DEVELOPING A DECISION SUPPORT SYSTEM FOR PACKAGING POSTPONEMENT

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ABSTRACT

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Postponement refers to a strategy which intentionally delays supply chain activities until the demand is known. Postponement decreases safety stock and the holding cost, while also incurring some additional costs. The main focus of this study is packaging postponement which is recommended if only the packaging of products destined at multiple retailers are different. This thesis summarizes research that exclusively studied packaging postponement and presents a decision support system that determines which postponement strategy, i.e., full, partial (tailored), or no postponement, is optimal. The decision support system is a mixed-integer nonlinear programming model with the objective of minimizing total costs, including the holding cost and the additional cost, and is constrained by the limited capacity of packaging production at a distribution center and the integrity of variables. In this research, the impact of various factors on optimal packaging postponement strategy is also analyzed. To sum up, this research provides a collection of research papers that exclusively studied packaging postponement and presents a decision support model for packaging postponement.

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KEY TO ABBREVIATIONS

HP	Hewlett Packard
CSL	Cycle Service Level
ROP	Reorder Point

CHAPTER 1 INTRODUCTION

1.1 Research Background

With customization requirements increasing, the variety and diversity of products become an emphasis of firms. As companies pay more attention to developing mass customization, they improve the level of customer satisfaction; however, they also need to face the difficulty of cost-control. In order to address the issue of increasing cost, many strategies have been practiced and identified. Delaying one or more than one process in a supply chain system (usually the process related to product differentiation) is one of these strategies, and this strategy is usually identified as "*postponement*".

Postponement and speculation are logistical concepts that question where and when to add value (e.g., time, place, and form utility) in distribution channels to reduce cost and risk (Twede et al., 2000). In speculation, manufacturing, packaging, and shipping should occur at the earliest possible time in the marketing flow to achieve economies of scale. Speculation relies on forecasts which can sometimes prove to be incorrect. Postponement, the opposite of speculation, is the practice of delaying the final configuration of a product until a customer order is received. This practice reduces a firm's need to forecast the exact product variation ordered by customers.

The concept of postponement was initially introduced by Alderson (1950, 1957) in the field of marketing and brought to the research scope of logistics and supply chain management by Bowersox (1982). Two well-known case studies of postponement in the literature are (1) Benetton, a manufacturer of knitted garments, that keeps inventories of unassembled raw clothing components and does not knit and dye them until a customer order specifying the desired style and color is received (Dapiran, 1992; Sasseen, 1984), and (2) paint retailers that only mix colors after a customer order is received (the original paper of this case study is unknown, but it has been repeated in several books and research papers; see e.g., Chopra, 2017; Zinn, 2019).

Postponement has many benefits such as better demand forecast accuracy and logistics cost reduction (see more in Rietze, 2006; Venkatesh & Swaminathan, 2004). One of the important benefits of implementing a postponement strategy is that postponement could reduce the safety stock and its holding cost because the firm's disruption system operates with less uncertainty (Alderson, 1950). If postponement is not applied, the firm must rely on past sales of each individual item of a product line to decide how much safety stock should be carried for that item. In contrast, if postponement is applied, and the firm only keeps inventories of unassembled products, the firm may rely on past aggregate sales for the entire product line to decide on the level of safety stock needed. For example, assume there is a firm producing bottles in three colors. Without applying postponement, the firm needs to predict demand and carry safety stock for bottles in each color based on past sales, respectively. Alternatively, with the postponement strategy, the firm only needs to predict overall demand and carry safety stock for bottles without color based on past sales of all bottles while delaying the process of dying until it is knowledgeable of the consumer's requirement. Thus, safety stock savings occur because the safety stock of the overall product line is less than the sum of individual safety stocks for each item. This happens because the total sum of the variability of demand for each individual item is greater than the variability of demand for the entire product line. The impact of postponement on safety stock can be estimated by the well-known concept of risk pooling (Mood et al., 1974). This is because the risk related to the uncertainty of demand for each item is pooled together when postponement is applied. As a result, a separate safety stock for each item is no longer needed. Instead, a single safety stock for the entire product line is required because an item may be assembled from available parts once an order is received.

In order to implement postponement, firms may need a considerable amount of additional financial investments. The investments may include (1) modularity improvement or component standardization, (2) supply chain reconstruction, and (3) manufacturing process improvement including process standardization and process re-sequencing (Rietze, 2006; Swaminathan & Lee, 2003). In my thesis, I call the sum of additional investments due to the implementation of postponement as *additional cost*.

1.2 Motivation and Main Contributions

Previous research has made important contributions to identify optimal postponement strategies; albeit the majority of these research works are qualitative studies providing qualitative recommendations regarding the impacts of different strategies (e.g., Feitzinger & Lee, 1997; Van Hoek, 1998; Wong et al., 2011). Although these studies identify important factors that should be considered by decision makers during the planning process, they do not incorporate dependencies between parameters to capture the cost trade-offs, and subsequently, do not provide managerial decision support to concretely measure the impact of such factors. To the best of my knowledge, very few studies (e.g., Cholette, 2009; Graman, 2010; Schwartz & Voß, 2007; Shao & Ji, 2008; Weskamp et al., 2019) focused on developing operations research models to quantitatively support this decision process. Among these studies, none of them presented a mathematical model exclusively for packaging postponement.

The main goal of this paper is to develop a decision support system on the packaging postponement. I note that the holding cost of safety stock and additional cost resulting from packaging postponement are the key decision factors that should be taken into consideration when developing mathematical models. Given related parameters, the decision support system finds the best strategy of packaging postponement to minimize total cost. The research aims to simplify assumptions and present an optimization model that could be used by decision makers who need to decide on packaging postponement. In this regard, I mathematically model the problems as a mixed-integer nonlinear programming model with a single side constraint and solve it by GAMS, distribution 30.3.0 and MATLAB, R2019b.

In addition, although several research papers have studied the impact of various types of postponement on supply chains, very few of them exclusively focus on packaging postponement. Another goal of my thesis is to provide valuable information to researchers and practitioners by summarizing the scientific state-of-the-art in the existing literature that were partially or completely dedicated to the study of packaging postponement. Thus, the main contributions of my thesis are (1) providing a collection of research papers and case studies that focus on packaging postponement, (2) developing a new mathematical model (i.e., a decision support system) for identifying the optimal packaging strategies (no postponement, full postponement, and partial postponement) considering packaging production capacity, and (3) exploring the impacts of factors (e.g., lead time, correlation coefficient, product unit cost, holding cost fraction, cycle service level, and additional cost) on packaging postponement by operating sensitivity analysis.

The rest of the thesis is organized as follows: Chapter 2 provides a literature review on various postponement strategies. Chapter 3 presents the basic information and knowledge about inventory in the supply chain. Chapter 4 presents the problem statement of packaging postponement and the mathematical model for this problem. Chapter 5 presents the computational results from sensitivity analysis on different factors. Chapter 6 concludes the thesis and shares various opportunities for future research.

CHAPTER 2 LITERATURE REVIEW

In this section, papers and articles focused on packaging postponement are the main literature review resources, since packaging postponement is the emphasis of this thesis. At the beginning, I explain different types of postponement and factors favoring postponement implementation. Then, I present existing optimization models for identifying optimal postponement strategies. Finally, I review articles that conducted case studies on packaging postponement.

2.1 Types of Postponement

The types of postponement vary among different papers and articles. Generally, there are three types of postponement: *form*, *time*, and *place postponement*. Form postponement refers to the postponement of final manufacturing or processing activities until a customer order is received (e.g., Cheng & GekWoo, 2002; Chiou et al., 2002). Time postponement refers to the postponement of the forward movement of goods as late as possible within a physical distribution process (e.g., Junior et al., 2018; Yang et al., 2004a). Place postponement refers to the postponement of the product differentiation by redesigning the location of a process (Cheng & GekWoo, 2002). With the combination of time and place postponement, it is referred to as logistics postponement which can be applied only if there are finished products (Yang et al., 2004a).

Zinn and Bowersox (1988) split up postponement into five different types: four *form postponement* (i.e., *labelling*, *packaging*, *assembly*, and *manufacturing postponement*) and *time postponement*. Labelling and packaging postponement are related to the postponement in deferred packaging (e.g., Seth & Panigrahi, 2015; Twede et al., 2000). Deferred packaging is recommended when only the label and packaging differ among products sold in multiple retailers. For assembly and manufacturing postponement, they are related to bundled manufacturing and deferred assembly (e.g., Gualandris & Kalchschmidt, 2015; Kisperska-Moron & Swierczek, 2011). Bundled manufacturing and deferred assembly are recommended when the products themselves vary among retailers. In this case, Table 2-1 presents the characteristics of potentially interested firms for each postponement type (Rietze, 2006; Zinn & Bowersox, 1988).

Table 2-1 Potentially Interested Firms

Postponement type	**Potentially interested firms**
Labeling	Several brands name High unit value products High product sales fluctuations
Packaging	Variability in package size High unit value products High product sales fluctuations
Assembly	Selling products with several versions High volume incurred by packaging High unit value products High product sales fluctuations
Manufacturing	High proportion of ubiquitous material High unit value products High product sales fluctuations
Time	High unit value products Large number of distribution warehouses

Depending on either the postponement strategy or speculation strategy being applied on manufacturing/packaging and logistics, Pagh and Cooper (1998) and Twede et al. (2000) identified four types of postponement/speculation strategies: *full speculation*, *logistics postponement*, *manufacturing/packaging postponement*, and *full postponement*. Full speculation is the traditional mass production model, where products are manufactured and packed at a central location. Then, the finished inventory is shipped to the end of the distribution channels to be close to customers in anticipation of demand. Full speculation reduces production and distribution costs due to economies of scale. But it also increases inventory costs because each stock keeping unit requires its own safety stock. This strategy requires high speed packaging equipment and long production runs. Logistics postponement keeps finished inventory at a central location, directly shipping products only on demand. This strategy has higher distribution costs but achieves a lowering of inventory level in the channel. Packages for such strategy need to have standardized dimension to ensure they are easy to sort quickly. Once the order triggers shipment, the packages need to move fast. Most are sorted in the form of a cross-dock situation, using automatic identification to accelerate the process. In the manufacturing/packaging postponement, semi-finished products are shipped in bulk to a point near to market. The final operations, such as light manufacturing, final assembly packaging and/or labelling, are performed once a customer order is received, or they are postponed at least until forecast of demand is firm in the short-term. This strategy reduces the distribution costs significantly as well as inventory risk due to bulked shipping and flexibility of diverting undifferentiated product. Finally, full postponement defers all final manufacturing, packaging, and logistics until the moment that a customer order is received. The products are stocked and customized in a single central location. The order triggers the final process to produce a customized product and ship it directly. Although this strategy results in higher production and distribution costs, it reduces the inventory cost and risk and provides a high level of customization.

Current research has developed more differentiated concepts of postponement such as price postponement, pull postponement, and production postponement. For further related information, one can refer to available literature review in this area (e.g., Boone et al., 2007; Van Hoek, 2001; Yang et al., 2004b)

2.2 Factors Favoring Postponement Implementation

(1) Product value: This factor affects the inventory savings significantly. Postponement strategy can delay adding value to product, so the higher the value of a product, the greater the potential benefit of postponement (Zinn & Bowersox, 1988). Twede et al. (2000) also stated that if much of

the total value of the product is added in the final operations, it makes sense to postpone such operations. A packaging example can be gift wrapping. Personal gift wrapping anoints the item with an intimate value. Therefore, it makes sense to wait and add this value once the taste of the recipient is known.

(2) Demand uncertainty and forecast error: Both factors affect the level of safety stock which is used to avoid stock risk such as product unavailability. Swaminathan and Tayur (1998), Weskamp et al. (2019),and Zinn and Bowersox (1988) suggested that the higher the level of demand uncertainty, the higher the potential benefit of postponement. Kisperska-Moron and Swierczek (2011) also showed that that the higher the level of forecast error, the greater the potential benefit of postponement.

(3) Product variation: This factor represents the level of product differentiation. Kisperska-Moron and Swierczek (2011), Swaminathan and Tayur (1998), Weskamp et al. (2019), and Zinn and Bowersox (1988) showed that the greater the number of variations offered to customers, the greater the potential benefit of postponement.

(4) Demand correlation: This factor reflects the influence of a version of the product on another version of the same product. The more negative the correlation of demand among different product versions, the greater the potential benefit of postponement (Garg & Tang, 1997; Swaminathan & Tayur, 1998; Weskamp et al., 2019; Zinn, 1990).

(5) Supply chain size: Twede et al. (2000) that the longer and wider the supply chain, the greater the potential benefit of postponement. Global businesses sell many products in a variety of sizes and formulations intended to meet the diverse needs of each market segment.

(6) Other factors: Zinn and Bowersox (1988) and Van Hoek et al. (1998) concluded that the higher the weight reduction obtained from postponement implementation (e.g., unpackaged products can

be shipped in bulk), the greater benefit of postponement. Twede et al. (2000) stated that packaging postponement is more beneficial for products that gain volume, weight, or value from packaging. Van Hoek et al. (1998) also found that the less complex that customization operations, the higher the benefit from postponement. Swaminathan and Tayur (1998) suggested that the higher the production capacity, the greater the benefit from postponement.

Focusing on packaging postponement, there are several articles which drew conclusions as to when packaging postponement is recommended. Twede et al. (2000) claimed that packaging postponement can reduce inventory and transportation costs as well as the risk of mis-forecasts and financial losses due to obsolescence and package damage. Chiou et al. (2002) concluded that packaging postponement is recommended for a business if it satisfies the following four criteria: (i) it produces/markets products in various bundles or package sizes, (ii) the final product is not packaged before customer's order is received, (iii) the proper bundle/bulk is packed and shipped once the customer's order is received, and (iv) the packaging process can be done at its distribution center (overseas unit). Cholette (2010) noted that packaging postponement is appropriate when the product is sold in multiple sizes or formats.

2.3 Decision Support Models for Identification of Optimal Postponement Strategies

Zinn (1990) developed four heuristics to facilitate the identification of postponement opportunities. The heuristics estimate percent safety stock savings from postponement. The study showed that these savings are justified by the correlation of sales among items, the number of items, and the magnitude (the ratio of standard deviations for every pair of items). Sales correlation and magnitude are negatively related to percent safety stock savings from postponement. By contrast, the number of items is positively related to percent safety stock savings from postponement. The author also showed that sales correlation and magnitude are the most and least important factors, respectively. Zinn and Bowersox (1988) designed a normative model to estimate the cost and benefit of adopting postponement as a distribution strategy.

Schwartz and Voß (2007) developed a mixed integer programming model for network design of a supply chain with possible postponement of assembly or packaging. Their model minimizes total costs (i.e., variable shipping costs, variable processing costs, and fixed infrastructure costs) with the following constraints: (i) material flow balance, (ii) demand satisfaction, (iii) limited supply, (iv) limited transportation capacity, and (v) limited infrastructure capacity. Shao and Ji (2008) presented an optimization model with the objective of minimizing total inventory costs and constrained by (i) a threshold for average customer waiting time, and (ii) the fill rate within a target waiting time window. Graman and Sanders (2009) developed two inventory models: one to evaluate the impact of increasing postponement capacity on inventory levels, while the other to measure the effect of improved forecast accuracy on inventory levels. Both inventory models are used as the basis for a cost model.

Cholette (2009) presented a two-stage stochastic linear programming model for labeling and packaging postponement in the wine industry. The model maximizes expected profit constrained by the following constraints: (i) limited supply, (ii) limited transformations (e.g., transformation of blank bottles to particular private label wines), (iii) no storage is allowed (i.e., all inventories should be either transformed into finished products or discarded), (iv) only finished products that were demanded are sold at full price, (v) demand shortage is possible, and (vi) excess supply should be discarded. Graman (2010) developed a nonlinear programming model for packaging postponement with the objective of minimizing total costs (i.e., assembly labor and material costs, postponement costs, packaging costs, holding costs of finished goods inventory, holding costs of postponed inventory, and shortage costs). The constraints of the problem are as follows: (i) fill rate constraints, i.e., the expected number of stockouts for each product is less than or equal to the target number of stockouts, (ii) boundary condition constraints, i.e., inventory levels should always be greater than or equal to the minimum level of demand for each product and less than or equal to the maximum level of demand for each product, (iii) postponement capacity allocation constraints, i.e., the amount of the postponed inventory used by various products is less than or equal to the postponement capacity, and (iv) postponement capacity constraints, i.e., the capacity can be set to zero (creating the non-postponement case), or some specified amount of capacity.

Recently, Weskamp et al. (2019) developed a two-stage stochastic mixed-integer linear programming model for solving an integrated production and distribution problem with the objective of expected profit maximization, taking into account stochastic demands. The objective function maximizes the expected profit while minimizes total costs which include fixed costs for establishing production activities in a facility, fixed costs for establishing inventory as well as transportation activities, variable production costs, transportation and inventory costs inclusive of capital commitment costs, and penalty costs for shortfalls. The constraints include (i) material flow balance, (ii) demand satisfaction, (iii) limited production capacity, (iv) limited transportation capacity, (v) limited inventory capacity, and (vi) risk attitude.

2.4 Case Studies of Packaging Postponement

Lee et al. (1993) and Feitzinger and Lee (1997) presented a case study in which Hewlett Packard (HP) adopted a packaging postponement strategy for its DeskJet printers and could realize over $3 million/month in logistics savings. In the early 1990s, there were 138 versions of HP's six basic inkjet printers around the world. Postponement enabled HP to present more varieties of printers in terms of country-specific power supply module, language specific manual, software, and shipping container. Rietze (2006) provided several case studies of companies (e.g., Dade Behring, Polaroid, Bic, and Imation) that applied packaging postponement strategies in their supply chain. Van Hoek (1998) studied food companies in Europe and compared them to other industries such as automotive, paint, and computers to identify the activities at which postponement could be applied. The author pointed out that postponing the labeling and packaging of products is appropriate for food industries. In the food industry, another study that can be mentioned is the one carried out by Wong et al. (2011). Using a case study approach, the authors evaluated the postponement as an option to improve the supply chain performance in a soluble coffee producer. The authors found that postponing the labeling and packaging processes until actual orders from customers are received may lead to significant cost savings. Cholette (2009, 2010) concluded that wineries should hold part of their production (either in tanks or at a later finishing point, in blanks, which are sealed but unlabeled bottles) to improve their profitability when they face demand uncertainties. Seth and Panigrahi (2015) conducted a study to evaluate the impact of packaging postponement on the performance of the sanitary pads supply chain. The authors showed that packaging postponement not only improves competitive advantage but also significantly contributes to improving product proliferation and supply chain responsiveness. Ferreira and Alcantara (2016) investigated the adoption of labeling and packaging postponement strategies in companies that produce tomato-derived products. The authors studied the implementation process and the major changes after this adoption.

CHAPTER 3 INVENTORY IN SUPPLY CHAIN

3.1 Cycle Inventory and Safety Stock

In a supply chain system, inventory generally consists of two kinds of inventory: cycle inventory and safety stock. Cycle inventory is the inventory needed to ensure continuous manufacturing or selling during the time interval of two consecutive orders (i.e., lead time). Cycle inventory is highly related to a lot or batch size which means the quantity of production or purchasing of a company at a time. Lot or batch size is denoted by Q. The relationship between cycle inventory and lot size is presented as follows:

$$Cycle\ inventory = Q/2 \tag{3.1}$$

If the demand of a product is constantly deterministic or the prediction of demand is accurate, cycle inventory would be enough to accomplish all orders in a supply chain; however, this perfect situation cannot always happen. The demand of a product is usually uncertain due to many factors including seasons, price, policy, etc. Once the actual demand exceeds prediction of demand, it may result in a product shortage and financial loss. In order to avoid such loss, the company usually carries some additional inventories to satisfy excess of demand in a given period. This excess inventory is called safety stock (Graves, 1987). Figure 3-1 presents these two kinds of inventory mentioned above.

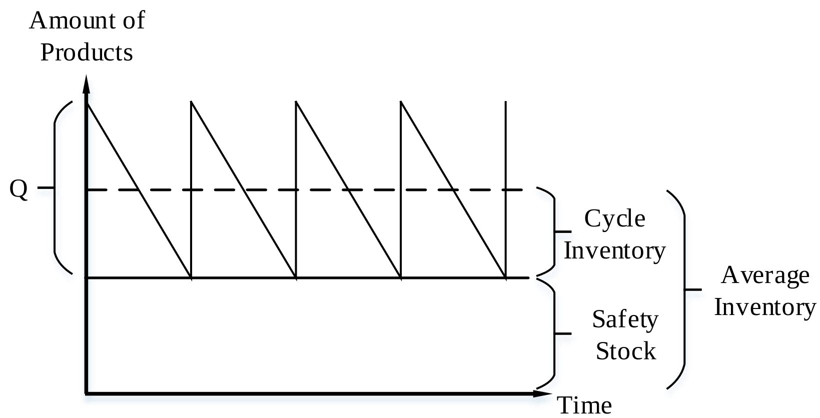

Figure 3-1 Inventory in Supply Chain System

Consider, for example, disinfecting wipes sold in a market. The market manager orders in lots of 600 cases every time. Weekly demand of disinfecting wipes averages 100 cases. If the demand is steady, the store manager can place a new order when the storage decreases to cycle inventory which is 300 and the products in each order will be sold out in 6 weeks. However, due to a sudden virus disease, customers choose to purchase more disinfecting wipes than usual, which leads to rapid demand increases. The new weekly demand increases up to 150 cases. Without safety stock, the disinfecting wipes would be sold out in 4 weeks. As a result, a wipes shortage would occur and last for 2 weeks. If the market carries excess 300 cases as safety stock and total inventory is 900 cases, the wipes will still be sold out in 6 weeks and the shortage will be avoided.

Although safety stock could increase product availability and thus retrieve a loss due to product shortage, safety stock is not useful for all kinds of products. If a product has a short shelf life, the cost of keeping the product fresh would be high, and overstocking may lead to another loss due to spoilage. In order to take full advantage of safety stock, it is important to consider how much stock is appropriate for a certain product.

3.2 Appropriate Level of Safety Stock

The appropriate level of safety stock is determined by two factors: the uncertainty of product demand and the desired level of product availability. With the growth of uncertainty of demand, the required level of safety stock increases. When a new product is introduced, demand of the product is highly uncertain due to lack of information about the market. It is reasonable to carry a high level of safety stock. After the product has been sold for a period of time, the market's reaction clarifies the demand and reduces product uncertainty. At that point, lower level of safety stock is preferred to decrease holding cost. Regarding the desired level of product availability, the required level of safety stock should increase as availability increases.

3.2.1 Measuring Demand Uncertainty

Assume that weekly demand of the product is normally distributed. Lead time is the time gap between the initiation and completion of an order. In this discussion, lead time is denoted by L. Whether the product is able to satisfy all demand from stock relies on two factors: demand of the product during the lead time and the inventory level of the product when a new order is placed. Thus, it is meaningful to estimate the uncertainty of demand during the whole lead time other than any single week. In order to evaluate the distribution of demand over L, assume that demand for each week m, $m = 1,2, \dots, L$ is normally distributed with a mean of D_m and a standard deviation of σ_m, and the total demand during L is normally distributed with a mean of D_L and a standard deviation of σ_L.

We denote the correlation coefficient of demand between weeks m and n by ρ_{mn}. If demand in weeks m and n is perfectly positively correlated, ρ_{mn} equals 1. If demand in weeks m and n is perfectly negatively correlated, ρ_{mn} equals -1. If demand in weeks m and n is independent, ρ_{mn} equals 0. Eq.(3.2) illustrates the relationship among these parameters.

$$D_L = \sum_{m=1}^{L} D_m \quad \sigma_L = \sqrt{\sum_{m=1}^{L} \sigma_m^2 + 2\sum_{m>n} \rho_{mn}\sigma_m\sigma_n} \tag{3.2}$$

We now assume that demand during L is independent and normally distributed with a mean of D and a standard deviation of σ_D (i.e., $D_m = D$ for each m, and $\rho_{mn} = 0$ for each m and n). Then, Eq.(3.3) could be obtained from Eq.(3.2).

$$D_L = D \times L \qquad \sigma_L = \sqrt{L}\sigma_D \tag{3.3}$$

3.2.2 Measuring Product Availability

Product availability reflects a firm's ability to fulfill a customer order out of available inventory. Usually, there are three ways to describe availability: namely, product fill rate, order fill rate and cycle service level, and two review policies: namely, continuous review and periodic review. In my discussion, I only consider cycle service level (CSL)and continuous review (Chopra, 2017).

Cycle service level (CSL) refers to the fraction of replenishment cycles that end with all the customer's demand being met. A replenishment cycle is the interval between two successive replenishment deliveries. CSL also refers to the probability of not having a stock-out in a replenishment cycle. *Continuous review* means the inventory of a product is continuously monitored, and a replenishment is placed once the inventory declines to the reorder point (ROP).

According to Eq.(3.2), expected demand during lead time is $D \times L$. Given the definition of CSL and continuous review, we have:

$$\text{Safety stock, } ss = ROP - DL \tag{3.4}$$

$$CSL = \text{ Prob (demand during lead time } \leq ROP) \tag{3.5}$$

Because weekly demand is normally distributed, we can calculate CSL by using the notations from APPENDIX A.

$$CSL = F(ROP, D_L, \sigma_L) \tag{3.6}$$

3.2.3 Evaluating Safety Stock

In this section, we still follow continuous review replenishment policy to evaluate required safety stock based on CSL. Given a desired cycle service level, from Eq.(3.4) and (3.6), we obtain:

$$ROP = D_L + ss, \qquad CSL = F(D_L + ss\,, D_L, \sigma_L)$$

Based on the definition of the standard normal distribution and its inverse in APPENDIX A, safety stock can be calculated by Eq.(3.7).

$$ss = F_s^{-1}(CSL) \times \sigma_L = F_s^{-1}(CSL) \times \sqrt{L}\sigma_D \tag{3.7}$$

3.3 Aggregation on Safety Stock and Holding Cost

The degree of inventory aggregation varies due to a firm's own decision. For example, some firms sell products from retail stores with inventory geographically distributed across the country. In contrast, some firms prefer to ship products from a few facilities.

In this section, we assume demand of a product in different k regions are normally distributed with the following characteristics:

D_u: Average weekly demand in region u, $u = 1, \dots, k$

σ_v: Standard deviation of weekly demand in region u, $u = 1, \dots, k$

ρ_{uv}: Correlation of weekly demand for regions u and v, $1 \le u \ne v \le k$

We discuss the impacts of aggregation by comparing safety stock in two scenarios. One is that product inventories are distributed in each region (i.e., decentralized system), and the other is all inventories are aggregated into one centralized facility (i.e., centralized system). Given a replenishment lead time of L and a desired cycle service level of CSL, the total safety stock in the decentralized scenario is obtained by Eq.(3.8)

$$ss^d = \sum_{u=1}^{k} F_S^{-1}(CSL) \times \sqrt{L} \times \sigma_u \tag{3.8}$$

In the aggregated scenario, aggregated demand is normally distributed with a mean of D^c, standard deviation of σ_D^C, and a variance of var(D^c) as follows:

$$D^c = \sum_{u=1}^{k} D_u \,; var(D^c) = \sum_{u=1}^{k} \sigma_u^2 + 2\sum_{u>v} \rho_{uv}\sigma_u\sigma_v \,;\; \sigma_D^C = \sqrt{var(D^c)} \tag{3.9}$$

Using Eq.(3.7), the safety stock at the centralized location is given as

$$ss^a = F_S^{-1}(CSL) \times \sqrt{L} \times \sigma_D^C \tag{3.10}$$

Holding cost is the cost of carrying one unit in inventory for a certain period. It is the combination of the cost of capital, the cost of physically storing the inventory, and the cost that results from the product becoming obsolete. The holding cost can also be obtained as a fraction h, of the unit cost of the product. Given the unit cost c, holding cost can be calculated as follow:

$$H = h \cdot c \tag{3.11}$$

Then , the holding cost savings on aggregation per unit sold are obtained as follow:

Holding-cost savings on aggregation per unit sold

$$= \frac{F_S^{-1}(CSL) \times \sqrt{L} \times H}{D^c} \times \left(\sum_{u=1}^{k} \sigma_u - \sigma_D^C\right) \tag{3.12}$$

From Eq.(3.12), we can conclude that the safety stock savings on aggregation increase with the desired service level CSL, replenishment lead time L and holding cost H. But they decrease as the correlation coefficients increase. This is because the difference (i.e., $\sum_{u=1}^{k} \sigma_u - \sigma_D^C$) enlarges as the correlation coefficients approach "-1" and shrinks as they approach "$+1$".

CHAPTER 4 PROBLEM STATEMENT AND MATHEMATICAL MODELING

4.1 Packaging Postponement Problem Statement

Suppose a manufacturer produces and packages private label products for a set of retailers. Let j denote product type and i denote the retailer index. In each case, the basic product is identical with the only difference being the packaging. Therefore, the labeled and packaged version of the product destined for retailer i cannot be sent to retailer i'. This is challenging because even though there is sufficient product inventory available at the distribution center, it is quite possible that the manufacturer could not meet a retailer's request because the excess available inventory was labeled and packed to other retailers. Suppose there are two different scenarios for the manufacture:

I. Packaging without postponement: The manufacturer produces and packages product j

II. Packaging with partial/full postponement: The manufacturer produces product j and postpone the final packaging of part/whole of the demand to the distribution center. The packaging production capacity of the distribution center for product j is respected

Let L_j denote the lead time of manufacturing and transporting the basic product from the manufacturer plant. Without loss of generality, we assume that L_j remains the same for both scenarios. This is a reasonable assumption since packaging is a relatively quick process, and the response time from the distribution center to the retailer's request is not expected to change.

In this problem, postponement will add additional cost. Let c_j^a denote the additional cost per unit of product j when postponement occurs. Let μ_{ij} and σ_{ij} denote the mean and standard deviation of the weekly demand of product j at retailer i. For simplicity, we assume that all demands are normally distributed. I also assume that the demand of product j is independent of the demand of product j' at retailer i. Let c_j denote the total product cost of product j. It is supposed that the manufacturer uses a holding cost of h percent when making its inventory decision and aims to provide a certain cycle service level for each product to every retailer. In addition, we assume that the manufacturer employs continuous review policy, and the packaging process is so fast that the response time from the distribution center to the retailer is not expected to change.

This problem is highly related to aggregation on safety stock, cause we postponed packaging process of products for different retailers (decentralized system) to a distribution center (centralized system). In the next section, I develop a mathematical model to help us understand which strategy is best for a business.

4.2 Model Development for Packaging Postponement

The following notations and definitions are used throughout the thesis:

Table 4-1 Notations Used throughout the Thesis

Indices	**Description**
i	Index of a retailer
j	Index of a product
Parameters	
L_j	Lead time of manufacturing and transporting product j
c_j^a	Additional cost per unit of product j when postponement occurs
c_j	Total production cost of product j
μ_{ij}	Average weekly demand of product j at retailer i
σ_{ij}	Standard deviation of weekly demand of product j at retailer i
h	Holding cost as a fraction of production cost per unit in one year
CSL	Desired cycle service level
C_j	The packaging production capacity in the distribution center for product j
$\rho_{ii'j}$	The correlation coefficient of demand for product j between retailer i and i'
Variables	
x_{ij}	Equals 1 if the packaging of product j destined for retailer i is postponed; 0 otherwise

Scenario I: The safety stock of product j destined for retailer i is denoted by ss_{ij} and its annual holding cost is denoted by H_{ij}. According to Eq.(3.7), ss_{ij} can be calculated by Eq.(4.1).

$$ss_{ij} = F_s^{-1}(CSL) \times \sqrt{L_j} \times \sigma_{ij} \qquad \forall i, \forall j \qquad (4.1)$$

Given a unit cost of c_j, H_{ij} is measured in \$/year by Eq.(4.2).

$$H_{ij} = ss_{ij} \times c_j \times h \qquad \forall i, \forall j \qquad (4.2)$$

Then, the total cost of scenario I, denoted by TC_I,can be calculated by Eq.(4.3).

$$TC_I = \sum_{ij}[(1 - x_{ij}) \cdot H_{ij}] \qquad (4.3)$$

Scenario II: Since packaging of product j destined for retailer i may be postponed to the distribution center together and according to the discussion on aggregation on safety stock, we can calculate the safety stock product j, denoted by ss_j, by Eq.(4.4):

$$ss_j = F_s^{-1} \times \sqrt{L_j} \times \sigma_j \qquad \forall j \qquad (4.4)$$

, where σ_j is the standard deviation of weekly demand of all product j destined for retailer i , whose packaging process is postponed. It can be obtained from Eq.(4.5):

$$\sigma_j = \sqrt{\sum_i x_{ij}\sigma_{ij}^2 + 2\sum_{i>i'} \rho_{jii'}\sigma_{ij}\sigma_{ij'}\, x_{ij}x_{ij'}} \qquad \forall j \qquad (4.5)$$

, where $\rho_{ijj'}$ is the correlation coefficient of demand between retailers i and i'. Then, annual holding cost H and total cost TC_{II} are given by Eqs. (4.6) and (4.7), respectively. I note that TC_{II} includes two terms: annual holding cost and annual additional cost. As I mentioned before, the additional cost is the result of postponement. Of note, I assume that the additional cost does not change from one week to another, and a year consists of 52 weeks.

$$H_j = ss_j \times c_j \times h \qquad \forall j \qquad (4.6)$$

$$TC_{II} = \sum_i \left(H_j + \sum_i \left(52 \times c_j^a \times \mu_{ij} \times x_{ij}\right)\right) \qquad (4.7)$$

The total cost can be obtained from Eq.(4.8):

$$TC = TC_I + TC_{II} \tag{4.8}$$

The constraints corresponding to the distribution center's capacity for packaging of product j can be written as follows:

$$\sum_i \mu_{ij} \times x_{ij} \leq C_j \qquad \forall j \tag{4.9}$$

I also need to define the binary definitional constraints for variable x_{ij} as follows:

$$x_{ij} \in \{0,1\} \qquad \forall i, \forall j \tag{4.10}$$

Then, the following optimization problem is a nonlinear programming model:

Problem *P*:

$Min\, TC$

$s.t.$

$\sum_i \mu_{ij} \times x_{ij} \leq C_j$

$x_{ij} \in \{0,1\}$

CHAPTER 5 COMPUTATIONAL RESULTS

Based on the mathematical formulation for problem *P*, we realize that decision-making on packaging postponement of product j is independent of packaging postponement of product j'. This is because (i) the cost imposed by product j is independent of the cost imposed by product j', and (ii) the production capacity of product j is independent of the production capacity of product j'. Therefore, one can decompose the main problem to several sub-problems and solve them independently.

In this chapter, without loss of generality, I conducted experiments and performed sensitivity analysis on packaging postponement of one product. Table 5-1 presents the distribution of weekly demand by retailer. These numbers are generated by the author to analyze the impact of relatively high and low μ_i and σ_i on packaging postponement decision. Retailer 1 has a relatively high mean and standard deviation, while retailer 2 has a relatively high mean and low standard deviation. Retailer 3 has a relatively low mean and high standard deviation, while retailer 4 has a relatively low mean and standard deviation.

Table 5-1 Distribution of Weekly Demand by Retailer

Retailer i	μ_i	σ_i
1	1000	500
2	1000	100
3	100	50
4	100	10

Table 5-2 presents the value of parameters that are used for sensitivity analysis. I note that in order to perform the sensitivity analysis, the value of parameters is discretized, while the accuracy and big picture of sensitivity analysis can be kept at the same time. In the sensitivity analysis, the goal is to evaluate the impact of parameter changing on the final packaging postponement decision. Since including capacity constraint for the sensitivity analysis eclipse the impact of parameter changing, I conduct several sensitivity analyses without considering the capacity constraint.

Table 5-2 Value of Parameters Used in the Experiment

Parameters	Baseline scenario	Sensitivity analysis on other values
L	9 weeks	1 week, 2 weeks, …, 13 weeks
c^a	\$1 per unit	\$0.0, \$0.5, \$1.0, \$1.5, \$2.0, \$2.5, \$3.0 per unit
c	\$1000 per unit	\$100, \$200, …, \$1300 per unit
h	30%	12%, 14%, 16%, …, 32%
CSL	95%	75%, 76%, 77%, …, 99%
C	\$2200	\$100, \$200, \$300, …, \$2200
ρ_{12}	0	-1, -0.8, -0.6, …, 0, …, 0.6, 0.8, 1
ρ_{13}	0	-1, -0.8, -0.6, …, 0, …, 0.6, 0.8, 1
ρ_{14}	0	-1, -0.8, -0.6, …, 0, …, 0.6, 0.8, 1
ρ_{23}	0	-1, -0.8, -0.6, …, 0, …, 0.6, 0.8, 1
ρ_{24}	0	-1, -0.8, -0.6, …, 0, …, 0.6, 0.8, 1
ρ_{34}	0	-1, -0.8, -0.6, …, 0, …, 0.6, 0.8, 1

The problem was solved in both GAMS and MATLAB to ensure the accuracy of the experiment. The code used for sensitivity analyses can be found in APPENDIX B and APPENDIX C. The results of the experiment are illustrated in different figures. In each figure, the blue circle means that packaging postponement should occur for the demand of retailer j, while the red circle means that postponement should not occur.

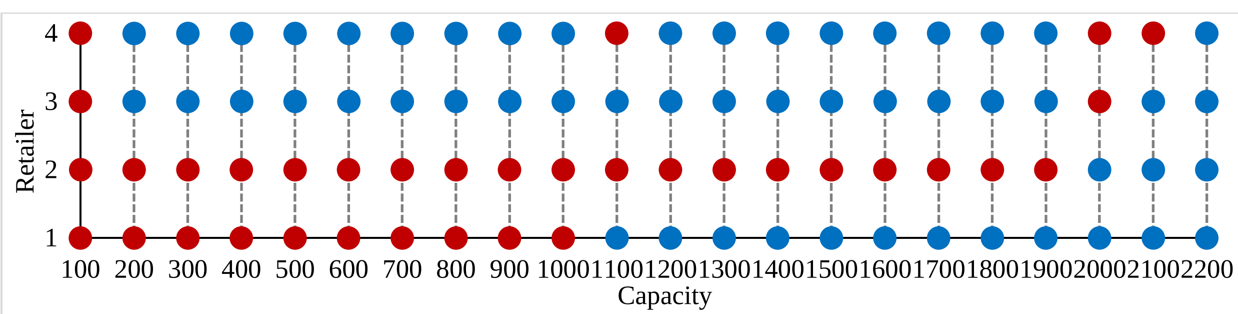

Figure 5-1 Sensitivity Analysis on Packaging Production Capacity C

Figure 5-1 presents the results of sensitivity analysis on packaging production capacity. In this figure, packaging postponement becomes more beneficial with the increase of packaging production capacity. When the capacity is less than 100, it cannot meet the weekly demand of product for any retailer, so it is meaningless to postpone packaging operation at the distribution center. When the capacity is 100, the packaging of products for either retailer 3 or 4 could be postponed. But none of them is recommended to apply packaging postponement. That is to say, the additional cost overwhelms the holding cost saving if we only postponed packaging of 100 units. While when the capacity is 200 to 1000, the distribution center can operate packaging of product for both retailer 3 and 4.

When the capacity is 1100 to 1900, packaging postponement can be applied on product for either retailer 1 or 2. In this case, retailer 1 is preferred, because the weekly demand of product for retailer 1 is less accurate and stable due to its higher standard deviation. The same reason can be used to explain why retailer 3 is preferred when the capacity is 1100. This conclusion is corresponding to the second point mentioned in chapter 2.2. When capacity is greater than or equal to 2000, the packaging of more products is deferred, the more benefit could be obtained.

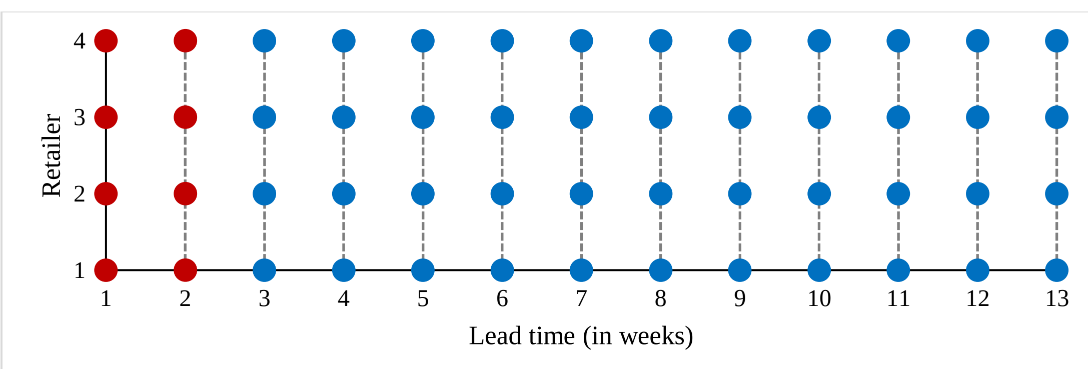

Figure 5-2 Sensitivity Analysis on Lead Time L

Figure 5-2 shows that when lead time increases, packaging postponement becomes more beneficial. This means that when lead time is short, responsiveness outweighs efficiency. This balance is reversed when lead time becomes longer. It makes sense that long lead time means more safety stock which makes packaging postponement become more impactful on holding cost savings are needed. In my experiment, for products with lead time greater than or equal to 3 weeks, packaging postponement is recommended.

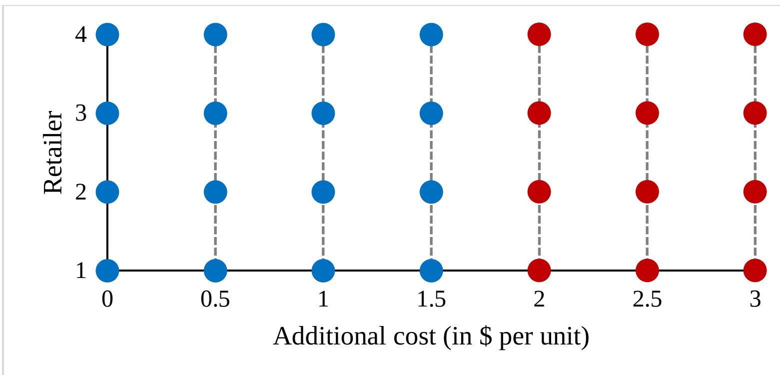

Figure 5-3 Sensitivity Analysis on Additional Cost c^a

Figure 5-3 presents the sensitivity analysis of additional cost. As you can see, if the additional cost is less than $1 per unit, packaging postponement is recommended, while for additional cost greater than or equal to $1 per unit, packaging postponement is not recommended. Obviously, additional cost is the factor diminishes the benefit of packaging postponement directly. If additional cost is high, postponement strategy will not be justifiable.

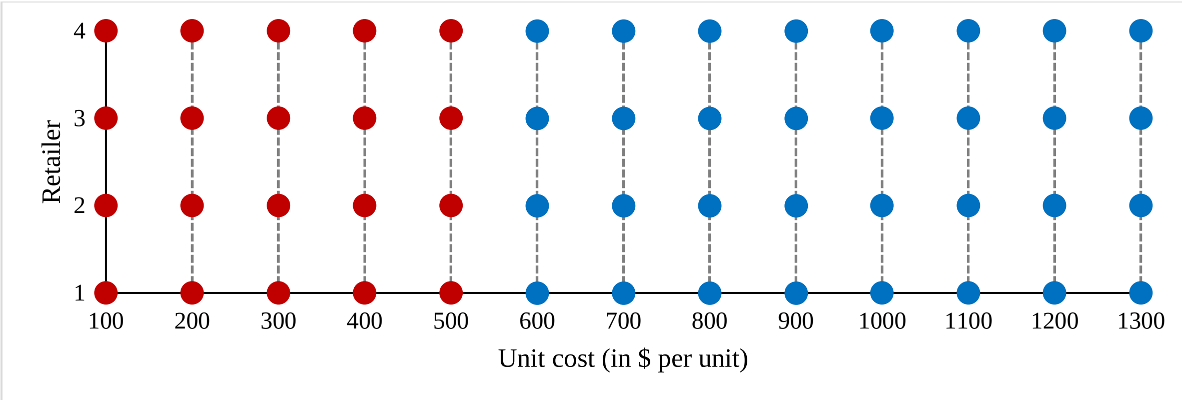

Figure 5-4 Sensitivity Analysis on Unit Cost c

Figure 5-4 demonstrates the sensitivity analysis of production cost per unit (i.e., unit cost). In the experiment, if unit cost is less than or equal to $500 per unit, postponement is not beneficial, while for a product with unit cost greater than $500 per unit, postponement is recommended. These results support the findings of Zinn and Bowersox (1988) and Twede et al. (2000). The model has a merit insofar as it identifies the exact unit cost of the product at which packaging postponement becomes beneficial.

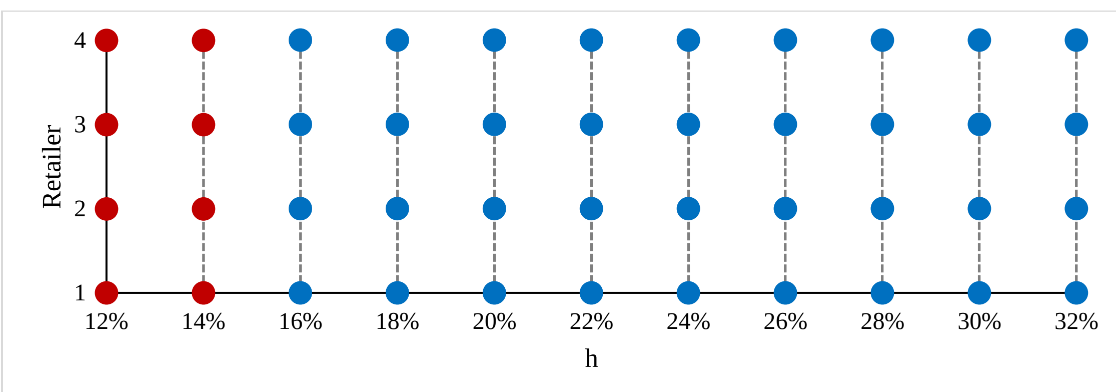

Figure 5-5 Sensitivity Analysis on Holding Cost Fraction h

Figure 5-5 demonstrates the sensitivity analysis on holding cost fraction. This figure shows that for $h \geq$ 16%, postponement could be beneficial, but for anything lower than the threshold of 16%, the packaging postponement is not recommended for any retailer's demand. When the holding cost fraction is high, the holding cost is also high if unit cost does not change. As a result, packaging postponement becomes beneficial.

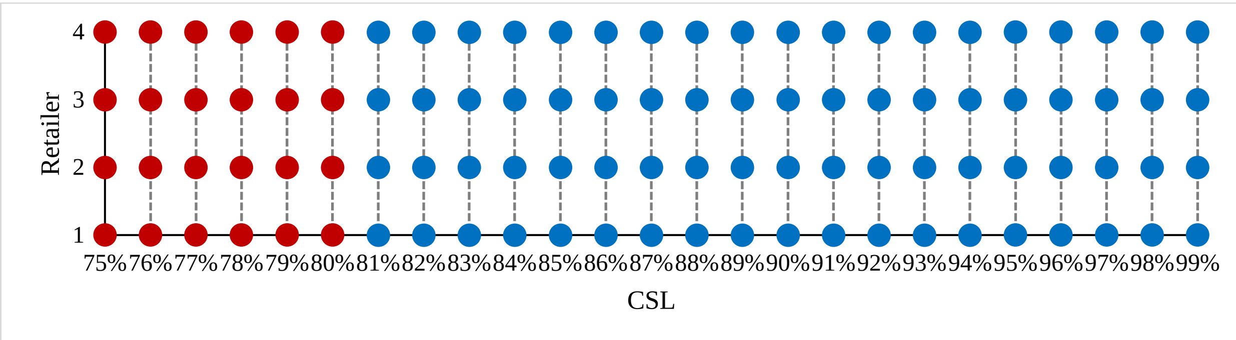

Figure 5-6 Sensitivity Analysis on CSL

CSL is the expected probability of not hitting a stock-out during lead time. High CSL reflects high difficulty to meet product demand in a period for a company and high level of safety stock. As mentioned before, postponement could reduce the risk of stock-out as well as the quantity of safety stock. Thus, it is not hard to understand why packaging postponement becomes beneficial when CSL is high. From Figure 5-6, packaging postponement is not recommended until CSL reaches up to 81%. The results obtained from sensitivity analysis on L, h and CSL also support the discussion on Eq.(3.12).

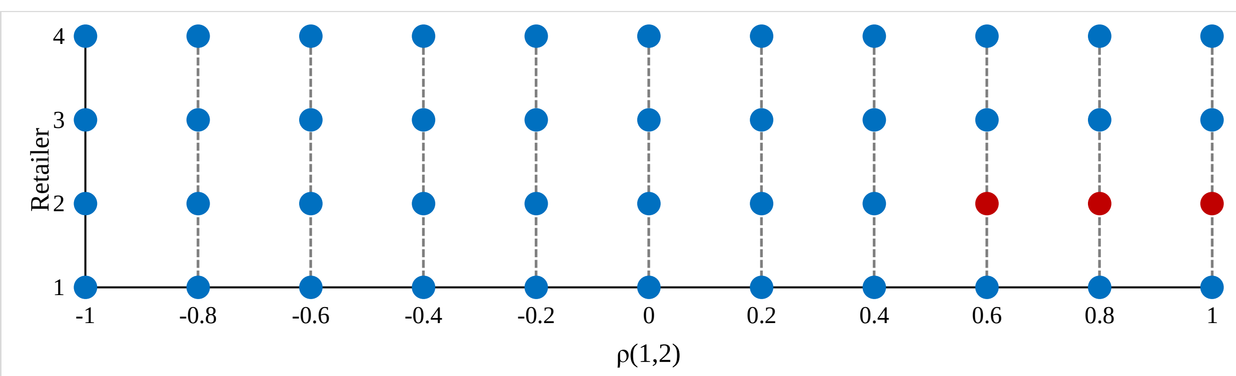

Figure 5-7 Sensitivity Analysis on $\rho_{1,2}$

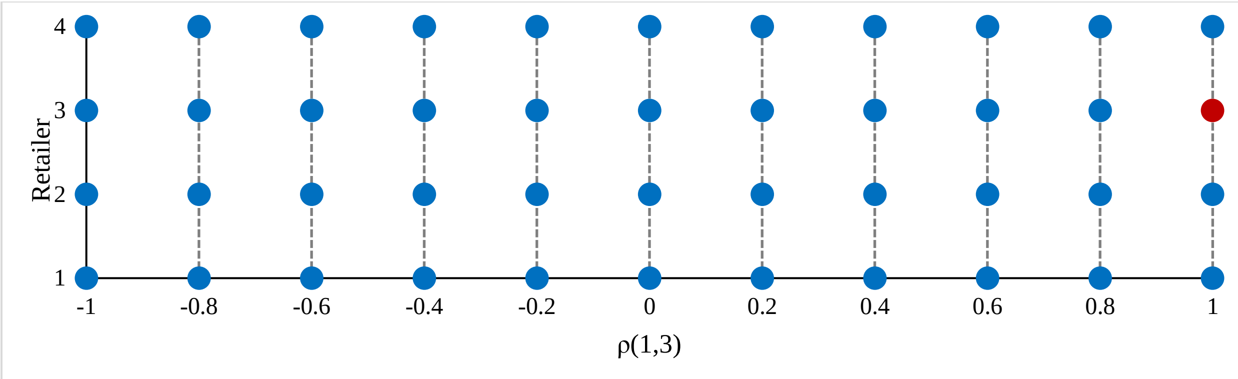

Figure 5-8 Sensitivity Analysis on $\rho_{1,3}$

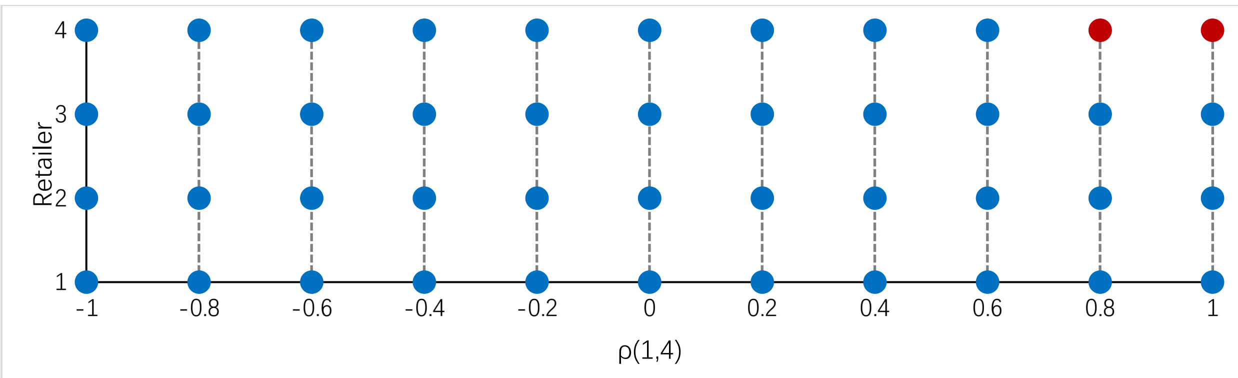

Figure 5-9 Sensitivity Analysis on $\rho_{1,4}$

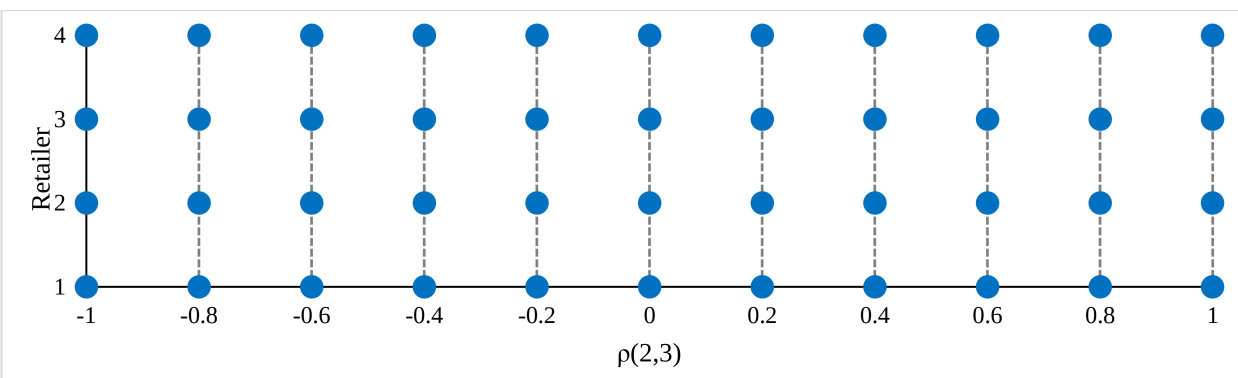

Figure 5-10 Sensitivity Analysis on $\rho_{2,3}$

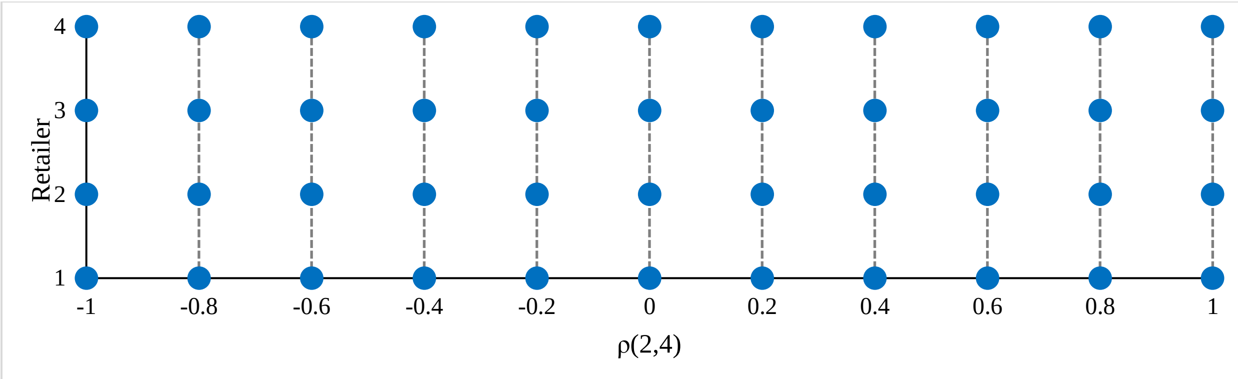

Figure 5-11 Sensitivity Analysis on $\rho_{2,4}$

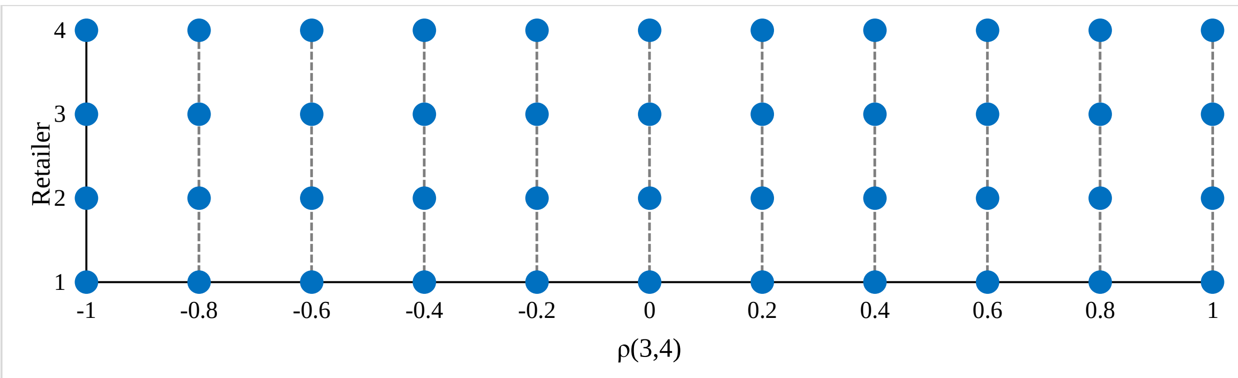

Figure 5-12 Sensitivity Analysis on $\rho_{3,4}$

Figure 5-7 to 5-12 show the results of sensitivity analyses on a different correlation coefficient. From the perspective of the big picture on the correlation coefficient, I observe that the changes in the value of ρ_{12}, ρ_{13}, and ρ_{14} have a more significant impact on packaging postponement decisions than the ones of ρ_{23}, ρ_{24}, and ρ_{34}. This is because demand of product for retailers 1 and 2 have higher μ compared to the one of retailers 3 and 4. In addition, packaging postponement is not recommended when the correlation coefficient is close to "+1" which supports the findings from previous research (e.g., Garg & Tang, 1997; Swaminathan & Tayur, 1998) and the discussion on Eq.(3.12).

Focusing on a specific correlation coefficient, I realize that when the correlation coefficient is so close to "+1" that full packaging postponement is not the optimal decision, the packaging of product for a retailer with lower μ (Figure 5-8 and Figure 5-9) and lower σ (Figure 5-7) is preferred not to be postponed.

CHAPTER 6 CONCLUSIONS

Postponement, as a deliberate action, has been applied in various fields. It delays some value-adding actions such as manufacturing, labelling, packaging and assembly until receipt of a customer order. This reduces the incidence of wrong manufacturing or incorrect inventory deployment but results in additional costs. Focusing on packaging postponement, my thesis presented a decision support system that determines which postponement strategy, i.e., full, partial (tailored), or no postponement, is recommended. After reviewing previous research and knowledge related to safety stock, I presented a mixed-integer nonlinear programming model with the objective of minimizing costs (i.e., holding cost and additional cost) and constrained by the limited capacity of packaging production and the integrity of variables. Based on this model, sensitivity analysis was conducted to explore the impacts of different factors on postponement decision. As a result, the factors such as packaging production capacity, lead time, unit cost of the product, holding cost as a fraction of unit cost, and cycle service level are in favor of packaging postponement, while additional cost is in adverse of packaging postponement. As to the correlation coefficient, the benefit of postponement decreases when the correlation coefficient approach "$+1$", while the benefit increases when the correlation coefficient approach "-1" . In addition, I also identified that product is preferred as the target for packaging postponement when its demand has high mean and high standard deviation. The presented work provides a valuable tool for planners who need to decide on the implementation of packaging postponement in their own industry.

There are still some limitations on the study. First, there might be various direct and indirect costs that have not been included in the objective function. Second, in addition to the production capacity constraint in the distribution center, there can be other constraints and limitations that have not been considered in the model.

Finally, solving the proposed mathematical model requires optimization tools such as Excel Solver, CPLEX, or GAMS. Although the first two optimization tools are open source, one can develop an algorithm to solve the proposed mixed-integer nonlinear programming model without using any optimization tool. In my proposed mathematical model, there are two sets of constraints: (i) the limited capacity of packaging production and (ii) the integrity of variables. One can relax the latter set of constraints to convert the problem to a nonlinear programming problem. Also, by relaxing the former set of constraints into the objective function and applying the Lagrangian relaxation method, the main problem is converted to an unconstrained nonlinear programming problem. Then, one can apply a Lagrangian heuristic and find the optimal linear solution at each iteration by Newton-Raphson method (Belegundu & Chandrupatla, 2019).Finally, a branch-and-bound algorithm can be developed to obtain the optimal integer solution.

To sum up, future research on this subject can continue in the following directions: (i) enhancing the mathematical model by improving the objective function and including more practical constraints, and (ii) developing a user-friendly program to solve such a complicated optimization problem.

APPENDICES

APPENDIX A

Normal Distribution

A continuous random variable X has a normal distribution with mean μ and standard deviation $\sigma > 0$ if the probability density function $f(x, \mu, \sigma)$ of the random variable is given by Eq.(A.1).

$$f(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp[\frac{(x-\mu)^2}{2\sigma^2}] \tag{A.1}$$

The cumulative normal distribution function is denoted by $F(x, \mu, \sigma)$ as Eq.(A.2) . It means the probability that X takes on a value less than or equal to x.

$$F(x, \mu, \sigma) = \int_{X=-\infty}^{x} f(x, \mu, \sigma) \tag{A.2}$$

A normal distribution with a mean $\mu = 0$ and standard deviation $\sigma = 1$ is referred to as the standard normal distribution. Its density function is denoted by $f_s(x)$ and the cumulative standard normal distribution function is denoted by $F_s(x)$, where $f_s(x) = f(x, 0,1)$ and $F_s(x) = F(x, 0,1)$.

Given a probability p, the inverse normal $F^{-1}(p, \mu, \sigma)$ is the value x such that p is the probability that X takes on a value less than or equal to x. In other words, if $F(x, \mu, \sigma) = p$ then $x = F^{-1}(p, \mu, \sigma)$. The inverse of the standard normal distribution is denoted by $F^{-1}(p)$, where $F^{-1}(p) = F^{-1}(p, 0,1)$.

Assume that demand is uniformly distributed with a mean of $\frac{a+b}{2}$ and a variance of $\frac{(b-a)^2}{12}$. Then, one can show that total demand during L weeks (L is the lead time) is uniformly distributed with a mean of D_L and a standard deviation of σ_L, where the following is true:

$$D_L = \frac{a+b}{2} L;\ \sigma_L = \sqrt{L.\frac{(b-a)^2}{12}} = \sqrt{\frac{L}{3}}.\frac{b-a}{2} \tag{A.3}$$

The cumulative distribution function for continuous uniform distribution is:

$$F(x) = \begin{cases} 0 & for\ x < a \\ \dfrac{x-a}{b-a} & for\ x \leq a \leq b \\ 1 & for\ x > b \end{cases} \tag{A.4}$$

From (A.2) and (A.3), $F(x) = CSL$, and from (A.4), $\frac{x-a}{b-a} = CSL$, for $x \leq a \leq b$. We also know that from the probability definition, $F^{-1}(CSL) = x$. Therefore:

$$F^{-1}(CSL) = x = a + CSL(b-a) \tag{A.5}$$

APPENDIX B

Code in GAMS for Packaging Postponement Decision in Baseline Scenario

Line 1 determines the optimization solver. From line 2 to line 5, I determined index of products and retailers. From line 6 to line 23, I input values of all parameters in baseline scenario. From line 24 to line 27, I calculated $F_s^{-1}(CSL)$. From line 28 to line 40, I input mean and standard deviation of weekly demand. From line 41 to line 53, I determined the safety stock, the holding cost and the total cost in scenario I. From line 54 to line 71, I determined the safety stock, the holding cost and the total cost in scenario II. From line 72 to line 82, I determined the optimal postponement decision and output corresponding decision variables.

```
1 option minlp=shot

2 sets
3   i   products   /1/
4   j   retailers   /1*4/;

5 alias (j, m);

6 *known
7 parameters
8   L       lead time in terms of weeks   /9/
9   CSL      desired cycle service level /0.95/
10   h_fr     annualy holding cost fraction /0.3/
11   cc(i,j,m) correlation coefficient
12   /1. 1. 2   0.0
13    1. 1. 3   0.0
14    1. 1. 4   0.0
15    1. 2. 3   0.0
16    1. 2. 4   0.0
17    1. 3. 4   0.0/
18   Add_cost   additional cost per unit of product
19   /1/
20   C(i)      unit cost of i in terms of dollars
21   /1 1000/
22   Cap(i)    weekly packaging capacity of product i
23   /1 2200/;

24 $funclibin stolib stodclib
25   function inv_nor /stolib.icdfnormal/;
26   Scalar FCSL;
27   FCSL = inv_nor(CSL,0,1);

28 *bsic

29 Table ave_dem(j,i) average demand of product i being sent to retailer j
per week
30        1
```

```
  1   1000
  2   1000
  3   100
  4   100   ;

Table sta_dev(j,i) SD of product i being sent to retailer j
       1
  1   500
  2   100
  3   50
  4   10   ;

binary variable x(j,i);

*Option I  without postponement
Variables
  ss(j,i)   safety stock of product i being sent to retailer j
  H(j,i)    holding cost of ss(ij) in termss of dollars
  TC_I      total cost of option I in terms of dollars;

Equations
  safety_sto(j,i)   safety stock of product i being sent to retailer j
  Hol_cost(j,i)     holding cost of ss(ij) in termss of dollars
  Total_cost_I      total cost of option I in terms of dollars;

  safety_sto(j,i)   ..  ss(j,i)  =e= FCSL*sqrt(L)*sta_dev(j,i);
  Hol_cost(j,i)     ..  H(j,i)   =e= ss(j,i)*C(i)*h_fr;
  Total_cost_I      ..  TC_I     =e= sum((j,i),(1-x(j,i))*H(j,i));

*Option II with postponement
Variables
  ave_dem_a(i)    average demand of portion of product i
  sta_dev_a(i)    SD of portion of product i
  ss_a(i)        safety stock of portion of product i
  H_a(i)         holding cost of ss_a(i)
  TC_II          total cost of portion of product i;

Equations
  AD_a(i)        average demand of portion of product i
  SD_a(i)        standard deviation of portion of product i
  safety_inv_a(i) safety stock of portion of product i
  Hol_cost_a(i)   holding cost of portion of product i
  Total_cost_II   total cost of product i;

  AD_a(i)        ..   ave_dem_a(i)   =e=  sum(j,x(j,i)*ave_dem(j,i));
  SD_a(i)        ..   sta_dev_a(i)   =e=
sqrt(sum(j,power(x(j,i)*sta_dev(j,i),2))+2*sum((j,m)$(ord(j)<ord(m)),x(j,i)*x
(m,i)*cc(i,j,m)*sta_dev(j,i)*sta_dev(m,i)));
  safety_inv_a(i) ..   ss_a(i)       =e=  FCSL*sqrt(L)*sta_dev_a(i);
  Hol_cost_a(i)   ..   H_a(i)        =e=  ss_a(i)*C(i)*h_fr;
  Total_cost_II   ..   TC_II         =e=
sum(i,H_a(i)+sum(j,52*Add_cost*x(j,i)*ave_dem(j,i)));

*mathematic modeling
Variables
  total_cost
```

```
Equations
  obj objective function
  capacity(i);

  obj            .. total_cost =e= TC_I+TC_II;
  capacity(i)     .. sum(j,x(j,i)*ave_dem(j,i)) =l= Cap(i);

Model packaging_postpoement /ALL/;

solve  packaging_postpoement using MINLP minimizing total_cost;

display x.l, total_cost.l, sta_dev_a.l;
```

APPENDIX C

Code in MATLAB for Sensitivity Analysis on Lead Time

From line 1 to line 13, I input values of all parameters in the baseline scenario. From line 14 to line 16, I input mean and standard deviation of weekly demand. From line 17 to line 18, I calculated $F_s^{-1}(CSL)$. From line 19 to line 63, I determined the optimal postponement decision and output corresponding decision variables and total cost when lead time ranges from 1 to 13.

```
1 clc;
2 clear;
3 %Variables
4    x=zeros(1,4);
5    x_min=zeros(1,4);

6 %Baseline
7   L_base  =9;                   %Lead time of product j
8   ca_base =1;               %Additional cost per unit of prodcut j when
postponement occurs
9   c_base  =1000;            %Unit cost of product j
10   h_base  =0.3;                %Holding cost as a fraction of prodcut cost
per year
11   CSL_base =0.95;          %Desired cycle service level
12   C_base  =2200;               %The pacakging prodcution capacity in the
distribution center for product j
13   cc_base  =zeros(4,4);     %correlation coefficient

14 %Distribution of weekly demand by retailer
15   ave_dem=[1000;1000;100;100]; %Average weekly demand of prodcut j sent to
retailer i
16   std_dev=[500;100;50;10]; %Standard deviation of prodcut j sent to
retailer i
17 %Inverse normal distribuion
18   inv_nor=norminv (CSL_base,0,1);


19 %Lead time
20 TC_Min=zeros(1,13);
21   for L = 1:13
22       for x1=0:1
23           for x2=0:1
24               for x3=0:1
25                   for x4=0:1
26                       x(1,1)=x1;
27                       x(1,2)=x2;
28                       x(1,3)=x3;
29                       x(1,4)=x4;
30                       TC_I=0;
31                           for i=1:4
32          TC_I=TC_I+((1-x(1,i))*inv_nor*sqrt(L)*std_dev(i,1)*c_base*h_base);
33                           end
34                       TC_II=0;
35                       z_1=0;
36                       z_2=0;
37                       AC=0;
```

```
                    for i=1:4
                         z_1=z_1+(x(1,i)*(std_dev(i,1))).^2;
                        for j=1:4
                             if i>j
     z_2 = z_2+2*(x(1,i)*x(1,j)*cc_base(i,j)*std_dev(i,1)*std_dev(j,1));
                             end
                        end
                     H_a=inv_nor*sqrt(L)*sqrt(z_1+z_2)*c_base*h_base;
                         AC=AC+(52*ca_base*ave_dem(i,1)*x(1,i));
                         TC_II=H_a+AC;
                    end

                   TC=TC_I+TC_II;
                       if TC_Min(1,L)==0
                           TC_Min(1,L)=TC;
                       elseif TC_Min(1,L)>TC
                           TC_Min(1,L)=TC;
                           x_min=x;
                       end
               end
           end
       end
   end
fprintf('When lead time is: %d\n',L)
 x_min
 fprintf('minmum cost is: %d\n', TC_Min(1,L));
end
```

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