding and warehousing, and the cost of buffer times - early arrival at the border crossing in making deliveries which leads to higher fuel consumption, and more environmental impact as the emissions increase. Buffer time strategy is the most used strategy to overcome the border crossing uncertainty (Goodchild, Globerman, and Albrecht 2007; Anderson and Coates 2010).

Some research was conducted to identify the causes behind the border crossing time uncertainty, its impact, and what measurements should be implemented to minimize its impact. For example, Anderson (2008) investigated the impact of truck inspection times in four main US-Canada border crossings after 9/11 to find that the average crossing time of inbound (to USA) shipment is as twice that of the border crossing time of outbound (to Canada) shipments. However, they did not highlight the economic impact of the delays in border crossing times.

This research makes contributions in the following three aspects. First, we analyzed the structure of the cross-border dual-channel global supply distribution centers, taking into account the border crossing lead times and the development of an inventory policy for the distribution center. Second, we developed a mathematical model that jointly determines multi-item products order quantities of the cross-border distribution center thereby minimizing the total expected cost taking into account the border crossing uncertainty, stochastic lead times and the uncertain demands. Third, we provided a closed-form solution for the normal distribution demand. Our proposed model is also an effective performance evaluation tool for any cross-border warehouse system. Finally, this model evaluates the impact of cross-border delays, and assists in the decision-making process as it is a very effective tool that converts the delays' impacts into cost impacts as necessary.

The chapter is structured as follows: In Section 4.2, the problem is defined. Section 4.3 highlights the proposed new mathematical model. Section 4.4 presents the solution methodology. Additionally, numerical examples and results are provided in Section 4.5. Finally, conclusions are presented in Section 4.6.

4.2 Problem Statement

The problem can be described as follows: To design a "green" RFID-based, cross-border global dual channel warehouse including the cross-border transportation system and lead time uncertainty. The cross-border cost is made up of 3 components (Anderson and Coates 2010):

1. Mean delay cost: Average cost of a truck driver's time, wasted fuel and idled capital in queues at the border crossing. The fuel emission is a crucial factor when dealing with green supply chains which nowadays is a vital topic especially with the increasing social awareness of pollution and environmental issues.
2. The cost of safety inventory: As we know, the safety stock increases as the level of uncertainty increases due to cross-border crossing times and delivery failures which have to be overcome to maintain superior service levels. More safety stock means more inventory holding as well. In our model, the increase in safety inventory will be reflected in the uncertainty of delivery lead time.
3. Compliance cost: This is the cost of membership in a "trusted shipper program" defined on per shipment basis. In our model, we considered the compliance cost as part of ordering cost. The ordering costs are the sum of ordering cost (Transportation and administrative costs), compliance cost which is the cost of membership in trusted shipper program defined on per shipment basis, we also considered as part of ordering costs the mean delay cost which is the average cost of a truck driver's time, as well as wasted fuel and idled capital in queues at the border crossing.

Lead time demand is treated as a continuous random variable with a probability density function. In calculating the lead time of cross-border supply chain systems, we divided the lead time into three components:

- Origin to border time: which includes the paperwork for preparing the shipment time, cargo inspection time before the shipment leaves for the border, and time between suppliers before the actual arrival at the border crossing,
- Cross-border time: which includes the documentation inspection time, secondary inspection time, safety inspection time, and detailed safety inspection time
- Border to destination time: which includes the time between border to dual-channel distribution center.

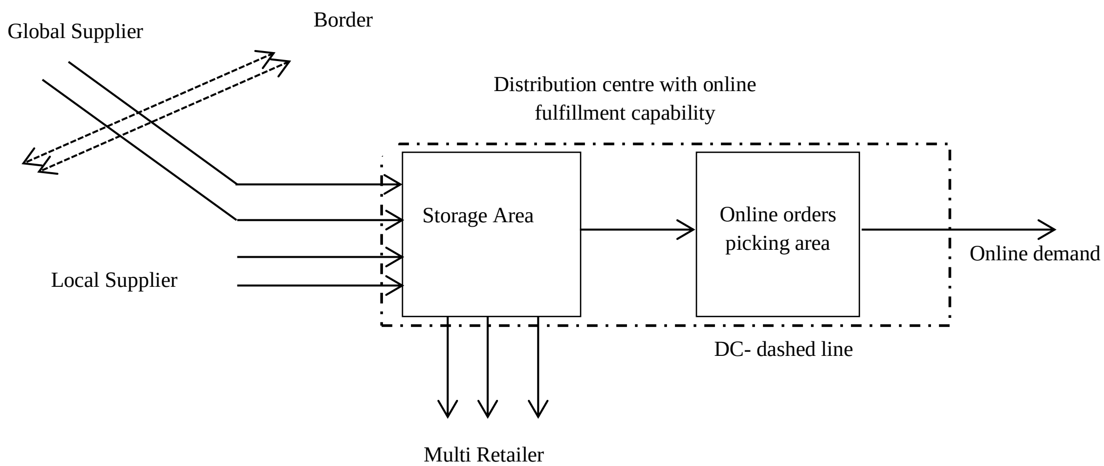

Figure 4.1 Distribution center with online fulfillment capability and local/ global supplier

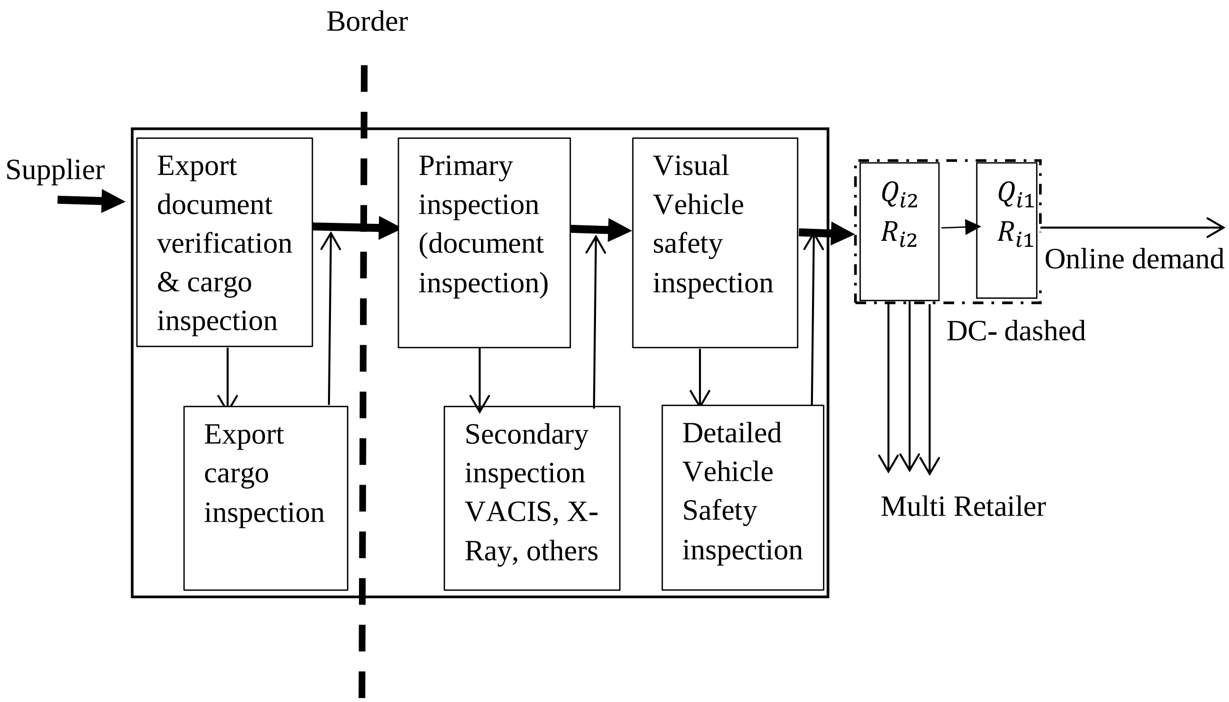

Figure 4.2 Cross-border supply chain

4.3 Model Formulation

4.3.1 Notations and Assumptions

In addition to the notations that we have presented in section 3.3.1, we have the following notations:

c_i: Compliance cost which is the cost of membership in a trusted shipper program defined on a per shipment basis for item i.

α_i: Mean delay cost which is the average cost of a truck driver's time, wasted fuel and idled capital in queues at the border crossing for item i.

Assumptions and preliminary analysis

1. We consider seven different scenarios based on supplier location and FAST and NON-FAST as defined by Cedillo-Campos et al., (2014) as follows:

- Scenario 1: When the company is not part of the FAST program, and with probability 1.0; in this case, the shipment must go through all the secondary inspections as we can see in Figure 4.3.
- Scenario 2: When the company is not part of the FAST program, and the probability is 0.9, the shipment must then go through all the secondary inspections.

- Scenario 3: When the company is not part of the FAST program, and probability 0.6, the shipment must then go through all the secondary inspections.
- Scenario 4: When the company is part of the FAST program, probability 0.4: the shipment must go through all the secondary inspections.
- Scenario 5: When the company is part of the FAST program, probability 0.1, the shipment must go through all the secondary inspections.
- Scenario 6: Hypothetical case, in which the company is part of FAST and special high-security measures are implemented, without any inspection at the border, as we can see in Figure 4.4 below.
- Scenario 7: local supplier, no cross-border between supplier and DC.

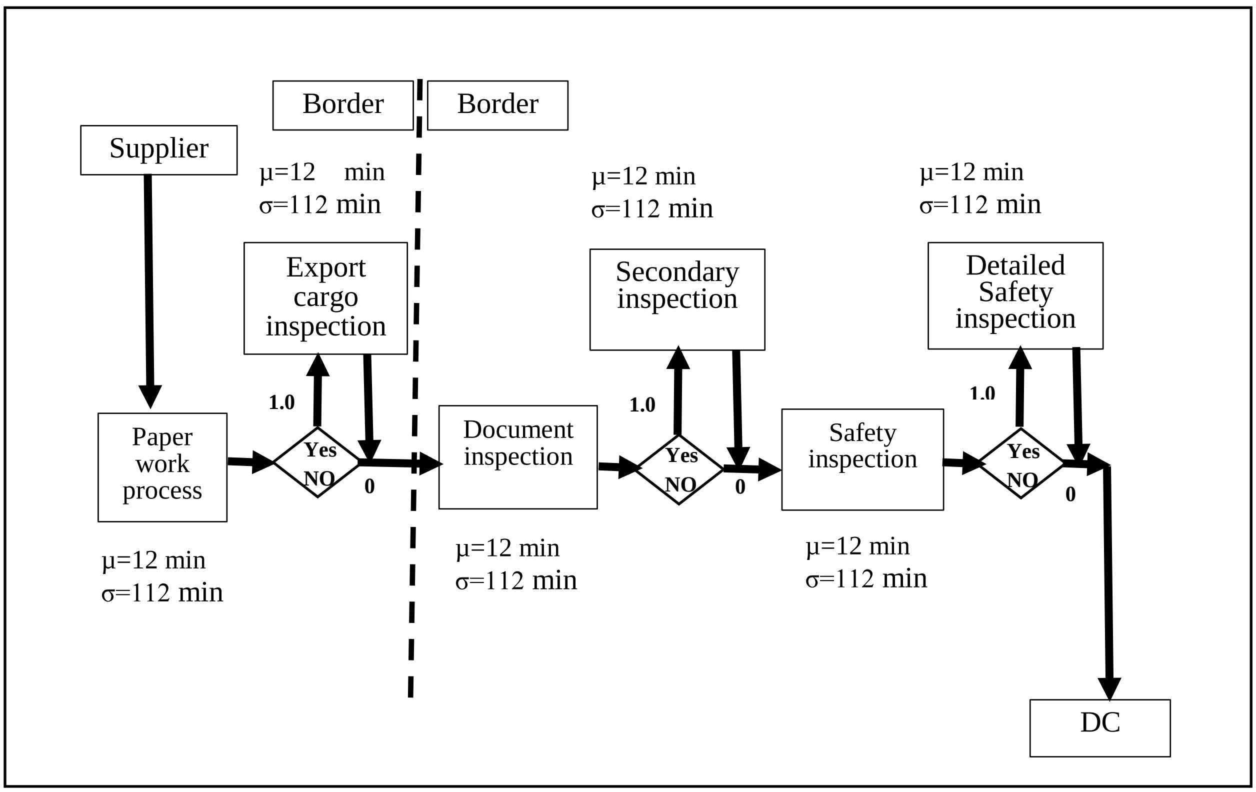

Figure 4.3 S_1: FAST program, 100% of shipments must go through the secondary inspections

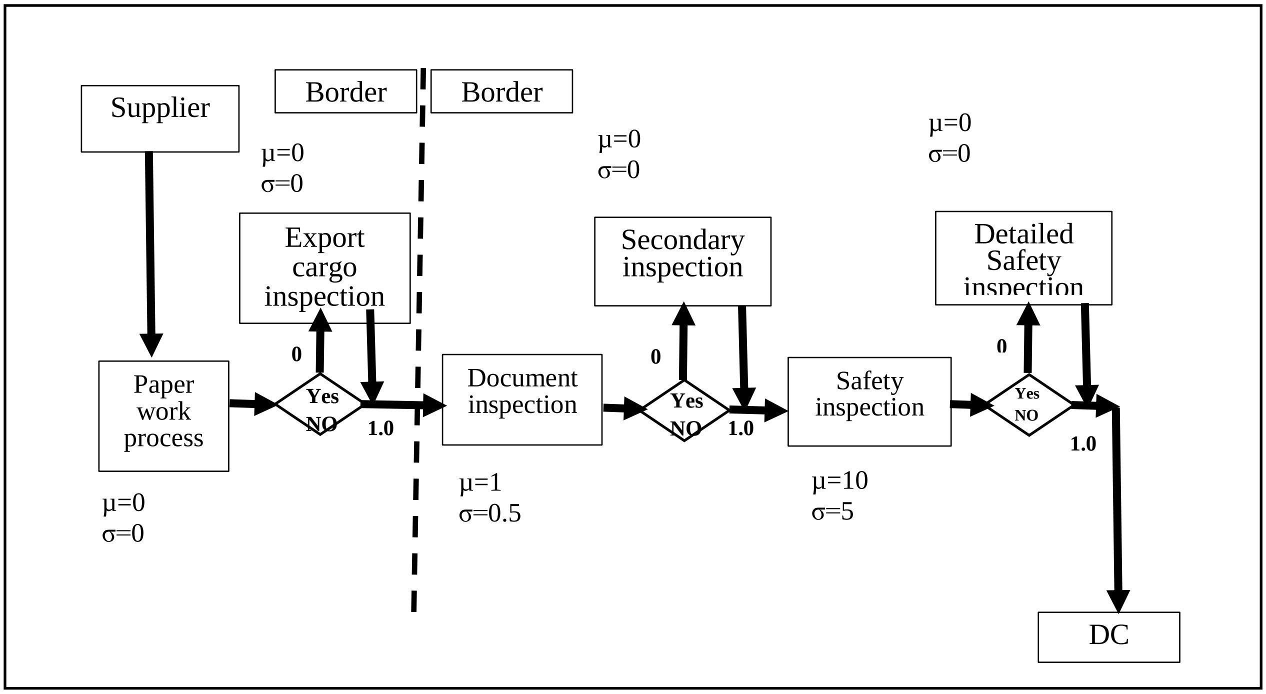

Figure 4.4 S6: FAST program, 0% of shipments must go through the secondary inspection

2. In calculating the lead time (including the cross-border time), we used the following parameters:

- μ_{PWi}: Mean of paper work (min)
- σ_{PWi}: Standard deviation of paper work (min) for item i
- μ_{CIi}: Mean of cargo inspection (min) for item i in
- σ_{CIi}: Standard deviation of cargo Inspection (min) for item i
- μ_{SPi}: Mean of time between suppliers to border crossing (min) for item i
- σ_{SPi}: Standard deviation of time between supplier and border crossing for item i
- μ_{DIi}: Mean of documentation inspection (min) for item i
- σ_{DIi}: Standard deviation of documentation inspection (min) for item i
- μ_{SIi}: Mean secondary inspection (min) for item i
- σ_{SIi}: Standard deviation of secondary inspection (min) for item i
- μ_{STi}: Mean of safety inspection (min) for item i
- σ_{STi}: Standard deviation of safety inspection (min) for item i
- μ_{DSTi}: Mean of detailed safety inspection (min) for item i
- σ_{DSTi}: Standard deviation of detailed safety inspection (min) for item i
- μ_{BDCis}: Mean time between border to DC (min) for item i

- σ_{BDCi}: Standard deviation between the borders to DC (min) for item i.
- Therefore, the mean and the variance of the lead time is the aggregation of the above independent parameters:
- $\mu_{Li} = [\mu_{PWi} + \mu_{CIi} + \mu_{SPi} + \mu_{DIi} + \mu_{SIi} + \mu_{STi} + \mu_{DSTi} + \mu_{BDCi}]$
- $\sigma_{Li}^2 = [\sigma^2{}_{PWi} + \sigma^2{}_{CIi} + \sigma^2{}_{SPi} + \sigma^2{}_{DIi} + \sigma^2{}_{SIi} + \sigma^2{}_{STi} + \sigma^2{}_{DSTi} + \sigma^2{}_{BDCi}]$

3. In determining the trusted shipper program cost, we did include the environmental impact as well when crossing the border. Logically if the shipper is a member of trusted shipper program, the idle time and therefore CO2 emissions will be decreased. In the global supply chain optimization, it is not only preferred to minimize the total operational cost (including operation, transportation, and holding costs) but also it is necessary to optimize other factors such as border crossing costs, environmental considerations, CO_2 emissions, truck idle time, and pollution. Many firms are looking to adopt the concept of the green supply chain.

All the above assumptions are either based on assumptions introduced in the literature or based on practical experience, the second author has extensive experience developing solutions to real case problems such as the one introduced in Zhang et al., (2017). Additionally, the first author is working as senior material flow engineer in a consulting company supporting one of the big 3 automotive manufactures in the USA.

4.3.2 Mathematical Model

The total cost is:

Let C (Q_i, R_i) be the total expected cost per year, then the total expected cost is formulated as follows in terrms of the decision variables Q_i, R_i.

$$
\begin{aligned}
\mathrm{C}(\mathrm{Q}_{i2}, \mathrm{R}_{i2}, \mathrm{Q}_{i1}, \mathrm{R}_{i1}) \\
&= \sum_i \frac{[[A_{i2} + c_i + \alpha_i]\mathrm{D}_{i2}]}{\mathrm{Q}_{i2}} + \sum_i \frac{A_{i1}\mathrm{D}_{i1}}{\mathrm{Q}_{i1}} + \sum_i \mathrm{h}_{i2}\left[\left(\frac{\mathrm{Q}_{i2}}{2}\right) + \left(\mathrm{R}_{i2} - \mu_{x_{i2}}\right)\right] \\
&+ \sum_i \mathrm{h}_{i1}\left[\left(\frac{\mathrm{Q}_{i1}}{2}\right) + \left(\mathrm{R}_{i1} - \mu_{x_{i1}}\right)\right] + \sum_i \frac{\mathrm{b}_{i2}\mathrm{D}_{i2}}{\mathrm{Q}_{i2}}\left[\int_{\mathrm{R}_{i2}}^{\infty} (x_{i2} - \mathrm{R}_{i2})\, f(x_{i2})\, \mathrm{d}x_{i2}\right] \\
&+ \sum_i \frac{\mathrm{b}_{i1}\mathrm{D}_{i1}}{\mathrm{Q}_{i1}}\left[\int_{\mathrm{R}_{i1}}^{\infty} (x_{i1} - \mathrm{R}_{i1})\, f(x_{i1})\, \mathrm{d}x_{i1}\right].
\end{aligned}
\tag{4.1}
$$

Subject to constraints 3.7-3.8.

The first term of the objective function (4.1) refers to the annual ordering cost, which is basically the order cost multiplied by the number of cycles, the ordering cost includes the membership cost in the trusted shipper program defined on per shipment basis, and the mean delay cost which is composed of the truck driver's time, wasted fuel and idled capital in queues at the border crossing. The second term refers to the annual holding cost, which is equal to the holding cost per unit per unit of time multiplied by the average cycle inventory plus the safety inventory. The integration limits of the safety inventory to infinity represents a good approximation of the safety inventory as it will end up equivalent to the reorder point R minus the mean of the demand during the lead time. The third term represents approximated annual backorder costs, which equal to the back-order cost per unit per unit of time multiplied by the expected number of shortages per cycle.

4.4 Solution Methodology

Applying the solution approach presented in Section 3.4, we obtain

$$
\begin{aligned}
&L(Q_{i2}, R_{i2}, Q_{i1}, R_{i1}, \theta) \\
&\quad = \sum_i \frac{\left[[A_{i2} + c_i + \alpha_i]\mathrm{D}_{i2}\right]}{\mathrm{Q}_{i2}} + \sum_i \frac{A_{i1} D_{i1}}{Q_{i1}} + \sum_i h_{i2}\left[\left(\frac{Q_{i2}}{2}\right) + \left(R_{i2} - \mu_{x_{i2}}\right)\right] \\
&\quad + \sum_i h_{i1}\left[\left(\frac{Q_{i1}}{2}\right) + \left(R_{i1} - \mu_{x_{i1}}\right)\right] + \sum_i \frac{b_{i2} D_{i2}}{Q_{i2}}\left[\int_{R_{i2}}^{\infty} (x_{i2} - R_{i2})\, f(x_{i2}) dx_{i2}\right] \\
&\quad + \sum_i \frac{b_{i1} D_{i1}}{Q_{i1}}\left[\int_{R_{i1}}^{\infty} (x_{i1} - R_{i1})\, f(x_{i1}) dx_{i1}\right] \\
&\quad + \theta\left[\sum_i \left(\gamma_{i2}(Q_{i2} + R_{i2}) + \gamma_{i1}(Q_{i1} + R_{i1})\right) - S - \mu_Y - z_{1-\alpha}\right],
\end{aligned} \tag{4.2}
$$

Using the necessary KKT conditions for minimization problems, we obtain

$$
\begin{aligned}
&b_{i2} D_i \left(1 - CSL(R_{i2})\right)^2 - 2(h_{i2} + (h_{i2} + 1)\gamma_{i2}\theta) ESC(R_{i2}) \\
&\qquad - \frac{2(h_{i2} + (h_{i2} + 1)\gamma_{i2}\theta)[A_{i2} + c_i + \alpha_i]}{b_{i2}} \\
&\qquad = 0,
\end{aligned} \tag{4.3}
$$

and

$$
b_{i1} D_{i1}\left(1 - CSL(R_{i1})\right)^2 - 2(h_{i1} + (h_{i1} + 1)\gamma_{i1}\theta) ESC(R_{i1}) - \frac{2(h_{i1} + (h_{i1}+1)\gamma_{i1}\theta) A_{i1}}{b_{i1}} = 0, \tag{4.4}
$$

$$\frac{\partial L}{\partial \theta} = \sum_i \big(\gamma_{i2}(Q_{i2} + R_{i2}) + \gamma_{i1}(Q_{i1} + R_{i1})\big) - S - \mu_Y - z_{1-\alpha}\sigma_y \leq 0. \quad (4.5)$$

The solution methodology discussed in section 3.4 can be used to solve the model for model for uniform and normal demands.

4.5 Numerical Examples and Results

In this section, we will present a numerical example to demonstrate the effectiveness of the proposed model and some parameters discussion.

4.5.1 Numerical Example

Consider as an example a single item in the cross-border warehouse inventory system, where, the demand is normally distributed, the goal is to find the reorder points for cross-border warehouse taking into account the cross-border crossing time. We analyzed the case of six different scenarios for FAST and NON-FAST firms as following:

Table C.1 in Appendix C demonstrates the input parameters for the NON-FAST firms which include scenario 1, scenario 2, and scenario 3. Note that the ordering cost is $180 for the three scenarios, which does not include neither the cost of membership in a trusted shipper program defined on per shipment basis nor the mean delay cost, as they are NON-FAST firms. Where we have the extreme case in scenario 1 with probability 1.0 of going through all the secondary inspections, the mean of demand during lead time is equal to 164 units and the standard deviation of demand during lead time is equal 724 units, mainly due to high variability in the secondary inspection processes times. Table C.2 in Appendix C demonstrates the input parameters for the FAST firms which include scenario 4, scenario 5, and scenario 6. Note that the cost of membership in a trusted shipper program is equal to $3.8 and the mean delay cost is equal to $1.2. Where we have the hypothetical case in scenario 6 with probability 0 of going through all the secondary inspections the mean of demand during lead time is equal to 72 units and the standard deviation of demand during lead time is equal to 17 units.

The solution output of the example is shown in Table 4.4 and Figure 4.5 and demonstrate the total cost of the cross-border warehouse system in different scenarios.

Table 4.1 Model output solution

	Q	R	TC
S_1: NON- FAST 1.0	3338	1782	20229
S_2: NON- FAST 0.9	3310	1612	19474

S_3: NON- FAST 0.6	3230	1105	17236
S_4: FAST 0.4	3220	758	15894
S_5: FAST 0.1	3144	248	13648
S_6: FAST 0.0	3124	110	13054

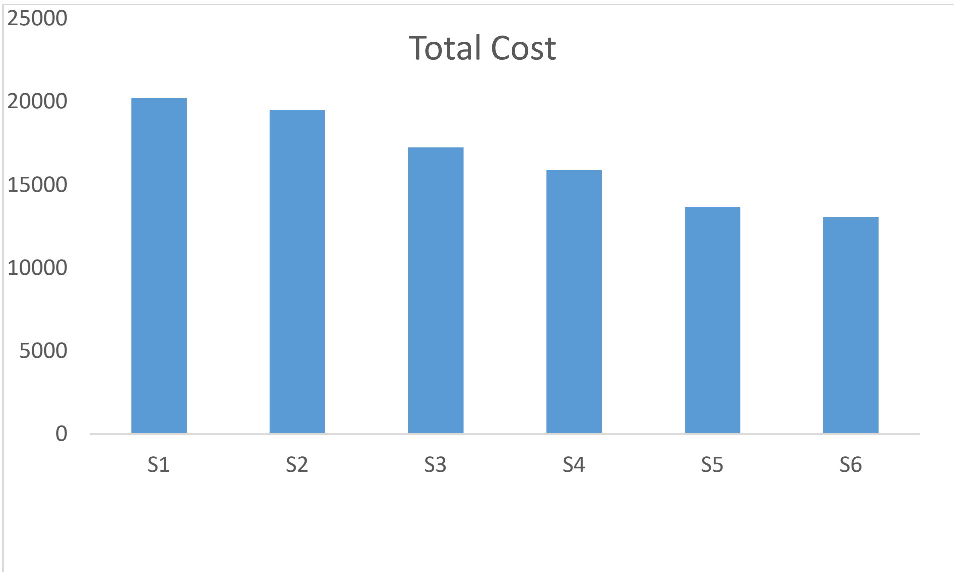

Figure 4.5 Total cost for FAST and NONFAST scenarios

4.5.2 Insights about Safety Stock for all Scenarios

Table 5.5 and figure 5.6 show the safety stock level for each scenario, note that the safety stock level dropped dramatically from 1618 units to just 38 units, this huge variability in the safety stock level is due mainly to extreme variability in the border crossing processes times.

Table 4.2 Safety stock results

Scenario	Safety Stock	Safety Factor *k*
S_1: NON- FAST 1.0	1618	2.18
S_2: NON- FAST 0.9	1457	2.24
S_3: NON- FAST 0.6	978	2.25
S_4: FAST 0.4	651	2.24
S_5: FAST 0.1	167	2.26
S_6: FAST 0.0	38	2.24

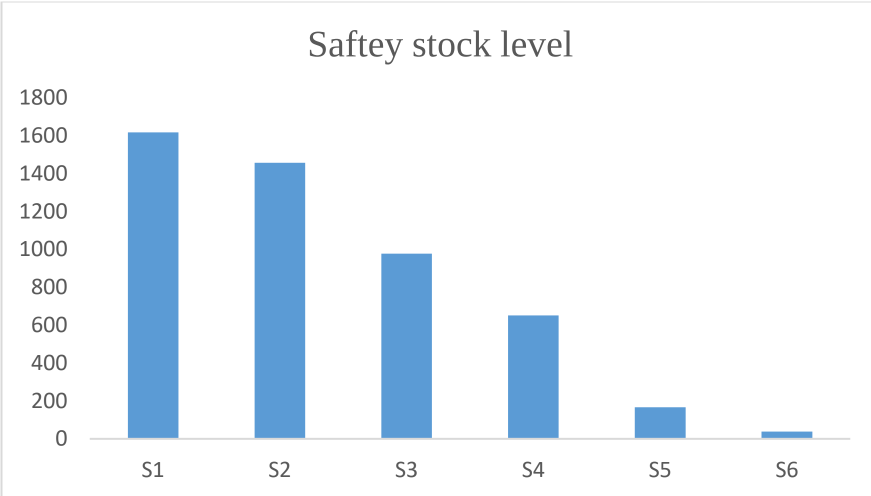

Figure 4.6 Safety stock level per scenario

4.5.3 Insights about FAST Program Cost

Table 4.6 and Figure 4.7 show the total cost of the cross-border dual-channel warehouse systems for a FAST company with different membership and delay costs. As we can see, we solved the proposed model for incremental membership and delay cost, we changed the membership cost from 3.8$ to 85$ and the delay cost from 1.2$ to 35$ and the system is still cost effective with total cost equal to 16508$ compared with NON FAST case (scenario 3) which has total cost of 17236$.

Table 4.3 Total cost vs. compliance and delay costs

Ordering cost	Compliance cost	Delay cost	Total Cost S_4: FAST 0.4	Total Cost S_5: FAST 0.1	Total Cost S_6: FAST 0.0
180	3.8	1.2	15894	13648	13054
180	7.6	2.4	16056	13814	13221
180	10	5	16216	13978	13386
180	12	8	16375	14140	13549
180	18	7	16456	14300	13710
180	20	10	16575	14458	13869
180	23	12	16694	14614	14025

180	25	15	16813	14768	14181
180	28	17	16932	14920	14304
180	45	25	17527	15660	15039
180	65	30	18122	16362	15774
180	85	35	18717	17034	16508

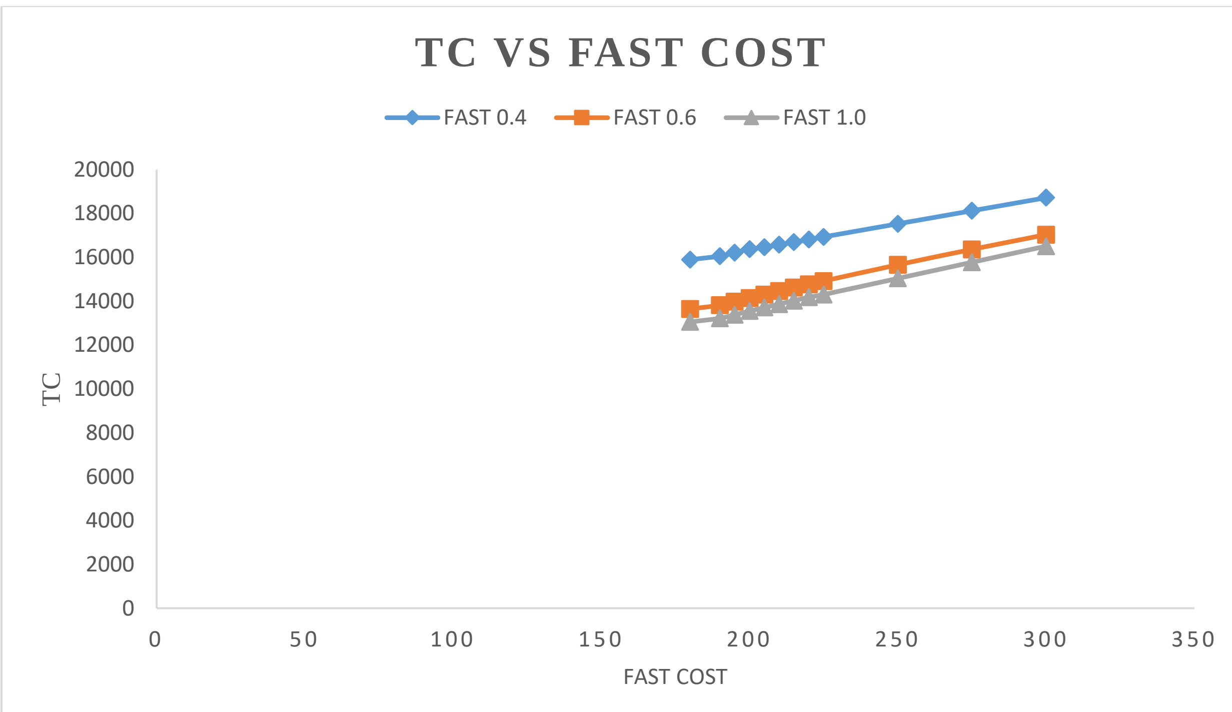

Figure 4.7 Total cost vs. compliance and delay costs

4.6 Conclusion

In this chapter, a cross-border inventory control model is proposed to determine the ordering quantity and the safety stock minimizing the ordering costs, holding costs, backorder costs, and cross-border costs. In our proposed model, the uncertainty in demand and the replenishment lead-time are considered using normal probability distribution. Moreover, a closed-form solution has been developed to solve the model. Numerical results have shown the effectiveness of the proposed model in determining the order quantity for the cross-border warehouse system.

Numerical examples are used to demonstrate how the proposed model can be used to evaluate the performance of the cross-border warehouse systems. Analysis was also conducted to highlight the impact of uncertainty of demand and lead-time where the cost of the system increased significantly. We compared the performance of the cross-border warehouse system in six different scenarios and whether or not the company was a FAST or NON-FAST participant.

Adopting the proposed inventory policy in the cross-border warehouse systems, we demonstrated that participation in the FAST program will add supply chain flexibility and can lead to overall reduction in the ordering costs, inventory holding costs, backordered sales costs, and cross-border costs.

This research makes contributions in the following three aspects. First, we analyzed the structure of the cross-border dual-channel global supply distribution centers, taking into account the border crossing lead times and the development of an inventory policy for the distribution center. Second, we developed a mathematical model that jointly determines multi-item products order quantities of the cross-border distribution center thereby minimizing the total expected cost taking into account the border crossing uncertainty, stochastic lead times and the uncertain demands. Third, we provided a closed-form solution for the normal distribution demand. Our proposed model is also an effective performance evaluation tool for any cross-border warehouse system. Finally, this model evaluates the impact of cross-border delays, and assists in the decision-making process as it is a very effective tool that converts the delays' impacts into cost impacts as necessary.

CHAPTER 5: OPTIMIZING CROSS-DOCKING OPERATION IN GLOBAL SUPPLY CHAINS WITH UNCERTAIN LEAD TIMES

5.1 Introduction and Motivation

Our research is motivated by a real-world cross-docking problem. We perform the study at a one of the big 3 automotive companies in the USA. The company always faces the challenges of optimizing their operations and managing the items in the 3PL when introducing new products. Thus, we investigate a dock assignment problem that considers the dock capacity and storage space and a cross-dock layout. We propose an integrated model to combine the cross-dock assignment problem with cross-dock layout problem so that cross-dock operations can be coordinated effectively.

New research papers investigating the cross-docking system have been published recently. Some papers have investigated the use of cross-dock in the reverse supply chain (Rezaei and Kheirkhah, 2017; Zuluaga et al., 2017). Others have focused on the cross-dock location and layout problems (Goodarzi and Zegordi, 2016; Horta et al., 2016; Barsing et al., 2018; Behnamian et al., 2018; Goodarzi et al., 2018; Nasiri et al., 2018). Some have investigated the vehicle scheduling and routing at a cross-docking center (Yu and Egbelu, 2008; Agustina et al., 2014; Serrano et al., 2017; Chiarello et al., 2018; Dulebenets, 2018; Heidari et al., 2018; Ladier and Alpan, 2018; Molavi et al., 2018; Schwerdfeger et al., 2018; Ye et al., 2018).

The dock assignment problem has been explored individually or integrated with vehicle routing and truck sequencing problems in the relevant literature (Tusi and Chang 1992; Zhu et al. 2009; Guignard et al., 2012; Kuo, 2013; Enderer et al., 2017; Nassief et al., 2018). However, none of the research papers investigate the dock assignment problem along with inventory management and storage layout considering real case constraints such as dock utilization, storage capacity and uncertain lead time including the cross-border time.

Another important aspect to consider when studying the global supply chain is the cross-border time. The cross-border time is often unpredictable due to various reasons such as increased security concerns which translate into more and longer inspection times; understaffing which means fewer open lanes; and the lack of specialized agents to deal with controlled items such as drugs and agricultural products (Smith et al., 2018). The variability of border crossing times is extremely costly, especially for firms that rely totally on their global suppliers (Smith et al., 2018). As the firms depend more on their global supplier, there is an urgent need to investigate the impact of cross-border time variability on the performance of the supply chain and suggest new approaches to enhance its performance. There is a need for analytical tools to help optimize cross-border supply chain considering border crossing time variability and its associated delays. Some researchers have investigated the border crossing time problem and tried to quantify the cross-border cost (Goodchild et al., 2007; Anderson and Coates, 2010; Cedillo-Campos et al., 2014; Lee and Lim,2014; Sardar and Lee,2015; Chung et al., 2018). However, none of the aforementioned papers have considered the effect of the cross-border time on 3PL center in terms of storage capacity and inventory levels. Therefore, this paper integrates the 3PL dock assignment, storage layout, and inventory management problems considering real case constraints including cross-border time.

The main contributions of this study to the existing cross dock literature can be summarized as follows. First, It's the first study to analyze the inventory policy of the cross dock and develop an integrated model of the 3PL center including the dock door assignment, safety stock, and intermediate storage locations inside the 3PL center. Second, the developed model considers real case constraints such as dock and storage capacities and stochastic lead time. Third, the proposed model identifies the cross-border cost and highlights its impact on the 3PL inventory level. Forth, the proposed model can be used as an analytical tool to help optimize the cross-border supply chain considering border crossing time variability and its associated delays. Fifth, a real-world industrial cross-dock and layout problem is solved, and the results obtained could be applied to optimize the cross-dock and layout at other similar cross-dock facilities. Sixth, the proposed model can be used as a decision support system when setting up new 3PL center for new programs when launching new products or building new plants. To the best of our knowledge, this paper is the first study to integrate the inventory management and storage layout along with dock door assignment in the global 3PL center, although, there have been some papers addressing these decisions individually.

The chapter is structured as follows: In Section 5.2, the problem is defined. Section 5.3 highlights the proposed new mathematical model. Section 5.4 Real case study and numerical examples are provided. Additionally, in Section 5.5 managerial insights and sensitivity analysis are provided. Finally, conclusions are presented in Section 5.6.

5.2 Problem Statement

The main objectives of a manufacturer's 3PL are to fulfill the demand with the minimal operation cost, maintain the service level, decrease the inventory level (Just in Time delivery), increase space utilization, and decrease the material handling cost. These objectives are usually conflicting.

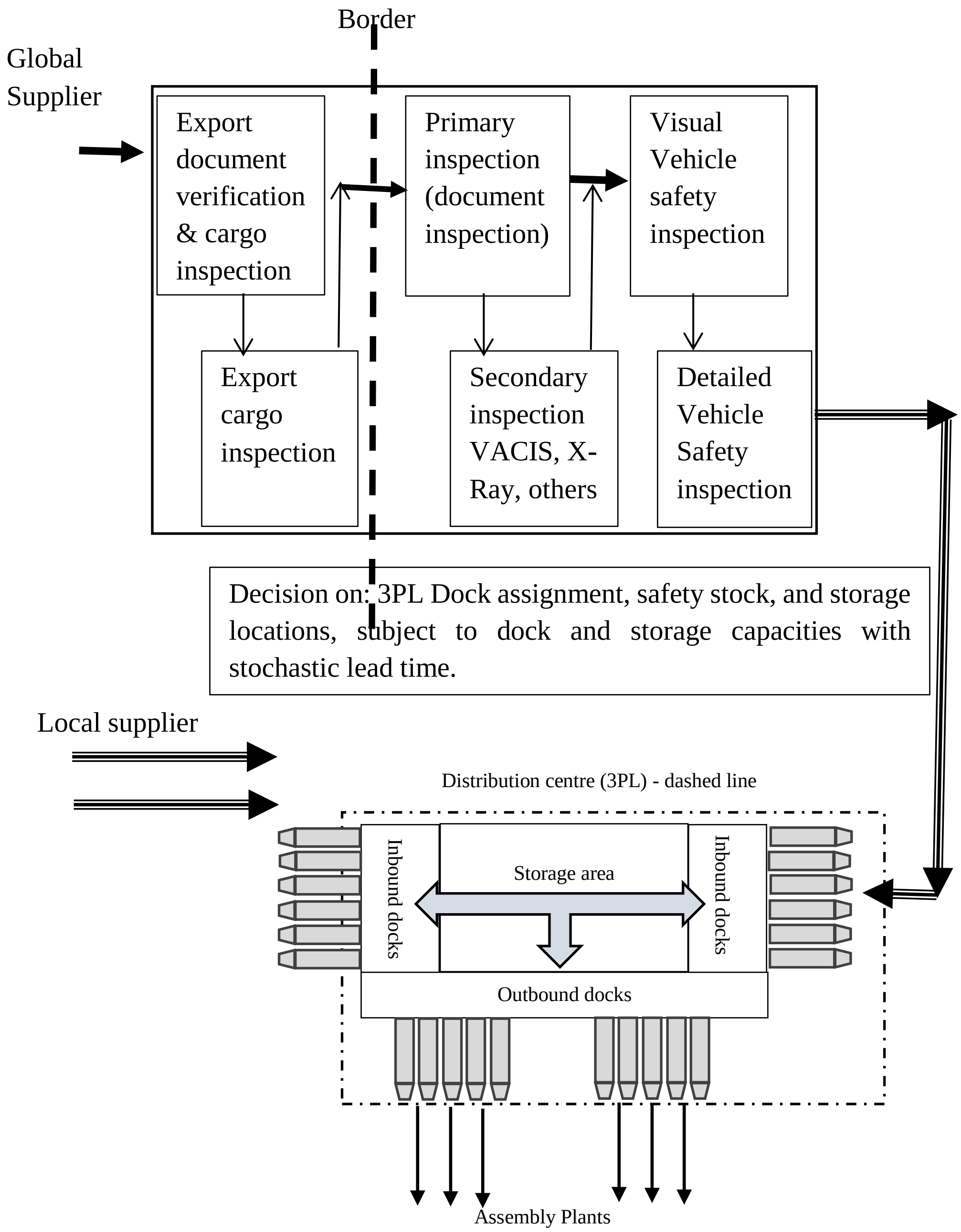

Figure 5.1 Global Cross-docking system

To obtain the cycle service level, we need to keep safety stock, for that we need to store items in 3PL to mitigate the impact of delivery time variability. Meanwhile, firms are looking to minimize the inventory holding cost, efficient material handling for items, as well as to optimize the space utilization. To obtain optimal performance, firms need to find the balance/ trade-off point amongst these goals.

In our work, we consider the emerging global cross-docking system dealing with global and local suppliers. The 3PL is divided into receiving/inbound area where the items are received, staged or moved to storage area, and to intermediate storage area where the items are kept for intermediate periods of time (usually a week), and the outbound shipping area where the items are shipped to the assembly plants with smaller sizes and more frequent deliveries as shown in Figure. 2 above.

Our goal is to develop a decision support tool for the operational and strategic decision related to 3PL. On the operational level, we intend to assist in determining the optimal dock assignment for the inbound and outbound docks, optimal inventory level in terms of safety stock for all the items, as well as an optimal storage location. On the strategic level, we will analyze the effect of the 3PL structure and available storage space on the cross-docking system performance.

5.3 Model Formulation

5.3.1 Notation and Assumptions

Notations

The notations used in developing the mathematical model are given as follows:

Index

i: Item

l: locations

s: scenarios

Parameters

L_i : length of lead-time for item i

h_i: Holding cost per unit per unit time for item i

OC_{is}: Ordering cost per order for item i in scenario s

SS_i the safety stock for item i in scenario s based on lead time and cycle service level (CSL).

n_i is the number of weekly shipment of item i from supplier to 3PL

f_i is the number of weekly shipment of item i from 3PL to assembly plant

Q_i is the shipment size based on trailer capacity of item i from supplier to 3PL

UIB_i The dock utilization of item i in the 3PL inbound dock

UOB_i The dock utilization of item i in the 3PL outbound dock

$P_{ld_{IB}}$ is the cost of moving item i from the inbound dock to location l in 3PL

$O_{ld_{OB}}$ is the cost of retrieving item i from location l to the outbound dock in 3PL

c_{is}: Compliance cost which is the cost of membership in a trusted shipper program defined on a per shipment basis for item i in scenario s.

α_{is}: Mean delay cost which is the average cost of a truck driver's time, wasted fuel and idled capital in queues at the border crossing for item i in scenario s

SP is the storage space in 3PL

γ_i is the storage space requirement for item i per unit in the 3PL

Decision variables

XS_{is} Scenario of shipping for item i.

$X_{id_{IB}}$ 1 if item i assigned to inbound dock in 3PL, 0 otherwise.

$Y_{id_{OB}}$ 1 if item i assigned to outbound dock in 3PL, 0 otherwise.

Z_{il} 1 if item i stored in location l in the 3PL, 0 otherwise.

RT_{il} 1 if item i retrieved from location l in the 3PL, 0 otherwise.

Assumptions and preliminary analysis

1. We consider seven different scenarios based on supplier location and FAST and NON-FAST as defined by Cedillo-Campos et al., (2014) as follows:

- Scenario 1: When the company is not part of the FAST program, and with probability 1.0; in this case, the shipment must go through all the secondary inspections as we can see in Figure 5.2 below.
- Scenario 2: When the company is not part of the FAST program, and the probability is 0.9, the shipment must then go through all the secondary inspections.
- Scenario 3: When the company is not part of the FAST program, and probability 0.6, the shipment must then go through all the secondary inspections.
- Scenario 4: When the company is part of the FAST program, probability 0.4: the shipment must go through all the secondary inspections.

- Scenario 5: When the company is part of the FAST program, probability 0.1, the shipment must go through all the secondary inspections.
- Scenario 6: Hypothetical case, in which the company is part of FAST and special high-security measures are implemented, without any inspection at the border, as we can see in Figure 5.3 below.
- Scenario 7: local supplier, no cross-border between supplier and 3PL.

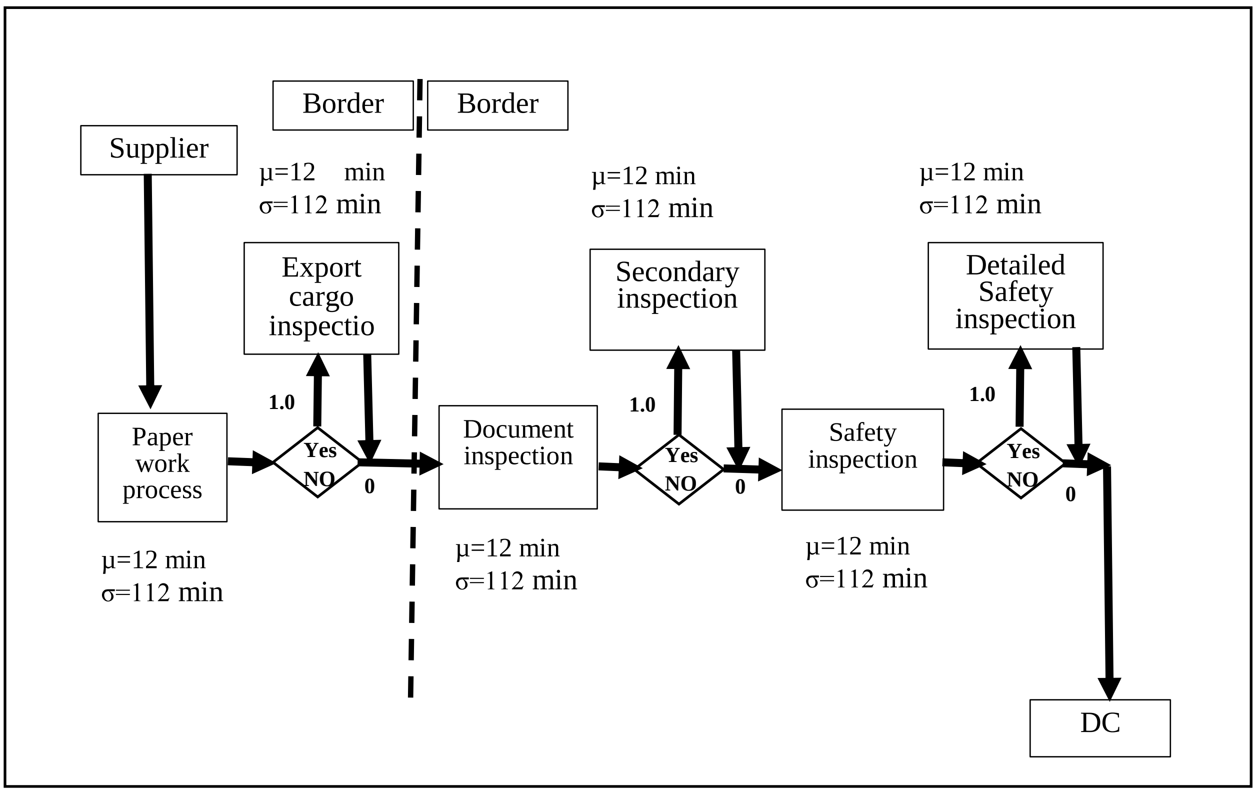

Figure 5.2 Scenario 1: FAST program, 100% of shipments must go through the secondary inspections

2. We assume that the demand is known, if the 3PL fulfilling the demand of several plants, the total demand use is the aggregated demand, $D_{Total}=D_1+D_2 \ldots D_T$.

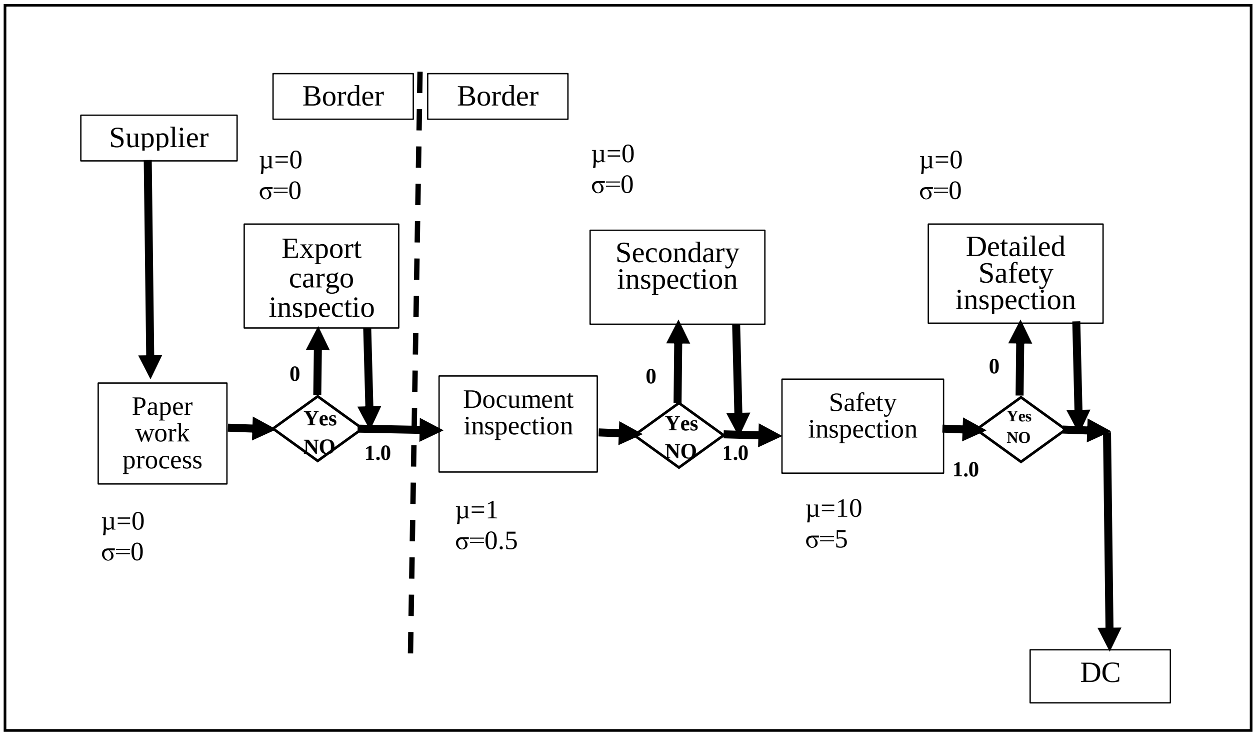

Figure 5.3 Scenario 6: Hypothetical case, a FAST program without any inspection at the border

3. We use the D_{Total} when calculating the number of shipment n_i, which is equal to the total weekly demand divide by the trailer capacity. The trailer capacity is determined based on the container information, the trailer used is the standard 53'x8.5'x8' trailer. Based on this information, we decide the optimal trailer pack-out/ shipment.

4. In calculating the number of daily shipment between 3PL and the assembly plant (f_i), we used the assembly plant dock assignment as input, we calculate the trailer capacity based on the parts delivered to the same dock on the same delivery route. Usually we have one-hour delivery routes between 3PL and the assembly plant, which means $f_i > n_i$.

5. We assume stochastic lead time, this includes the border crossing time for the global suppliers The mean and the standard deviation of the demand during the lead time (DDLT) for item i, are:

$\mu_{Xi} = \mu_{Li} * \mu_{Di}$

And $Var(X_i) = \sigma^2_{X_i} = \mu^2_{D_i} * \sigma^2_{L_i}$

6. The safety stock for item i is defined as a function of cycle service level (CSL) as:

$SS_i = F_i^{-1}[CSL] \times \sigma_{Xi}$ where CSL is the cycle service level.

7. In calculating the lead time (including the cross-border time), we used the following parameters:

μ_{PWis}: Mean of paper work (min) in scenario s

σ_{PWis}: Standard deviation of paper work (min) for item i in scenario s

μ_{CIis}: Mean of cargo inspection (min) for item i in scenario s

σ_{CIis}: Standard deviation of cargo Inspection (min) for item i in scenario s

μ_{SPis}: Mean of time between suppliers to border crossing (min) for item i in scenario s

σ_{SPis}: Standard deviation of time between supplier and border crossing for item i in scenario s

μ_{DIis}: Mean of documentation inspection (min) for item i in scenario s

σ_{DIis}: Standard deviation of documentation inspection (min) for item i in scenario s

μ_{SIis}: Mean secondary inspection (min) for item i in scenario s

σ_{SIis}: Standard deviation of secondary inspection (min) for item i in scenario s

μ_{STis}: Mean of safety inspection (min) for item i in scenario s

σ_{STis}: Standard deviation of safety inspection (min) for item i in scenario s

μ_{DSTis}: Mean of detailed safety inspection (min) for item i in scenario s

σ_{DSTis}: Standard deviation of detailed safety inspection (min) for item i in scenario s

μ_{BDCis}: Mean time between border to DC (min) for item i in scenario s

σ_{BDCis}: Standard deviation between border to DC (min) for item i in scenario s.

Therefore, the mean and the variance of the lead time is the aggreging of the above:

$\mu_{Li} = [\mu_{PWi} + \mu_{CIi} + \mu_{SPi} + \mu_{DIi} + \mu_{SIi} + \mu_{STi} + \mu_{DSTi} + \mu_{BDCi}]$

$\sigma_{Li}^2 = [\sigma^2{}_{PWi} + \sigma^2{}_{CIi} + \sigma^2{}_{SPi} + \sigma^2{}_{DIi} + \sigma^2{}_{SIi} + \sigma^2{}_{STi} + \sigma^2{}_{DSTi} + \sigma^2{}_{BDCi}]$

8. In the calculation of the dock utilization, UIB_i, UOB_i, we considered the 20-20-20 approach, which is 20 minutes to unload the trailer, 20 minutes to load the trailer, and 20 minutes to lock/unlock the trailer to the dock. We assumed that all docks have identical capacity. This is a well-known assumption used in the industry.

9. In calculating the material handling costs $P_{ld_{IB}}$ and $O_{ld_{OB}}$, we did not consider only the travel distance, but we combined it with the travel time to account for congestion inside the 3PL. We used the method introduced by Guignard et al., (2012) to calculate the travel distance which we convert to costs to account for the congestion. All instances were generated for a rectangular cross docking system where the number of inbound and outbound docks is the same.

10. In determining the trusted shipper program cost, we did include the environmental impact as well when crossing the border. Logically if the shipper is a member of trusted shipper program, the idle time and therefore CO_2 emissions will be decreased. In the global supply chain

optimization, it is not only preferred to minimize the total operational cost (including operation, transportation, and holding costs) but also it is necessary to optimize other factors such as border crossing costs, environmental considerations, CO_2 emissions, truck idle time, and pollution. Many firms are looking to adopt the concept of the green supply chain.

All the above assumptions are either based on assumptions introduced in the literature or based on practical experience, the second author has extensive experience developing solutions to real case problems such as the one introduced in Zhang et al., (2017). Additionally, the first author is working as senior material flow engineer in a consulting company supporting one of the big 3 automotive manufactures in the USA.

5.3.2 Mathematical Model

The problem is to determine the dock door assignment for inbound and outbound shipment, the safety stock to keep in the 3PL, as well as storage location such that the material handling and holding costs are minimized subject to real case constraints which include the dock utilization and storage capacity constraints. The formulation of the problem is given as follows.

$$TC = \sum_{S}\sum_{i}\left[((OC_{is} + c_{is} + \alpha_{is}) \times \mathrm{n}_i + \mathrm{h}_i\left[\left(\frac{\mathrm{Q}_i}{2}\right) + SS_{is}\right]\right] \times XS_{is} + \sum_{i}\sum_{d_{\mathbf{IB}}} \mathrm{n}_i \times X_{id_{IB}}$$

$$+ \sum_{i}\sum_{d_{OB}} \mathrm{f}_i \times Y_{id_{OB}} + \sum_{i}\sum_{l}\sum_{d_{IB}} \mathrm{n}_i \times P_{ld_{IB}} \times Z_{il} + \sum_{i}\sum_{l}\sum_{d_{OB}} \mathrm{f}_i \times O_{ld_{OB}} \times RT_{il} \quad 5.1$$

S.T.

$$\sum_{i}[(Q_i + SS_{is}) \times \gamma_i] \times XS_{is} \leq SP \;\forall\, S \quad 5.2$$

$$\sum_{s} XS_{is} \leq 1,\ \forall i \quad 5.3$$

$$\sum_{i} UIB_i \times X_{id_{IB}} \leq 1\,, \forall d_{IB} \quad 5.4$$

$$\sum_{i} UOB_i \times Y_{id_{OB}} \leq 1\,, \forall d_{OB} \quad 5.5$$

$$Z_{il} \leq 1, \forall\, i, l \quad 5.6$$

$$X_{id_{IB}} \leq \sum_{l} Z_{il} \;\forall\, i, d_{IB} \quad 5.7$$

$$Z_{il} \leq RT_{il} \forall\, i, l \quad 5.8$$

$$(Q_i + SS_i)\gamma_i \leq \sum_{l} Z_{il} \; \forall \; i, S \qquad 5.9$$

$$(QOi)fi = \sum_{l} RT_{il} \; \forall \; i, d_{OB} \qquad 5.10$$

$$\sum_{d_{IB}} X_{id_{IB}} \geq 1 \,, \forall \; i \qquad 5.11$$

$$\sum_{d_{OB}} Y_{id_{OB}} \geq 1 \,, \forall \; i \qquad 5.12$$

$$XS_{is}, X_{id_{IB}}, Y_{id_{OB}}, Z_{id_{A}}, U_{il}, RT_{il} \in [0,1] \qquad 5.13$$

The first term of the objective function (5.1) refers to the ordering and transportation, and holding costs per scenario, which is basically the order cost multiplied by the number of cycles, the ordering cost includes the membership cost in the trusted shipper program defined on per shipment basis, and the mean delay cost which is composed of the truck driver's time, wasted fuel and idled capital in queues at the border crossing and the transportation cost. While the holding cost is equal to the holding cost per unit per unit of time multiplied by the average cycle inventory plus the safety inventory. The second term represents the inbound dock assignment in the third party logistic center (3PL). The third term represents outbound 3PL dock assignment, while the fourth and fifth terms represent the storage locations assignment inside the 3PL.

Constraints (5.2) is the 3PL warehouse space capacity constraint

Constraints (5.3) guarantee that we each item can be shipped according to one scenario

Constraints (5.4) guarantee that will not exceed the inbound dock utilization in the 3PL

Constraints (5.5) guarantee that will not exceed the outbound dock utilization in the 3PL

Constraints (5.6) are the storage location constraints in the 3PL where only one item can be stored in the same location

Constraints (5.7) guarantee that we will only store items assigned to inbound dock in the 3PL.

Constraints (5.8) guarantee that can retrieve only stored items in the 3PL.

Constraints (5.9) inbound shipping per item space constraints in the 3PL.

Constraints (5.10) Q_O shipping out from 3 PL constraints.

Constraints (5.11) guarantee that each item will be assigned to an inbound dock in the 3PL.

Constraints (5.12) guarantee that each item will be assigned to an outbound dock in the 3PL.

Constraints (5.13) are the binary constraints.

5.4. Numerical Examples and Results

The proposed model was implemented in GAMS and was tested using real data from one of the big 3 car manufactures in the USA using i5-3210M CPU @ 2.50GHz station. We present numerical examples to verify the model and to show the results for different scenarios. We also conduct sensitivity analysis to show the effects of lead time features, and 3PL space.

We solved two examples to demonstrate the effectiveness and the robustness of the proposed model. The input data used is available upon request. We solved small size problem 5x5x5x20x2 (5 items, 5 inbound dock, 5 outbound dock, 20 locations, and 2 scenarios) and a real case problem 123x6x6x400x2 (123 item, 6 inbound dock, 6 outbound dock, 400 locations, and 2 scenarios), we have 30 suppliers based in the USA, 3 suppliers are based in Mexico, and 5 suppliers based in Canada.

The obtain results are shown in Table 5.1 below: For instance, we can see that item 1 is received from inbound dock 4, stored in location 2, 5, and 9, shipped out from the outbound dock 4 and shipped from the supplier to 3PL according to scenario 2.

Table 5.1 Solution for Example 1: I_{ns}55x20x2

Item	Inbound dock	Outbound dock	Storage location	Scenario	Total cost
i_1	dIB_4	dOB_4	L_2, L_5, L_9	S_2	$11813
i_2	dIB_4	dOB_5	L_{13}, L_{16}	S_2	
i_3	dIB_3	dOB_3	L_3, L_8	S_1	
i_4	dIB_1	dOB_1	L_7, L_{18}	S_2	
i_5	dIB_4	dOB_4	L_6, L_{11}	S_2	

Real case study results are shown in Table 5.2 below. As we can see, we need 6 inbound docks, 4 outbound docks, 390 storage locations, and 71 items are shipped according to scenario 1 and 52 items according to scenario 2 with total operating cost of $2336962.

Table 5.2 Solution for real case: Ins123x6x6x400x2

Number of Inbound dock	6
Number of Outbound dock	4
Number of storage location	390
Number of items shipped according to S1	71
Number of items shipped according to S2	52
Total cost	$2336962

We also solved example 1 for a single item in the cross-border cross-docking system to highlight the system inventory, where the lead time (including the border crossing times) follows the normal distribution. The goal is to find the reorder points which are equal to safety stock plus the mean of demand during lead time (DDLT) for cross-border warehouse taking into account the cross-border crossing time. We also analyzed the case of six different scenarios for FAST and NON-FAST firms. Table D.1 in Appendix D demonstrates the input parameters for the NON-FAST firms which include scenario 1, scenario 2, and scenario 3. Note that the ordering cost is $180 for the three scenarios, which does not include neither the cost of membership in a trusted shipper program defined on per shipment basis nor the mean delay cost, as they are NON-FAST firms. Where we have the extreme case in scenario 1 with probability 1.0 of going through all the secondary inspections, the mean of demand during lead time is equal to 164 units and the standard deviation of demand during lead time is equal 724 units, mainly due to high variability in the secondary inspection processes times. Table D.2 in Appendix D demonstrates the input parameters for the

FAST firms which include scenario 4, scenario 5, and scenario 6. Note that the cost of membership in a trusted shipper program is equal to $3.8 and the mean delay cost is equal to $1.2. While we have the hypothetical case in scenario 6 with probability 0 of going through all the secondary inspections with the mean of demand during the lead time equal to 72 units and the standard deviation of demand during lead time is equal to 17 units. The solution output of the example is shown in Table 5.3 and Figure 5.4 where we demonstrate the total cost of the cross-border warehouse system in different scenarios. As we can see, the higher the variability of lead time, the higher the safety stock we need to hold in the 3PL to keep with the cycle service level. This shows how the model can be used to put a quantitative price of the border crossing.

Table 5.3 Example 1 output solution

Scenario	Reorder point=(SS + DDLT)	Total cost
S_1: NON- FAST 100%	1924	26576
S_2: NON- FAST 0.9	1755	25776
S_3: NON- FAST 0.6	1228	23276
S_4: FAST 0.4	857	12666
S_5: FAST 0.1	322	10116
S_6: FAST 0.0	182	9466

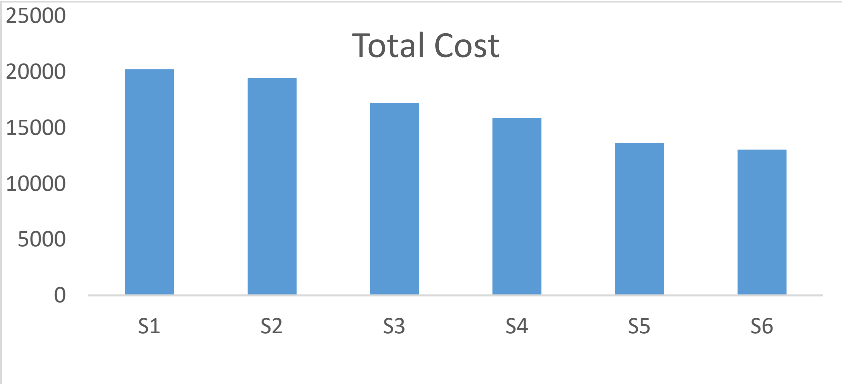

Figure 5.4 Total cost for FAST and NONFAST scenarios

5.5 Managerial Insights and Sensitivity Analysis

In the next section, we highlight how the proposed model can be used to gain some managerial insights and perform sensitivity analysis.

5.5.1 Safety Stock

We solved the model for a single item to show how the safety stock would change based upon whether the supplier is a full member of the FAST program or not. The obtained results are shown in Table 5.4 and Figure 5.5. Note that the safety stock level dropped dramatically from 1618 units to just 110 units, this huge variability in the safety stock level is due mainly to extreme variability in the border crossing processes times.

Table 5.4 Safety stock results

Scenario	SS	CSL
S_1: NON- FAST 100%	1618	98%
S_2: NON- FAST 0.9	1457	98%
S_3: NON- FAST 0.6	978	98%
S_4: FAST 0.4	651	98%
S_5: FAST 0.1	240	98%
S_6: FAST 0.0	110	98%

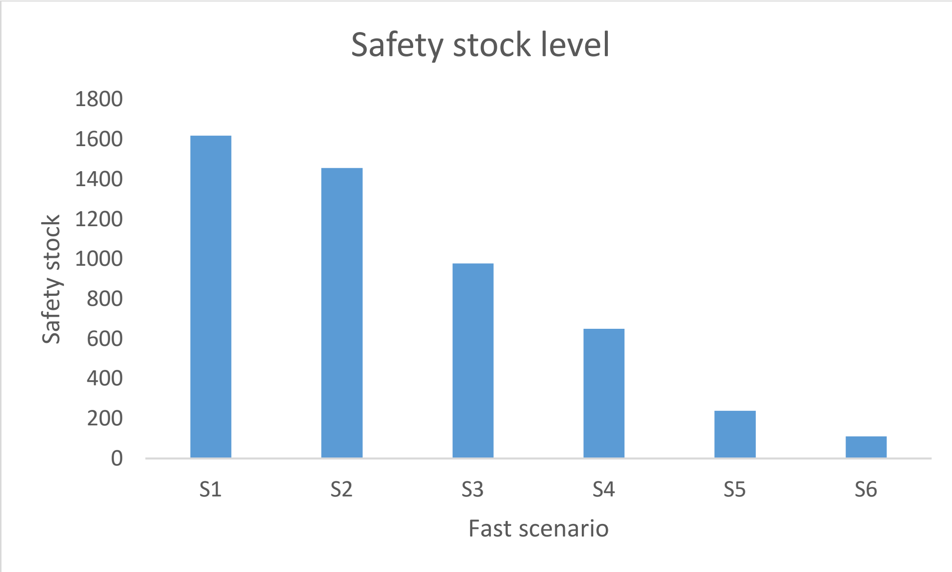

Figure 5.5 Safety stock level per scenario

5.5.2 Insights about FAST Program Cost

Table 5.5 and Figure 5.6 show the total cost of the cross-border cross-docking system for a FAST company with different membership and delay costs. We solved the proposed model for incremental membership and delay cost, we changed the membership cost from $3.8 to $125 and the delay cost from $1.2 to $60. As we can see, the results show that S_4 is cost effective until we reach the $125 and $60 costs respectively, at this point the saving in safety stock does not compensate for the higher FAST program costs with the total cost of $13250 compared to $12005 for the NON-FAST program.

Table 5.5 Total cost vs. compliance and delay costs

Ordering cost	Compliance cost	Delay cost	Total Cost S_1	Total Cost S_4: FAST 0.4
180	3.8	1.2	12005	11063
180	17	3	12005	11138
180	25	10	12005	11213
180	35	15	12005	11288
180	45	20	12005	11363
180	55	25	12005	11438
180	65	30	12005	11513
180	75	35	12005	11588
180	85	40	12005	11663

180	95	45	12005	11738
180	105	50	12005	11813
180	115	55	12005	11888
180	125	60	12005	13250

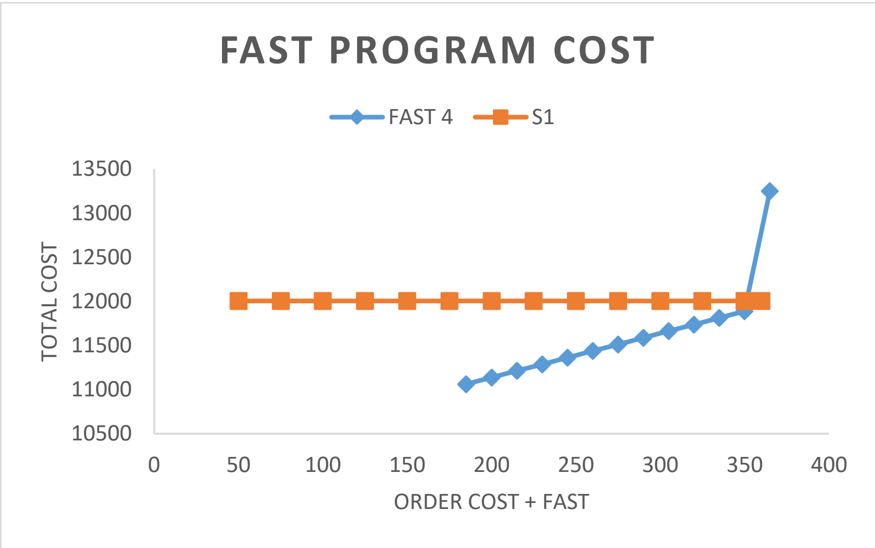

Figure 5.6 Total cost vs. compliance and delay costs

5.5.3. Insights about Available Space at the 3PL

In this section, we show how to use the proposed model as a decision support tool in analyzing what-if situations. One of the decisions we need to make is about how much space we need to lease in the 3PL for the intermediate storage and its effect on the total system costs. As we can see in Figure 5.7, if the available storage capacity is less than 400, the model provides an infeasible solution as we cannot fit the minimum requirement. As the available space increases, the total system costs decrease as we have the available space to store more safety stock. After certain limit (in this case 1000), the storage capacity constraint becomes inactive and has no effect on the cross-docking system.

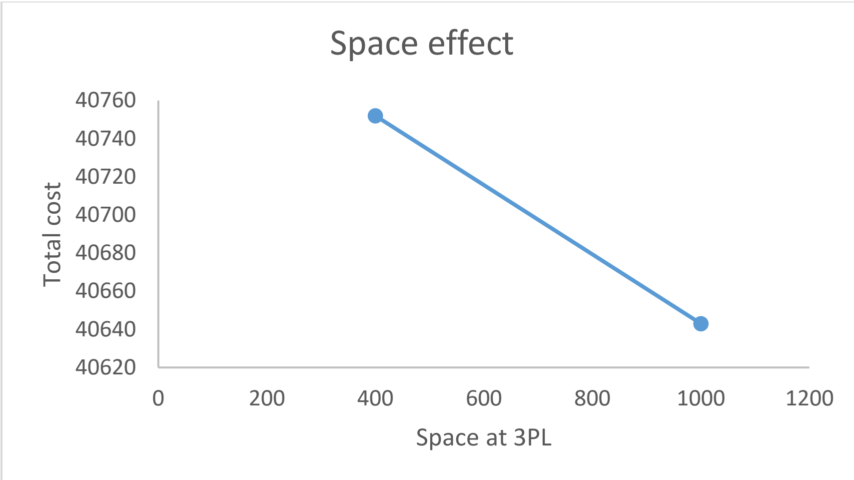

Figure 5.7 Storage space effect on total system cost

5.6. Conclusion

In this chapter, we study the global cross-docking system with inventory level, storage capacity, and cross order suppliers. We propose a cross-docking system mathematical model to determine the dock door assignment, safety stocks. In the proposed mathematical model, we did consider real-life constraints such as storage space, dock capacities, and the cross-border time for the global suppliers. The objective is to minimize the total costs which include the ordering costs, holding costs, material handling costs, and cross-border costs. In the proposed model, the uncertainty in the replenishment lead-time is considered using uniform and normal probability distribution. Numerical results have shown the effectiveness of the proposed model in determining the dock door assignment, safety stock quantity for the cross-border cross-docking system.

Real case problem and numerical examples are used to demonstrate how the proposed model can be used to evaluate the performance of the cross-border cross docking systems. The analysis is also conducted to highlight the impact of uncertainty of the lead-time where the cost of the system increased significantly. We compare the performance of the cross-border cross-docking system in six different scenarios based on whether the company is a FAST or NON-FAST participant.

We demonstrate that participation in the FAST program will add supply chain flexibility and can lead to overall reduction in the ordering costs, inventory holding costs, and cross-border costs. We also provide some managerial insights and sensitivity analysis showing how the model can be used as a decision support system when analyzing what-if situations.

This research makes contributions in the following aspects. First, we analyze the inventory policy of the cross dock and develop an integrated model of the 3PL center including the dock door assignment, safety stock, and intermediate storage locations inside the 3PL center. Second, the developed model considers real case constraints such as dock and storage capacities and stochastic lead time. Third, the proposed model identifies the cross-border cost and highlights its impact on the 3PL inventory level. Fourth, the model can be used as an analytical tool to help optimize cross-border supply chain considering border crossing time variability and its associated delays. Fifth, a real-world industrial cross-dock and layout problem is solved, and the results obtained could be applied to optimize the cross-dock and layout at other similar cross-dock facilities. Finally, the model can be used as a decision support system when setting up new 3PL center for new programs when launching new products or building new plants.

CHAPTER 6: CONCLUSIONS AND FUTURE RESEARCH

6.1 Conclusions

The research objectives are to develop decision methods/tools to support the warehouse and inventory management in dual channel supply chains along with the use of RFID and product identification in the cross-border supply chains. In the decision support tools (mathematical models) there is a continuous need to study the impact of uncertainty and multi-objective factors on the supply chain. Therefore, there is urgent need to extensively study the new technologies and their applicability in the field of supply chain and the development of appropriate mathematical model and solution methodologies to support the new digital era.

In Chapter 3, a dual-channel warehouse with online fulfillment capability and inventory control model is proposed to determine the ordering quantity for the offline and online channel taking into account the warehouse capacity and the minimization of the ordering cost, holding cost and backorder cost. In the proposed model, the uncertainty in demand and in lead-time are considered using various probability distributions. Moreover, a closed form solution is developed for the special case of uniform distribution without warehouse space constraint. Numerical results have shown the effectiveness of the proposed model in determining the order quantity for the dual channel warehouse.

Numerical example is used to demonstrate how the proposed model can be used to evaluate the performance of the two-echelon dual-channel warehouse system. Some analysis is conducted to highlight the impact of uncertainty of demand and lead-time where the cost of the system increased significantly. We compare the performance of three types of warehouse strategies: online, offline, and dual-channel warehouse. Adopting the proposed inventory policy in the dual-channel warehouse inventory system, we demonstrate that considering the online sales channel alongside the off-line retailer's sales channel will add supply chain flexibility and can lead to overall reduction in the ordering cost, inventory holding cost, and back ordered sales cost. Additionally, we consider two options for the operation of the online fulfillment area: in the first case (randomized), items are stored randomly in the warehouse space without any dedicated area for the online fulfillment process; and in the second case (dedicated), the area of online fulfillment is predetermined, and the items are stored randomly within it. A numerical example has shown that we obtained a 1.23% decrease of the operational cost just by assigning the suitable space for online fulfillment process.

This research makes contributions in the following three aspects. First, we analyze the structure of dual-channel distribution center and develop inventory policy for the distribution center. Second, we develop a mathematical model that jointly determines multi-item products order quantities to the areas in the integrated dual-channel distribution center minimizing the total expected cost. Our model considers the distribution center space constraints and uncertain demands. Besides, both deterministic and stochastic lead-time are also considered in our model. Third, we provide a closed-form solution for the case of uniform distribution demand and a solution algorithm for the normally distributed demand. Additionally, the proposed model can be used as a performance evaluation tool of the two-echelon dual-channel warehouse system. The model evaluates the performance of three types of warehouse strategies: online, offline, and dual-channel warehouse, shown in Figure 1.1, and assists in whether deciding either randomized or dedicated online fulfillment area should be used.

In Chapter 4, the RFID-based cross-border dual-channel distribution center model has been proposed to evaluate the border impact on the supply chain. Also, in the proposed model, the uncertainty of cross-border time has been considered using the stochastic programming approach. Moreover, the usefulness and effectiveness of the model has been highlighted via an illustrative numerical example. The results have been shown that the model can be used as a decision support system to gain insights regarding the cross-border supply chain. To the best of our knowledge, this model is among the first research in considering the cross-border time uncertainty and its effects on the cross-border dual-channel warehouse in an uncertain environment.

In Chapter 5, a global cross-docking system model is developed that integrates the 3PL dock assignment, storage layout, and inventory management problems considering real case constraints including cross-border time. The main contributions of this paper to existing cross dock literature can be summarized as follow. First, It's the first paper to analyze the inventory policy of the cross dock and develop an integrated model of the 3PL center including the dock door assignment, safety stock, and intermediate storage locations inside the 3PL center. Second, the developed model considers real case constraints such as dock and storage capacities and stochastic lead time. Third, the proposed model identifies the cross-border cost and highlights its impact on the 3PL inventory level. Fourth, the proposed model can be used as an analytical tool to help optimize cross-border supply chain considering border crossing time variability and its associated delays. Fifth, a real-world industrial cross-dock and layout problem is solved, and the results obtained could be applied to optimize the cross-dock and layout at other similar cross-dock facilities. Sixth, the proposed model can be used as a decision support system when setting up new 3PL center for new programs when launching new products or building new plants. To the best of our knowledge, this paper is the first study to integrate the inventory management and storage layout along with dock door assignment in the global 3PL center, although, there have been some papers addressing these decisions individually.

6.2 Future Research

The future works for this dissertation includes:

a) The Return Products: Chapter 3, future research could consider investigating the warehouse layout in each stage and its effect on the total cost. Moreover, how to include the returns in designing the dual-channel warehouse as well as a sustainable and green dual-channel warehouse would be investigated. Future research can also examine the network configuration of such dual-channel warehouses so that both the responsibility and efficiency of the entire dual-channel business can be significantly improved.

b) Quantity Discount: Another future research direction for the dual-channel dual-channel supply chain proposed model in chapter 3 might be the consideration of the well-known practical quantity discount approach as well as further model validation via its application on a real case study.

c) The model presented in Chapter 3 deals with dual channel warehouse, it can be extended to the case of multi-channel warehouse and study the impact on the model.

d) The model presented in Chapter 4 considers dual channel warehouse with global supplier within North America (NAFTA region), it would be beneficial to consider other global suppliers from other regions such as Europe or Asia and study the impact on the model.

e) In chapter 5, future research may consider additional processes that are taking placing in the 3PL such as repacking, sequencing, or sub-assemblies and the development of the corresponding solution approach.

f) The model presented in Chapter 5 considers cross dock warehouse with global supplier within North America (NAFTA region), it would be beneficial to consider other global suppliers from other regions such as Europe or Asia and study the impact on the model.

APPENDICES

APPENDIX A. Proof of Theorem 1 (Chapter 3)

$$C(Q_{i2}, R_{i2}, Q_{i1}, R_{i1}) = \sum_i \frac{A_{i2}D_{i2}}{Q_{i2}} + \sum_i \frac{A_{i1}D_{i1}}{Q_{i1}} + \sum_i h_{i2}\left[\left(\frac{Q_{i2}}{2}\right) + \left(R_{i2} - \mu_{x_{i2}}\right)\right] + \sum_i h_{i1}\left[\left(\frac{Q_{i1}}{2}\right) + \left(R_{i1} - \mu_{x_{i1}}\right)\right] + \sum_i \frac{b_{i2}D_{i2}}{Q_{i2}}\left[\int_{R_{i2}}^{\infty}(x_{i2} - R_{i2})\, f(x_{i2})\, dx_{i2}\right] + \sum_i \frac{b_{i1}D_{i1}}{Q_{i1}}\left[\int_{R_{i1}}^{\infty}(x_{i1} - R_{i1})\, f(x_{i1})\, dx_{i1}\right]$$

We have

$$C_{Q_{i1}Q_i} = \frac{\partial^2 C}{\partial Q_{i1}^2} = \frac{2D_{i1}}{Q_{i1}^3}\left\{A_{i1} + b_{i1}\int_{R_{i1}}^{\infty}(x_{i1} - R_{i1}) f(x_{i1}) dx_{i1}\right\} > 0$$

$$C_{Q_{i1}R_{i1}} = \frac{\partial^2 C}{\partial Q_{i1}\partial R_{i1}} = \frac{D_{i1}b_{i1}}{Q_{i1}^2}\left\{\int_{R_{i1}}^{\infty} f(x_{i1}) dx_{i1}\right\} > 0$$

$$C_{R_{i1}Q_{i1}} = \frac{\partial^2 C}{\partial R_{i1}\partial Q_{i1}} = \frac{D_{i1}b_{i1}}{Q_{i1}^2}\left\{\int_{R_{i1}}^{\infty}(x_{i1} - R_{i1}) f(x_{i1})\, dx_{i1}\right\} > 0$$

$$C_{R_{i1}R_{i1}} = \frac{\partial^2 C}{\partial R_{i1}^2} = \frac{A_{i1}D_{i1}}{Q_{i1}} f(R_{i1}) > 0$$

$$C_{Q_{i2}Q_{i2}} = \frac{\partial^2 C}{\partial Q_{i2}^2} = \frac{2D_{i2}}{Q_{i2}^3}\left\{A_{i2} + b_{i2}\int_{R_{i2}}^{\infty}(x_{i2} - R_{i2}) f(x_{i2}) dx_{i2}\right\} > 0$$

$$C_{Q_{i2}R_{i2}} = \frac{\partial^2 C}{\partial Q_{i2}\partial R_{i2}} = \frac{D_{i2}b_{i2}}{Q_{i2}^2}\left\{\int_{R_{i2}}^{\infty} f(x_{i2}) dx_{i2}\right\} > 0$$

$$C_{R_{i2}Q_{i2}} = \frac{\partial^2 C}{\partial R_{i2}\partial Q_{i2}} = \frac{D_{i2}b_{i2}}{Q_{i2}^2}\left\{\int_{R_{i2}}^{\infty}(x_{i2} - R_{i2}) f(x_{i2}) dx_{i2}\right\} > 0$$

$$C_{R_{i2}R_{i2}} = \frac{\partial^2 C}{\partial R_{i2}^2} = \frac{A_{i2}D_{i2}}{Q_{i2}} f(R_{i2}) > 0$$

All second order derivatives are greater than 0 for all non-negative $Q_{i1}, R_{i1}, Q_{i2}, R_{i2}$. Thus, C is strictly convex. Furthermore, as constraints (3) and (5) are linear, the problem *(P)* is convex.

APPENDIX B. Data for the numerical examples (Chapter 3)

Table B.1 Parameters for Example 1 with uniform distribution demand and deterministic lead time with space constraint

Parameter	Value	Parameter	Value	Parameter	Value
i	1, 2	U_{22}	800	h_{11}	8
j	1, 2	A_{11}	10	h_{12}	1
D_{11}	3000	A_{12}	125	h_{21}	8
D_{12}	24 000	A_{21}	10	h_{22}	1
D_{21}	1200	A_{22}	125	γ_{11}	0.2
D_{22}	9600	b_{11}	10	γ_{12}	1
U_{11}	250	b_{12}	60	γ_{21}	1
U_{12}	2000	b_{21}	10	γ_{22}	0.2
U_{21}	100	b_{22}	60	S	90 000

Table B.2 Parameters for Example 3 with normal distribution demand

Parameter	Value	Parameter	Value	Parameter	Value
i	1, 2	σ_{11}	0.5	b_{21}	0.5
j	1, 2	σ_{12}	4	b_{22}	8
D_{11}	240	σ_{21}	0.3	h_{11}	1
D_{12}	2400	σ_{22}	2.9	h_{12}	10
D_{21}	350	A_{11}	50	h_{21}	0.5
D_{22}	4500	A_{12}	125	h_{22}	8
μ_{11}	3	A_{21}	40	γ_{11}	2
μ_{12}	120	A_{22}	100	γ_{12}	0.2
μ_{21}	2.5	b_{11}	10	γ_{21}	1
μ_{22}	100	b_{12}	60	γ_{22}	0.1

Table B.3 Parameters for Example 5 with normal distribution demand with space constraint

Parameter	Value	Parameter	Value	Parameter	Value
i	1	σ_{12}	50	b_{11}	50
j	1, 2	A_{11}	40	b_{12}	2000
D_{11}	120	A_{12}	4000	γ_{11}	100
D_{12}	1600	h_{11}	20	γ_{12}	50
μ_{11}	30	h_{12}	10	S	3500
μ_{12}	750	A	0.99		
σ_{11}	10	$z_{1-\alpha}$	−1.3		

Table B.4 Input parameters for sensitivity analysis example

Parameter	Value	Parameter	Value	Parameter	Value
i	1, 2	σ_{11}	2	b_{21}	10
j	1, 2	σ_{12}	8.5	b_{22}	10
D_{11}	165	σ_{21}	1.5	h_{11}	8
D_{12}	1650	σ_{22}	10	h_{12}	8
D_{21}	185	A_{11}	6.5	h_{21}	8
D_{22}	1850	A_{12}	85	h_{22}	8
μ_{11}	5	A_{21}	8.5	γ_{11}	10
μ_{12}	85	A_{22}	85	γ_{12}	1
μ_{21}	4	b_{11}	10	γ_{21}	10
μ_{22}	100	b_{12}	10	γ_{22}	1
				S	1000

Table B.5 Parameters for warehouse space comparisons example

Parameter	Value	Parameter	Value	Parameter	Value
i	1, 2	σ_{11}	2	b_{21}	10
j	1, 2	σ_{12}	8.5	b_{22}	10
D_{11}	165	σ_{21}	1.5	h_{11}	8
D_{12}	1650	σ_{22}	10	h_{12}	8
D_{21}	185	A_{11}	6.5	h_{21}	8
D_{22}	1850	A_{12}	85	h_{22}	8
μ_{11}	5	A_{21}	8.5	γ_{11}	10
μ_{12}	85	A_{22}	85	γ_{12}	1
μ_{21}	4	b_{11}	10	γ_{21}	10
μ_{22}	100	b_{12}	10	γ_{22}	1

APPENDIX C. Data for the numerical examples (Chapter 4)

Table C.1. NON- FAST input parameters

Parameter	NON-FAST 100%	NON-FAST 0.9	NON-FAST 0.6
	S_1	S_2	S_3
Order cost ($)	180	180	180
Holding cost ($)	4	4	4
Back order cost ($)	10	10	10
Storage requirement per unit m^2 per item	0.01	0.01	0.01
Storage space m^2	14000	14000	14000
Annual demand (items)	105120	105120	105120
Mean demand per unit time (items/min)	0.2	0.2	0.2
Standard deviation of demand per unit time (items/min)	0.08	0.08	0.08
Mean of lead time LT (min)	820	774	636
Standard deviation of lead- time LT (min)	3619	3257	2173
Mean of demand of DDLT (items)	164	154.8	127.2
Standard deviation of DDLT (items)	724	651	435
Mean of paper work (min)	40	36	24
Standard deviation of paper work (min)	30	27	18
Mean of cargo inspection (min)	30	27	18
Standard deviation of cargo Inspection (min)	25	22.5	13.5
Mean of time between supplier to border crossing (min)	180	180	180
Standard deviation of time between supplier and border crossing (min)	60	60	60
Mean of documentation inspection (min)	15	13.5	9
Standard deviation of documentation inspection (min)	10	9	6
Mean secondary inspection (min)	180	162	108
Standard deviation of secondary inspection (min)	360	324	216
Mean of safety inspection (min)	15	13.5	9
Standard deviation of safety inspection (min)	3	2.7	1.8
Mean of detailed safety inspection (min)	180	162	108

Standard deviation of detailed safety inspection (min)	3600	3240	2160
Mean time between border to DC (min)	180	180	180
Standard deviation between border to DC (min)	60	60	60

Table C.2. FAST input parameters

Parameter	FAST 0.4	FAST 0.1	FAST 0.0
	S_4	S_5	S_6
Order cost ($)	180	180	180
Compliance cost	3.8	3.8	3.8
Delay Cost	1.2	1.2	1.2
Holding cost ($)	4	4	4
Back order cost ($)	10	10	10
Storage requirement per unit m^2 per item	0.01	0.01	0.01
Storage space m^2	14000	14000	14000
Annual demand (items)	105120	105120	105120
Mean demand per unit time (items/min)	0.2	0.2	0.2
Standard deviation of demand per unit time (items/min)	0.08	0.08	0.08
Mean of lead time LT (min)	533	406	360
Standard deviation of lead- time LT (min)	1450	372	85
Mean of demand of DDLT (items)	106.6	81.2	72
Standard deviation of DDLT (items)	290	74	17
Mean of paper work (min)	5	4	0
Standard deviation of paper work (min)	2	3	0
Mean of cargo inspection (min)	12	3	0
Standard deviation of cargo Inspection (min)	10	2.5	0
Mean of time between supplier to border crossing (min)	180	180	180
Standard deviation of time between supplier and border crossing (min)	60	60	60
Mean of documentation inspection (min)	6	1.5	0
Standard deviation of documentation inspection (min)	4	1	0
Mean secondary inspection (min)	72	18	0
Standard deviation of secondary inspection (min)	144	36	0
Mean of safety inspection (min)	6	1.5	0
Standard deviation of safety inspection (min)	1.2	0.3	0
Mean of detailed safety inspection (min)	72	18	0
Standard deviation of detailed safety inspection (min)	1440	360	0
Mean time between border to DC (min)	180	180	180
Standard deviation between border to DC (min)	60	60	60

APPENDIX D. Data for the numerical examples (Chapter 5)

Table D.1. NON- FAST input parameters

Parameter	NON- FAST 1	NON- FAST 0.9	NON- FAST 0.6
	S_1	S_2	S_3
Order cost ($)	180	180	180
Holding cost ($)	4	4	4
Storage requirement per unit m^2 per item	0.01	0.01	0.01
DC space m^2	14000	14000	14000
Annual demand (items)	105120	105120	105120
Mean of lead time LT (min)	820	774	636
Standard deviation of lead- time LT (min)	3619	3257	2173
Mean of demand of DDLT (items)	164	154.8	127.2
Standard deviation of DDLT (items)	724	651	435
Mean of paper work (min)	40	36	24
Standard deviation of paper work (min)	30	27	18
Mean of cargo inspection (min)	30	27	18
Standard deviation of cargo Inspection (min)	25	22.5	13.5
Mean of time supplier to border crossing (min)	180	180	180
Standard deviation supplier to border crossing (min)	60	60	60
Mean of documentation inspection (min)	15	13.5	9
Standard deviation of documentation inspection (min)	10	9	6
Mean secondary inspection (min)	180	162	108
Standard deviation of secondary inspection (min)	360	324	216
Mean of safety inspection (min)	15	13.5	9
Standard deviation of safety inspection (min)	3	2.7	1.8
Mean of detailed safety inspection (min)	180	162	108
Standard deviation of detailed safety inspection (min)	3600	3240	2160
Mean time between border to DC (min)	180	180	180
Standard deviation between border to DC (min)	60	60	60

Table D.2. FAST input parameters

Parameter	FAST 0.4	FAST 0.1	FAST 0.0
	S_4	S_5	S_6
Order cost ($)	180	180	180
Compliance cost	3.8	3.8	3.8
Delay Cost	1.2	1.2	1.2
Holding cost ($)	4	4	4
Storage requirement per unit m^2 per item	0.01	0.01	0.01
DC space m^2	14000	14000	14000
Annual demand (items)	105120	105120	105120
Mean of lead time LT (min)	533	406	360
Standard deviation of lead- time LT (min)	1450	372	85
Mean of demand of DDLT (items)	106.6	81.2	72
Standard deviation of DDLT (items)	290	74	17
Mean of paper work (min)	5	4	0
Standard deviation of paper work (min)	2	3	0
Mean of cargo inspection (min)	12	3	0
Standard deviation of cargo Inspection (min)	10	2.5	0
Mean of time supplier to border crossing (min)	180	180	180
Standard deviation supplier to border crossing (min)	60	60	60
Mean of documentation inspection (min)	6	1.5	0
Standard deviation of documentation inspection (min)	4	1	0
Mean secondary inspection (min)	72	18	0
Standard deviation of secondary inspection (min)	144	36	0
Mean of safety inspection (min)	6	1.5	0
Standard deviation of safety inspection (min)	1.2	0.3	0
Mean of detailed safety inspection (min)	72	18	0
Standard deviation of detailed safety inspection (min)	1440	360	0
Mean time between border to DC (min)	180	180	180
Standard deviation between border to DC (min)	60	60	60

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