

A CONTINUOUS APPROXIMATION APPROACH FOR SUPPLY NETWORK DESIGN CONSIDERING RADIO FREQUENCY IDENTIFICATION ADOPTION

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Abstract. The design and management of multiechelon supply networks is one of the most crucial and challenging problems that managers encounter. In this study, supply networks are designed for both single-item and multi-item cases by considering RFID adoption. To maximize total profits, the objective is to determine the following: (1) the locations of distribution centers, (2) the allocation of retail stores to distribution centers, (3) the replenishment cycle time at distribution centers, and (4) whether RFID was adopted. In this study, a continuous approximation model is developed and an algorithm for solving this problem is proposed. Numerical studies are adopted to demonstrate the solution procedure and the effects of changing parameters on decisions and profits. The results also show how RFID adoption affects the design of supply networks. This paper provides novel management implications that business managers can use as a reference.

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1. INTRODUCTION

Radio frequency identification (RFID) is the application of a wireless noncontact system that uses radio frequency electromagnetic fields to transfer data from a tag attached to an object. RFID has been adopted in numerous supply chains, particularly for the universal of “Internet of Things (IoT)”. The IoT integrates and enables information communication technologies such as RFID, wireless sensor networks, machine-to-machine systems, and mobile apps. The application of RFID is considered to have revolutionized supply chain and logistics management, releasing great values.

International companies commonly use multiechelon supply networks to support manufacturing and distribution because of global sourcing and markets. For example, Walmart and Target maintain complex supply networks in the United States. When products arrive at international seaports, they are delivered to retail stores through multiechelon supply networks. Other examples include Frito-Lay Inc., which operates a distribution network that consists of 42 plants, one national distribution center (DC), and 325 regional DCs; and Palmer & Harvey McLane Ltd., which uses 18 regional DCs throughout the United Kingdom for distributing products to its retail outlets [6].

Keywords. Internet of Things, RFID, supply network design, logistics, optimization.

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In China, when imported products arrive at Tianjin, they can be shipped to DCs in inland cities such as Beijing, Shijiazhuang, or Taiyuan. Products are consolidated in DCs and delivered from these DCs to retail stores. Multinational corporations typically use multiechelon distribution networks to support their manufacturing and marketing efforts [24]. However, the inventory literature has tended to ignore the strategic location decision-making process and the associated costs, whereas the location-focused literature has tended to ignore optional inventory decisions and the related costs [23]. The design and management of multiechelon supply networks in the current competitive business environment is one of the most crucial and challenging problems that managers encounter. Therefore, considering RFID adoption is essential when designing a supply network.

This paper contributes to the literature in several ways. First, this is the first study to incorporate the RFID adoption decision into a supply network design model. In the literature regarding supply network design, the RFID adoption decision has not been considered. Second, this study is also the first study to simultaneously determine the optimal DC influence area, replenishment cycle time, and RFID adoption decision. In addition, both single-item and multi-item cases are considered in this paper. Third, our model is the first study to consider that RFID not only affects demand, costs, and lead time, but also affects product shrinkage and reverse logistics process time. This enables the model to cope with a large number of practical situations. Also, this paper is the first to highlight the importance of adopting RFID in supply network design problems. This paper demonstrates that RFID adoption can benefit companies in designing supply networks. Fourth, the supply network design problem with RFID adoption is modeled as a multivariable and two-branch nonlinear function. This paper provides a solution procedure for solving the supply network design problem by considering RFID adoption. This paper also discusses the effects of related parameters (including costs, lead time, and reverse logistics process time) on decisions and profits. The study results can serve as a reference for business managers and administrators.

The remainder of this paper is organized as follows. In Section 2, this paper reviews the related studies. In Section 3, models are formulated. The solution approach are provided in Section 4. Section 5 extends the single-item model to consider multi-item. Section 6 conducts the numerical study. Conclusion is made in Section 7.

2. LITERATURE REVIEW

This paper reviews the related papers about supply network design and RFID adoption.

2.1. Supply network design

Several studies have focused on the design of supply networks (see the literature review). In academic research, two major models are used for solving the supply network design problem: the discrete model and continuous approximation (CA) model. For discrete model, recently, Lu *et al.* [15] focused on collaboratively designing a structured and comprehensive supply chain network management key processes model and analyzing the relative importance of these key processes for semiconductor industry. Tsao [30] designed a carbon-efficient supply chain network under trade credits. Tsao [31] determined the joint location, inventory and preservation decisions for non-instantaneous deterioration items under delay in payments. These studies illustrate that supply network design problems are popular in this field of research.

For CA model, CA approaches are commonly used in solving supply network design problems, particularly for large size data. Tsao *et al.* [32] used the two phase based CA approach to design supply networks. Tsao and Lu [33] extended the model of Tsao *et al.* [32] to consider both distance discounts and quantity discounts for transportation costs. Yolmeh and Salehi [40] used an outer approximation method for an integration of supply chain network designing and assembly line balancing under uncertainty. More related studies about CA approaches in supply network design can refer to Tsao [34]. Our paper applies a CA technique to formulate a supply network model. The proposed solution defines the input data in terms of continuous functions and can formulate these functions for a data set of any size. Table 1 shows the comparisons with other recent researches.

TABLE 1. Comparisons with other recent researches.

	<i>Papers</i>			
	Daskin (1995), Nozick and Turnquist [20]	Shen <i>et al.</i> [22]	Tsao <i>et al.</i> [33], Tsao [30], Tsao [31]	This study
<i>Decisions</i>				
Inventory decision	⊙	⊙	⊙	⊙
Location decision	⊙		⊙	⊙
Allocation decision		⊙	⊙	⊙
RFID Adoption decision				⊙

Notes. ⊙ means that the decision is considered in his/her paper.

2.2. RFID adoption

Ngai *et al.* [19] presented an excellent literature review of RFID-related academic journal papers published between 1995 and 2005. Sarac *et al.* [21] reviewed the effects of RFID on supply chain management. They concluded that RFID technologies can enhance the level of supply chain management by reducing inventory losses, increasing the efficiency and speed of processes, and improving information accuracy. Ustundag and Tanyas [35] constructed a simulation to analyze the benefits of RFID system integration on a three-echelon supply chain. They considered that RFID systems can improve the efficiency, accuracy, visibility, and security level in supply chains. Total supply chain cost increases and demand uncertainty decreases with increasing product value. Whang [36] proposed incentives for the adoption of RFID in a supply chain. He observed that the RFID cost is a one-sided *free-rider* problem in which the downstream waits for free rides based on the first move of the upstream, but not *vice versa*. Compared with the first-best solution, firms in equilibrium tend to adopt RFID too late.

Szmerekovsky *et al.* [25] studied the benefits of adopting RFID. They observed that RFID adopted in a decentralized supply chain costs the same as RFID adopted in an integrated supply chain with a single decision maker. However, retailers that establish product shelf-space prices can force the adoption of RFID even if doing so does not maximize a chain's total profit. Jakkhupan *et al.* [11] proposed a significant approach to adopting RFID system into a simple supply chain using simulation technique. Dai and Tseng [3] presented a systematic approach with analytical models to discuss the effects of RFID implementation on reducing inventory inaccuracy in a multistage supply chain. Nativi and Lee [16] modeled the implementation of RFID in a supply chain to determine if real-time inventory monitoring and information sharing can help the system attain enhanced environmental and economic benefits.

As a new information-capture technology, RFID has attracted the attention of supply chain managers [13]. When Walmart requested that their top suppliers start shipping selected cases and pallets equipped with RFID tags to their DCs in 2005, the widespread adoption of RFID began [12]. Ngai *et al.* [17, 18] conducted case studies concerning RFID in a sushi restaurant and an aircraft parts supply chain, respectively. Ellogood *et al.* [5]. Developed continuous approximation models for mixed load school bus routing. Chong *et al.* [2] predicted RFID adoption in healthcare supply chain from the perspectives of users. Other application of RFID are in playing Mahjong [26], managing smart cities [41] and smart healthcare systems [1].

3. MODEL FORMULATION

The network studied in this paper is a three-echelon supply chain with an outside supplier selling goods to DCs. The DCs are located at level two, and help to consolidate shipments arriving from the supplier and deliver them to the retailers. The retailers at the downstream meet the demands from end customers. Goods flow from upper-stream facilities to the downstream facilities (see Fig. 1).

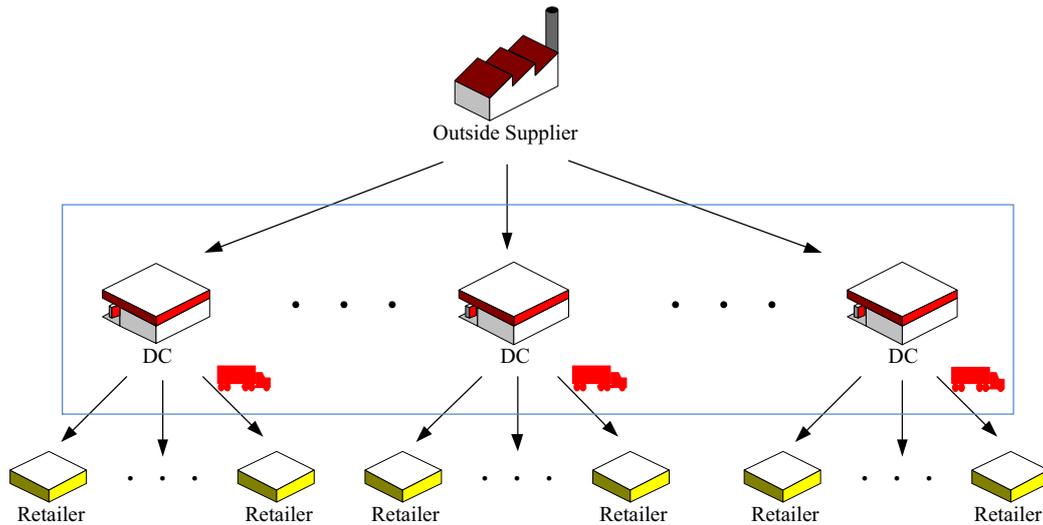


FIGURE 1. Multi-level supply network.

This study uses the following notations.

Decision variable:

- T_i : replenishment cycle time for each DC in cluster i , where $i = 1, 2, \dots, n$
 A_i : influence area for each DC in cluster i , where $i = 1, 2, \dots, n$

Parameters:

- F : facility cost of opening each DC
 δ_i : retail store density in cluster i , where $i = 1, 2, \dots, n$
 λ_i : demand rate for retail store in cluster i , where $i = 1, 2, \dots, n$
 ξ : length of the planning horizon
 c_T : transportation cost per unit distance per item
 f : constant that depends on the distance metric and shape of the DC service region
 S_i : ordering cost per order for DC in cluster i
 h : inventory holding cost for DC
 C_i : area in cluster i , where $i = 1, 2, \dots, n$
 c : unit purchasing cost
 p : unit selling price
 τ : unit RFID adoption cost
 θ : efficiency of the replenishment process with respect to satisfying consumer demand
 μ_N : the mean of the lead time without RFID adoption
 σ_N : the standard error of the lead time without RFID adoption
 μ_{RFID} : the mean of the lead time with RFID adoption
 σ_{RFID} : the standard error of the lead time with RFID adoption
 v_{RFID} : factor by which order quantity must be increased relative to demand when RFID is used, where $v_N \geq 1$
 v_N : factor by which order quantity must be increased relative to demand when RFID is not used, where $v_N \geq 1$
 r : unit process cost for reverse logistics
 χ : fixed fraction of items that must go into reverse logistics process
 t_N : average process time for reverse logistics without RFID adoption
 t_{RFID} : average process time for reverse logistics with RFID adoption

The mathematical model in this study is based on the following assumptions:

- (1) Demand per unit time for retail store in cluster i is an independent and identically distributed with rate λ_i [33].
- (2) Each DC's influence area is close to circular. Service regions have somewhat irregular shapes as opposed to circles, hexagons, or squares in the economics literature. This irregular service area is shown to have little effect on the optimal solution [4].
- (3) Each DC is located in the center of the influence area [33].
 4. Each retailer is assigned to a particular DC and served only by that DC [30].
- (5) RFID technology can improve the operation efficiency [14]. That means the mean of lead time and the standard error of lead time under RFID adoption could be assumed to be less than those without RFID adoption, *i.e.* $\mu_{\text{RFID}} < \mu_N$ and $\sigma_{\text{RFID}} < \sigma_N$.
- (6) Without RFID adoption, the products are easily subject to shrinkage due to damage, theft, or other incidents. Therefore, the DCs should replenish more products when RFID is not adopted. This means $v_N > v_{\text{RFID}}$.
- (7) The average process time for reverse logistics without RFID adoption is larger than the average process time for reverse logistics with RFID adoption, *i.e.* $t_N > t_{\text{RFID}}$.
- (8) RFID adoption affects the efficiency of the replenishment process with respect to satisfying consumer demand. When RFID is adopted in the supply chain, $\theta = 1$; otherwise, $0 < \theta < 1$.

This study uses a continuous approximation technique [33] to divide the supply network area into smaller regions over which the discrete variable can be modeled using the slow varying functions. Using the method the given supply network area is covered with clusters $i, i = 1, 2, \dots, n$. Clusters $i, i = 1, 2, \dots, n$, exist within the given service region such that the store density is nearly constant over each cluster. The area in cluster i is C_i and the influence area for each DC in cluster i is A_i . The retailer is assigned to a particular DC and served only by that DC when the retailer is within the influence area of that DC. Consider a given supply network area, this model calculates the components of the total network cost as follows.

- (1) The total revenue is $\sum_{i=1}^n p\theta\xi\lambda_i\delta_iC_i$.
- (2) The total purchasing cost without RFID adoption is $\sum_{i=1}^n cv_N\theta\xi\lambda_i\delta_iC_i$, the total purchasing cost under RFID adoption is $\sum_{i=1}^n cv_{\text{RFID}}\theta\xi\lambda_i\delta_iC_i$.
- (3) The cost for RFID adoption is $\sum_{i=1}^n \tau\theta\xi\lambda_i\delta_iC_i$.
- (4) The total facility cost is given by multiplying the facility cost of opening each DC with the number of DCs, namely, $\sum_{i=1}^n \left(F \frac{C_i}{A_i} \right)$.
- (5) Assuming "close to circular" service regions with the facility at the center, the average distance traveled by each item is $f\sqrt{A_i}$ [4]. The total transportation cost is $\sum_{i=1}^n \left(c_T f \sqrt{A_i} \theta \xi \lambda_i \delta_i C_i \right)$.
- (6) The total ordering cost is $\sum_{i=1}^n \left(\frac{S_i}{T_i} \frac{C_i}{A_i} \right)$.
- (7) The total inventory holding cost is $\sum_{i=1}^n \left(\frac{h\theta\xi\lambda_i\delta_iC_iT_i}{2} + hZ_\alpha \sqrt{\mu\theta\xi\lambda_i\delta_i\frac{C_i^2}{A_i} + \sigma^2(\theta\xi\lambda_i\delta_iC_i)^2} \right)$, where Z_α is the safety stock factor and α is the service level at RDCs.
- (8) The total process cost for reverse logistics is $\sum_{i=1}^n r\chi\theta\xi\lambda_i\delta_iC_i$.
- (9) The total inventory holding cost for reverse logistics is $\sum_{i=1}^n ht\chi\theta\xi\lambda_i\delta_iC_i$.

Our model considers several costs including the purchasing cost, the cost for RFID adoption, the facility cost, the transportation cost, the ordering cost, the holding cost, the process cost for reverse logistics, and the inventory holding cost for reverse logistics, which includes most costs in practice. One may incorporate a new cost into our model easily if the cost could be calculated based on the order quantity or the influence area. Figure 2 shows the model formulation.

The total network profit is

$$\Pi(A_i, T_i) = \begin{cases} \Pi_N(A_i, T_i), & \text{if RFID is not adopted;} \\ \Pi_{\text{RFID}}(A_i, T_i), & \text{if RFID is adopted.} \end{cases} \tag{3.1}$$

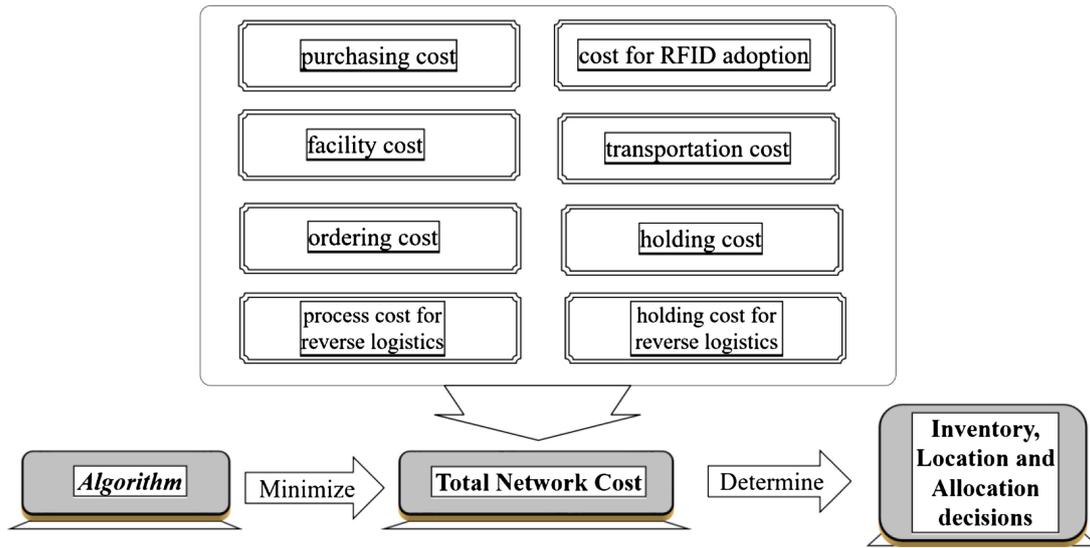


FIGURE 2. The model formulation.

The total network profit without RFID adoption $\Pi_N(A_i, T_i)$ is

$$\begin{aligned} \Pi_N(A_i, T_i) = & \sum_{i=1}^n (p - v_N c) \theta \xi \lambda_i \delta_i C_i - \sum_{i=1}^n \left(F \frac{C_i}{A_i} \right) - \sum_{i=1}^n \left(c_T f \sqrt{A_i} \theta \xi \lambda_i \delta_i C_i \right) \\ & - \sum_{i=1}^n \left(\frac{h \theta \xi \lambda_i \delta_i C_i T_i}{2} + h Z_\alpha \sqrt{\mu_N \theta \xi \lambda_i \delta_i \frac{C_i^2}{A_i} + \sigma_N^2 (\theta \xi \lambda_i \delta_i C_i)^2} \right) \\ & - \sum_{i=1}^n \left(\frac{S_i C_i}{T_i A_i} \right) - \sum_{i=1}^n r \chi \theta \xi \lambda_i \delta_i C_i - \sum_{i=1}^n h t_N \chi \theta \lambda_i \delta_i C_i, \text{ where } i = 1, 2, \dots, n. \end{aligned} \quad (3.2)$$

The total network profit with RFID adoption $TNC_{\text{RFID}}(A_i, T_i)$ is

$$\begin{aligned} \Pi_{\text{RFID}}(A_i, T_i) = & \sum_{i=1}^n (p - v_{\text{RFID}} c - \tau) \xi \lambda_i \delta_i C_i - \sum_{i=1}^n \left(F \frac{C_i}{A_i} \right) - \sum_{i=1}^n \left(c_T f \sqrt{A_i} \xi \lambda_i \delta_i C_i \right) \\ & - \sum_{i=1}^n \left(\frac{h \xi \lambda_i \delta_i C_i T_i}{2} + h Z_\alpha \sqrt{\mu_{\text{RFID}} \xi \lambda_i \delta_i \frac{C_i^2}{A_i} + \sigma_{\text{RFID}}^2 (\xi \lambda_i \delta_i C_i)^2} \right) \\ & - \sum_{i=1}^n \left(\frac{S_i C_i}{T_i A_i} \right) - \sum_{i=1}^n r \chi \xi \lambda_i \delta_i C_i - \sum_{i=1}^n h t_{\text{RFID}} \chi \xi \lambda_i \delta_i C_i, \text{ where } i = 1, 2, \dots, n. \end{aligned} \quad (3.3)$$

The crucial decisions are the location of the DCs, the manner in which to assign retail stores to DCs, inventory policy at DCs, and the RFID adoption decision to maximize total profit.

4. OPTIMAL DC INFLUENCE AREA AND REPLENISHMENT CYCLE TIME

The problem analyzed here is to determine the optimal influence area for each DC A_i^* and replenishment cycle time for each DC T_i^* to maximize the total network profit $\Pi(A_i, T_i)$, $i = 1, 2, \dots, n$. The problem is a two-branch

nonlinear function with $2n$ decision variables. To solve the problem, this paper first finds the maximal values of $\Pi_N(A_i, T_i)$ and $\Pi_{\text{RFID}}(A_i, T_i)$ respectively. Then the optimal A_i^* and T_i^* are chosen to maximize $\Pi(A_i, T_i)$, *i.e.* $\Pi^*(A_i^*, T_i^*) = \max\{\Pi_N(A_i^\Delta, T_i^\Delta), \Pi_{\text{RFID}}(A_i^\diamond, T_i^\diamond)\}$, where A_i^Δ and T_i^Δ are the values to maximize $\Pi_N(A_i, T_i)$ and A_i^\diamond and T_i^\diamond are the values to maximize $\Pi_{\text{RFID}}(A_i, T_i)$.

To find the maximal value of $\Pi_N(A_i, T_i)$, this paper first deals with the decisions T_i . Given A_i , we have

$$\frac{\partial^2 \Pi_N(T_i | A_i)}{\partial T_i^2} = -\frac{2S_i C_i}{A_i T_i^3} < 0, \quad i = 1, 2, \dots$$

T_i and T_j (where $i \neq j$; $i = 1, 2, \dots, n$ and $j = 1, 2, \dots, n$) are independent. Therefore, $\Pi_N(T_i | A_i)$ is a concave function of T_i . This means that the critical number $T_i(A_i)$ can be obtained by solving $\frac{\partial \Pi_N(T_i | A_i)}{\partial T_i} = 0$:

$$T_i(A_i) = \sqrt{\frac{2S_i}{h\theta\xi\lambda_i\delta_i A_i}} \quad i = 1, 2, \dots, n. \tag{4.1}$$

Equation (4.1) lead to Property 4.1.

Property 4.1. (a) *The replenishment cycle time T_i will increase as the ordering cost S increases.*
 (b) *The replenishment cycle time T_i will increase as the inventory holding cost h decreases.*

Substituting $T_i(A_i), i = 1, 2, \dots, n$, into the corresponding $\Pi_N(A_i, T_i)$ reduces the model to a function with A_i as its n variables: $\Pi_N(A_i)$.

$$\begin{aligned} \Pi_N(A_i) = & \sum_{i=1}^n (p - v_N c) \theta \xi \lambda_i \delta_i C_i - \sum_{i=1}^n \left(F \frac{C_i}{A_i} \right) - \sum_{i=1}^n \left(c_T f \sqrt{A_i} \theta \xi \lambda_i \delta_i C_i \right) \\ & - \sum_{i=1}^n \left(\sqrt{\frac{2h\theta\xi\lambda_i\delta_i S_i}{A_i}} C_i + hZ_\alpha \sqrt{\mu_N \theta \xi \lambda_i \delta_i \frac{C_i^2}{A_i} + \sigma_N^2 (\theta \xi \lambda_i \delta_i C_i)^2} \right) \\ & - \sum_{i=1}^n r \chi \theta \xi \lambda_i \delta_i C_i - \sum_{i=1}^n h t_N \chi \theta \lambda_i \delta_i C_i, \text{ where } i = 1, 2, \dots, n. \end{aligned} \tag{4.2}$$

From equation (4.2), we know that $\Pi_N(A_i)$ is a continuous function. The problem is to find optimal A_i^Δ , $i = 1, 2, \dots, n$, to maximize $\Pi_N(A_i)$. Let

$$\begin{aligned} \Pi_{N_i}(A_i) = & (p - v_N c) \theta \xi \lambda_i \delta_i C_i - F \frac{C_i}{A_i} - c_T f \sqrt{A_i} \theta \xi \lambda_i \delta_i C_i - r \chi \theta \xi \lambda_i \delta_i C_i - h t_N \chi \theta \lambda_i \delta_i C_i \\ & - \left(\sqrt{\frac{2h\theta\xi\lambda_i\delta_i S_i}{A_i}} C_i + hZ_\alpha \sqrt{\mu_N \theta \xi \lambda_i \delta_i \frac{C_i^2}{A_i} + \sigma_N^2 (\theta \xi \lambda_i \delta_i C_i)^2} \right), \text{ then } \Pi_N(A_i) = \sum_{i=1}^n \Pi_{N_i}(A_i). \end{aligned}$$

For any i , to obtain the optimal A_i^Δ , we should compare all critical numbers and both endpoints of A_i . The appropriate interval of A_i is $0 \leq A_i \leq C_i$. The critical points can be the endpoints (0 and C_i) and can be determined by solving $\frac{\partial \Pi_{N_i}(A_i)}{\partial A_i} = 0$, where $i = 1, 2, \dots, n$. It is then necessary to check the second-order condition of concavity, *i.e.* $\frac{\partial^2 \Pi_{N_i}(A_i)}{\partial A_i^2} < 0$, where $i = 1, 2, \dots, n$.

To find the maximal value of $\Pi_{\text{RFID}}(A_i, T_i)$, this paper first deals with the decision T_i . Given A_i , we have

$$\frac{\partial^2 TNC_{\text{RFID}}(T_i | A_i)}{\partial T_i^2} = -\frac{2S_i C_i}{A_i T_i^3} < 0, \quad i = 1, 2, \dots, n. \tag{4.3}$$

Therefore, $TNC_{RFID}(T_i|A_i)$ is a concave function of T_i . This means that the critical number $T_i(A_i)$ can be obtained by solving $\frac{\partial TNC_{RFID}(T_i|A_i)}{\partial T_i} = 0$:

$$T_i(A_i) = \sqrt{\frac{2S_i}{h\theta\xi\lambda_i\delta_iA_i}} \quad i = 1, 2, \dots, n. \tag{4.4}$$

Substituting $T_i(A_i)$, $i = 1, 2, \dots, n$, into the corresponding $\Pi_{RFID}(A_i, T_i)$ reduces the model to a nonlinear function with A_i as its n variables: $\Pi_{RFID}(A_i)$.

$$\begin{aligned} \Pi_{RFID}(A_i) = & \sum_{i=1}^n (p - v_{RFID}c - \tau) \xi\lambda_i\delta_iC_i - \sum_{i=1}^n \left(F \frac{C_i}{A_i}\right) - \sum_{i=1}^n \left(c_T f \sqrt{A_i} \xi\lambda_i\delta_iC_i\right) \\ & - \sum_{i=1}^n \left(\sqrt{\frac{2h\theta\xi\lambda_i\delta_iS_i}{A_i}} C_i + hZ_\alpha \sqrt{\mu_{RFID}\xi\lambda_i\delta_i \frac{C_i^2}{A_i} + \sigma_{RFID}^2(\xi\lambda_i\delta_iC_i)^2}\right) \\ & - \sum_{i=1}^n r\chi\xi\lambda_i\delta_iC_i - \sum_{i=1}^n ht_{RFID}\chi\xi\lambda_i\delta_iC_i, \text{ where } i = 1, 2, \dots, n. \end{aligned} \tag{4.5}$$

Let $\Pi_{RFID_i}(A_i) = (p - v_{RFID}c - \tau) \xi\lambda_i\delta_iC_i - \left(F \frac{C_i}{A_i}\right) - (c_T f \sqrt{A_i} \xi\lambda_i\delta_iC_i) - \left(\sqrt{\frac{2h\theta\xi\lambda_i\delta_iS_i}{A_i}} C_i + hZ_\alpha \sqrt{\mu_{RFID}\xi\lambda_i\delta_i \frac{C_i^2}{A_i} + \sigma_{RFID}^2(\xi\lambda_i\delta_iC_i)^2}\right) - r\chi\xi\lambda_i\delta_iC_i - ht_{RFID}\chi\xi\lambda_i\delta_iC_i$, then $\Pi_{RFID}(A_i) = \sum_{i=1}^n \Pi_{RFID_i}(A_i)$.

Use the similar method in finding the maximal value of $\Pi_N(A_i)$, we can find the optimal A_i^\diamond and T_i^\diamond to maximize $\Pi_{RFID}(A_i)$.

Based on the above discussion, the following algorithm determines the optimal values for A_i^* and T_i^* , $i = 1, 2, \dots, n$ and decides whether the RFID is adopted or not.

Algorithm

Step 1: For $i = 1; i = i + 1; i = n$.

Step 1.1: Find A'_i to satisfy $\frac{\partial \Pi_{N_i}(A_i)}{\partial A_i} = 0$ and $\frac{\partial^2 \Pi_{N_i}(A_i)}{\partial A_i^2} < 0$.

Step 1.2: Determine $T_i(A'_i)$ by (4.1) and calculate $\Pi_{N_i}(A'_i)$.

Step 1.3: Determine $T_i(0)$ by (4.1) and calculate $\Pi_{N_i}(0)$.

Step 1.4: Determine $T_i(C_i)$ by (4.1) and calculate $\Pi_{N_i}(C_i)$.

Step 1.5: Let $\Pi_{N_i}(A_i^\Delta, T_i^\Delta) = \text{Max}\{\Pi_{N_i}(T_i(A'_i), A'_i), \Pi_{N_i}(T_i(0), 0), \Pi_{N_i}(T_i(C_i), C_i)\}$.

Step 2: For $i = 1; i = i + 1; i = n$.

Step 2.1: Find A'_i to satisfy $\frac{\partial \Pi_{RFID_i}(A_i)}{\partial A_i} = 0$ and $\frac{\partial^2 \Pi_{RFID_i}(A_i)}{\partial A_i^2} < 0$.

Step 2.2: Determine $T_i(A'_i)$ by (4.4) and calculate $\Pi_{RFID_i}(A'_i)$.

Step 2.3: Determine $T_i(0)$ by (4.4) and calculate $\Pi_{RFID_i}(0)$.

Step 2.4: Determine $T_i(C_i)$ by (4.4) and calculate $\Pi_{RFID_i}(C_i)$.

Step 2.5: Let $\Pi_{RFID_i}(A_i^\diamond, T_i^\diamond) = \text{Max}\left\{\begin{matrix} \Pi_{RFID_i}(T_i(A'_i), A'_i), \Pi_{RFID_i}(T_i(0), 0), \\ \Pi_{RFID_i}(T_i(C_i), C_i) \end{matrix}\right\}$.

Step 3: Let $\Pi^*(A_i^*, T_i^*) = \text{Max}\{\Pi_N(A_i^\Delta, T_i^\Delta), \Pi_{RFID}(A_i^\diamond, T_i^\diamond)\}$.

5. EXTENSION: MULTI-ITEM MODEL

In a multi-item supply chain, considerable savings can be achieved during replenishment by coordinating the ordering of several items. Joint multi-item distribution policy is widely applied in the real world. This section extends the single-item model to consider the multi-item model. This paper uses the new notations in this model:

- c_j : unit purchasing cost for item j , where $j = 1, 2, \dots, k$
- p_j : unit selling price for item j , where $j = 1, 2, \dots, k$
- $\lambda_{i,j}$: demand rate for item j for retail store in cluster i
- h_j : inventory holding cost for item j , where $j = 1, 2, \dots, k$
- R_i : major ordering cost per order for DC in cluster i
- $r_{i,j}$: minor ordering cost for adding item j into the order for DC in cluster i

The total network profit without RFID adoption $\Pi_N(A_i, T_i)$ is

$$\begin{aligned} \Pi_N(A_i, T_i) = & \sum_{i=1}^n \sum_{j=1}^k (p_j - v_N c_j) \theta \xi \lambda_{i,j} \delta_i C_i - \sum_{i=1}^n \left(F \frac{C_i}{A_i} \right) - \sum_{i=1}^n \left[c_T f \sqrt{A_i} \sum_{j=1}^k (\theta \xi \lambda_{i,j} \delta_i C_i) \right] \\ & - \sum_{i=1}^n \left(\sum_{j=1}^k \frac{h \theta \xi \lambda_{i,j} \delta_i C_i T_i}{2} + \sum_{j=1}^k h Z_\alpha \sqrt{\mu_N \theta \xi \lambda_{i,j} \delta_i \frac{C_i^2}{A_i} + \sigma_N^2 (\theta \xi \lambda_{i,j} \delta_i C_i)^2} \right) \\ & - \sum_{i=1}^n \left[\frac{C_i}{A_i} \left(\frac{R_i}{T_i} + \sum_{j=1}^k \frac{r_{i,j}}{T_i} \right) \right] - \sum_{i=1}^n \left[r \chi \sum_{j=1}^k (\theta \xi \lambda_{i,j} \delta_i C_i) \right] - \sum_{i=1}^n \left[t_N \chi \sum_{j=1}^k (h_j \theta \xi \lambda_{i,j} \delta_i C_i) \right], \end{aligned} \tag{5.1}$$

where $i = 1, 2, \dots, n$.

The total network profit with RFID adoption $TNC_{\text{RFID}}(A_i, T_i)$ is

$$\begin{aligned} \Pi_{\text{RFID}}(A_i, T_i) = & \sum_{i=1}^n \sum_{j=1}^k (p_j - v_{\text{RFID}} c_j - \tau) \xi \lambda_{i,j} \delta_i C_i - \sum_{i=1}^n \left(F \frac{C_i}{A_i} \right) \\ & - \sum_{i=1}^n \left[c_T f \sqrt{A_i} \sum_{j=1}^k (\xi \lambda_{i,j} \delta_i C_i) \right] \\ & - \sum_{i=1}^n \left(\sum_{j=1}^k \frac{h \xi \lambda_{i,j} \delta_i C_i T_i}{2} + \sum_{j=1}^k h Z_\alpha \sqrt{\mu_{\text{RFID}} \xi \lambda_{i,j} \delta_i \frac{C_i^2}{A_i} + \sigma_{\text{RFID}}^2 (\xi \lambda_{i,j} \delta_i C_i)^2} \right) \\ & - \sum_{i=1}^n \left[\frac{C_i}{A_i} \left(\frac{R_i}{T_i} + \sum_{j=1}^k \frac{r_{i,j}}{T_i} \right) \right] - \sum_{i=1}^n \left[r \chi \sum_{j=1}^k (\xi \lambda_{i,j} \delta_i C_i) \right] - \sum_{i=1}^n \left[h t_{\text{RFID}} \chi \sum_{j=1}^k (\xi \lambda_{i,j} \delta_i C_i) \right], \end{aligned} \tag{5.2}$$

where $i = 1, 2, \dots, n$.

The critical number $T_i(A_i)$ can also be obtained by solving $\frac{d\Pi_N(T_i|A_i)}{dT_i} = 0$ or $\frac{dTNC_{\text{RFID}}(T_i|A_i)}{dT_i} = 0$:

$$T_i(A_i) = \sqrt{\frac{2(R_i + \sum_{j=1}^k r_{i,j})}{\sum_{j=1}^k h \theta \xi \lambda_{i,j} \delta_i A_i}}, \quad i = 1, 2, \dots, n. \tag{5.3}$$

Substituting $T_i(A_i)$, $i = 1, 2, \dots, n$, into the corresponding $\Pi_N(A_i, T_i)$ and $\Pi_{\text{RFID}}(A_i, T_i)$ reduces the model to a function with A_i as its n variables: $\Pi_N(A_i)$ and $\Pi_{\text{RFID}}(A_i)$.

$$\begin{aligned} \Pi_N(A_i) = & \sum_{i=1}^n \sum_{j=1}^k (p_i - v_N c_i) \theta \xi \lambda_{i,j} \delta_i C_i - \sum_{i=1}^n \left(F \frac{C_i}{A_i} \right) - \sum_{i=1}^n \left[c_T f \sqrt{A_i} \sum_{j=1}^k (\theta \xi \lambda_{i,j} \delta_i C_i) \right] \\ & - \sum_{i=1}^n \left[C_i \sqrt{\frac{2(R_i + \sum_{i=1}^k r_{i,j}) \sum_{j=1}^k h \theta \xi \lambda_{i,j} \delta_i}{A_i} + \sum_{j=1}^k h Z_\alpha \sqrt{\mu_N \theta \xi \lambda_{i,j} \delta_i \frac{C_i^2}{A_i} + \sigma_N^2 (\theta \xi \lambda_{i,j} \delta_i C_i)^2}} \right] \\ & - \sum_{i=1}^n \left[r \chi \sum_{j=1}^k (\theta \xi \lambda_{i,j} \delta_i C_i) \right] - \sum_{i=1}^n \left[h t_N \chi \sum_{j=1}^k (\theta \xi \lambda_{i,j} \delta_i C_i) \right], \text{ where } i = 1, 2, \dots, n. \end{aligned} \tag{5.4}$$

$$\begin{aligned} \Pi_{\text{RFID}}(A_i) = & \sum_{i=1}^n \sum_{j=1}^k (p - v_{\text{RFID}} c - \tau) \xi \lambda_{i,j} \delta_i C_i - \sum_{i=1}^n \left(F \frac{C_i}{A_i} \right) - \sum_{i=1}^n \left[c_T f \sqrt{A_i} \sum_{j=1}^k (\xi \lambda_{i,j} \delta_i C_i) \right] \\ & - \sum_{i=1}^n \left(C_i \sqrt{\frac{2(R_i + \sum_{i=1}^k r_{i,j}) \sum_{j=1}^k h \xi \lambda_{i,j} \delta_i}{A_i} + \sum_{j=1}^k h Z_\alpha \sqrt{\mu_{\text{RFID}} \xi \lambda_{i,j} \delta_i \frac{C_i^2}{A_i} + \sigma_{\text{RFID}}^2 (\xi \lambda_{i,j} \delta_i C_i)^2}} \right) \\ & - \sum_{i=1}^n \left[r \chi \sum_{j=1}^k (\xi \lambda_{i,j} \delta_i C_i) \right] - \sum_{i=1}^n \left[h t_{\text{RFID}} \chi \sum_{j=1}^k (\xi \lambda_{i,j} \delta_i C_i) \right], \text{ where } i = 1, 2, \dots, n. \end{aligned} \tag{5.5}$$

The procedure for obtaining a solution for the multi-item model is similar to that for the single-item model. When determine the optimal values for A_i^* and T_i^* , $i = 1, 2, \dots, n$ and decides whether the RFID is adopted or not, we can utilize the Algorithm described in Section 4, but replace equation (4.1) by equation (5.3), and equation (4.4) by equation (5.3), we can easily find the optimal solution.

6. NUMERICAL STUDY

This section presents a numerical study to illustrate the proposed solution approach and provide quantitative insights. The goals of the numerical study in this study are as follows:

- (1) To illustrate the procedure of the solution approach;
- (2) To discuss the effects of the related parameters on decisions and profit.

6.1. Numerical example

To illustrate the single-item model, consider the parameters of a commodity in a supply chain: $p = 10$, $c = 5$, $F = 5000$, $n = 3$, $C_1 = 8000$, $C_2 = 10000$, $C_3 = 12000$, $h = 1$, $c_T = 5$, $r = 2$, $S_1 = S_2 = S_3 = 500$, $f = 0.01$, $\tau = 0.4$, $\lambda_1 = 11$, $\lambda_2 = 10$, $\lambda_3 = 9$, $\xi = 12$, $\delta_1 = 0.06$, $\delta_2 = 0.05$, $\delta_3 = 0.04$, $Z_{0.95} = 1.645$, $v_{\text{RFID}} = 1$, $v_N = 1.05$, $\mu_{\text{RFID}} = 0.5$, $\sigma_{\text{RFID}} = 0.05$, $\mu_N = 1$, $\sigma_N = 0.1$, $\chi = 0.02$; $t_{\text{RFID}} = 1$, $t_N = 1.5$. Table 1 shows the computed results after applying the Algorithm. When adopt RFID technology ($\theta = 1$), the influence areas for DCs in cluster 1, cluster 2 and cluster 3 are $A_1^\diamond = 1017.63$, $A_2^\diamond = 1215.75$ and $A_3^\diamond = 1501.14$, respectively; the replenishment cycle times for DCs in cluster 1, cluster 2 and cluster 3 are $T_1^\diamond = 0.352$, $T_2^\diamond = 0.370$ and $T_3^\diamond = 0.393$, respectively; the total profit $\Pi_{\text{RFID}} = 289418$. When $\theta = 0.9$ (without RFID adoption), the influence areas for DCs in cluster 1, cluster 2 and cluster 3 are $A_1^\Delta = 1088.66$, $A_2^\Delta = 1300.76$ and $A_3^\Delta = 1606.32$,

TABLE 2. The decisions with different value of θ for single-item model.

θ	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
1	1017.63	1215.75	1501.14	0.352	0.370	0.393	289418	–	RFID adoption
0.9	1088.66	1300.76	1606.32	0.359	0.377	0.400	–	254821	without RFID adoption
0.8	1174.02	1402.92	1732.73	0.367	0.385	0.409	–	211306	
0.7	1278.99	1528.57	1888.21	0.376	0.395	0.418	–	169191	
0.6	1412.01	1687.82	2085.30	0.386	0.406	0.430	–	128749	

TABLE 3. The decisions with different value of θ for multi-item model.

θ	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
1	490.45	585.91	723.42	0.273	0.287	0.304	1061520	–	RFID adoption
0.9	524.69	626.89	774.13	0.278	0.292	0.310	–	968125	without RFID adoption
0.8	565.82	676.12	835.03	0.284	0.298	0.316	–	828895	
0.7	616.40	736.66	909.95	0.291	0.306	0.324	–	692582	
0.6	680.50	813.40	1004.92	0.299	0.314	0.333	–	559753	

respectively; the replenishment cycle times for DCs in cluster 1, cluster 2 and cluster 3 are $T_1^\Delta = 0.359$, $T_2^\Delta = 0.377$ and $T_3^\Delta = 0.400$, respectively; the total profit $\Pi_N = 254\,821$. Therefore, in this case, the maximal profit is \$289418 when the RFID is adopted. Figures 2 and 3 show the graphic illustrations of Π versus A_i and T_i .

Table 1 also shows the system behaviors when the value of θ is different. When θ decreases, this means the less the efficiency of the replenishment process with respect to satisfying consumer demand is. From Table 1, the profit decreases as the value of θ decreases. In other words, the system can get more benefits from the RFID adoption when the value of θ for a community is smaller. Also, A_i and T_i increase as the value of θ decreases. In practice, accumulating an entire truckload is one of the main economic issues for a distribution system. Therefore, it is reasonable to increase the distribution area and replenishment cycle time to accumulate more products when the total demand rate decreases (the decrease in θ means the decrease in the total demand rate).

To illustrate the multi-item model, consider the parameters of three commodities in a supply chain: $p_1 = 10$, $p_2 = 9$, $p_3 = 8$, $c_1 = 5$, $c_2 = 4.5$, $c_3 = 4$, $F = 5000$, $n = 3$, $C_1 = 8000$, $C_2 = 10\,000$, $C_3 = 12\,000$, $h_1 = 1$, $h_2 = 0.9$, $h_3 = 0.8$, $c_T = 5$, $r = 2$, $R_1 = R_2 = R_3 = 300$, $r_{1,1} = r_{2,1} = r_{3,1} = r_{1,2} = r_{2,2} = r_{3,2} = r_{1,3} = r_{2,3} = r_{3,3} = 30$, $f = 0.01$, $\tau = 0.4$, $\lambda_{1,1} = 11$, $\lambda_{2,1} = 10$, $\lambda_{3,1} = 9$, $\lambda_{1,2} = 11$, $\lambda_{2,2} = 10$, $\lambda_{3,2} = 9$, $\lambda_{1,3} = 11$, $\lambda_{2,3} = 10$, $\lambda_{3,3} = 9$, $\xi = 12$, $\delta_1 = 0.06$, $\delta_2 = 0.05$, $\delta_3 = 0.04$, $Z_{0.95} = 1.645$, $v_{\text{RFID}} = 1$, $v_N = 1.05$, $\mu_{\text{RFID}} = 0.5$, $\sigma_{\text{RFID}} = 0.05$, $\mu_N = 1$, $\sigma_N = 0.1$, $\chi = 0.02$; $t_{\text{RFID}} = 1$, $t_N = 1.5$. Table 1 shows the computed results after applying the Algorithm. When adopt RFID technology ($\theta = 1$), the influence areas for DCs in cluster 1, cluster 2 and cluster 3 are $A_1^\diamond = 490.45$, $A_2^\diamond = 585.91$ and $A_3^\diamond = 723.42$, respectively; the replenishment cycle times for DCs in cluster 1, cluster 2 and cluster 3 are $T_1^\diamond = 0.273$, $T_2^\diamond = 0.287$ and $T_3^\diamond = 0.304$, respectively; the total profit $\Pi_{\text{RFID}} = 1\,061\,520$. When $\theta = 0.9$ (without RFID adoption), the influence areas for DCs in cluster 1, cluster 2 and cluster 3 are $A_1^\Delta = 524.69$, $A_2^\Delta = 626.89$ and $A_3^\Delta = 774.13$, respectively; the replenishment cycle times for DCs in cluster 1, cluster 2 and cluster 3 are $T_1^\Delta = 0.278$, $T_2^\Delta = 0.292$ and $T_3^\Delta = 0.310$, respectively; the total profit $\Pi_N = 968\,125$. Therefore, in this case, the maximal profit is \$1061520 when the RFID is adopted.

6.2. Sensitivity analysis

This paper considers a supply network design that includes RFID adoption and discusses the effects of related parameters (such as costs, lead time, and reverse logistics process time) on decisions and profits. Several

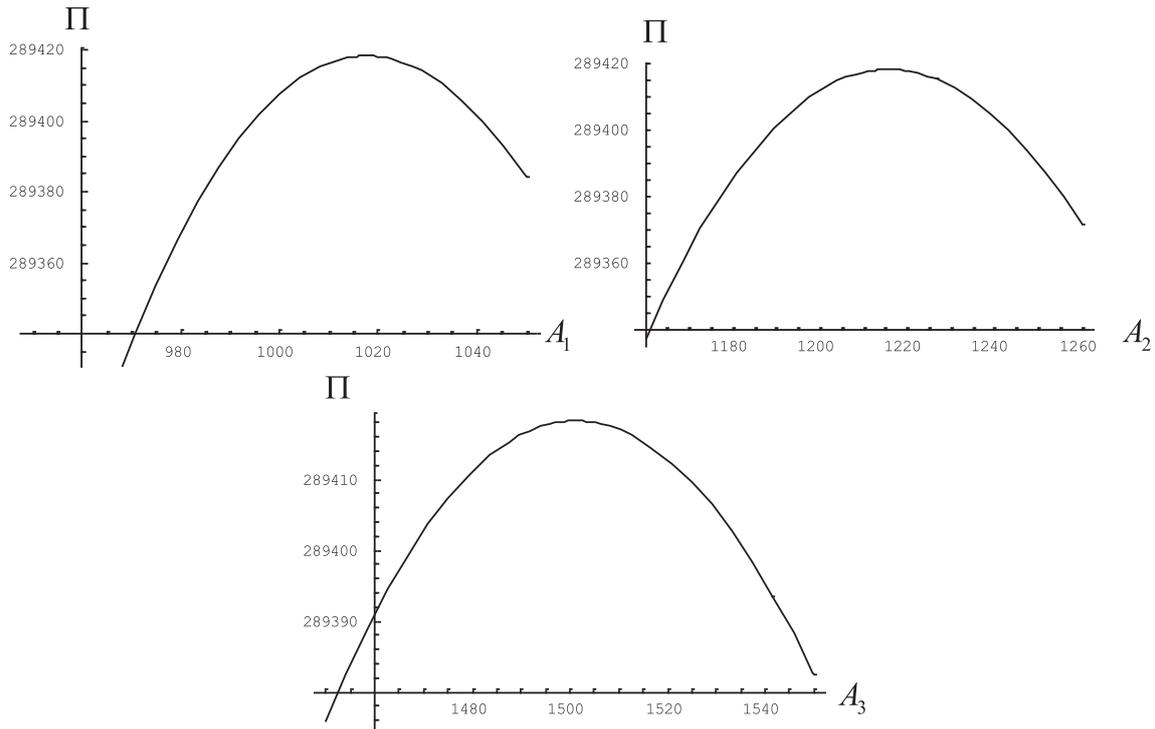


FIGURE 3. Graphic illustration of Π versus A_i .

numerical analyses are conducted to gain quantitative insights into the structures of the proposed policies. The following numerical analyses are used to demonstrate the effects of F , c_T , h_i , R_i , r , τ, χ , v_N , μ_{RFID} , σ_{RFID} , and t_{RFID} on the optimal influence area, optimal replenishment cycle time, and total profit. In this study, experiments are conducted by increasing these parameter values to $\pm 50\%$ in the multi-item case. Tables 4–14 present the following numerical results:

- (1) In Table 4, when the facility cost F increases, the optimal DC influence area increases and the replenishment cycle time decreases. If the facility cost increases, a company must open fewer DCs to reduce the cost. This indicates that each DC serves an increased number of influence of each DC increases. When the area of influence of a DC increases (and the number of DCs decreases), each DC must reduce its replenishment cycle time to increase the replenishment frequency to enable each DC to handle more products than previously necessary. In this case, the profit with RFID adoption is higher than that without RFID adoption.
- (2) In Table 5, when the transportation cost c_T increases, the optimal DC influence area decreases and the replenishment cycle time increases. If the transportation cost increases, it is reasonable for each DC to reduce its area of influence to decrease the transportation distance because transportation costs are calculated based on delivery distance. In this case, the profit with RFID adoption is higher than that without RFID adoption.
- (3) In Table 6, when the inventory holding cost h increases, the replenishment cycle time decreases and the optimal DC influence area increases. When the inventory holding cost increases, each DC must decrease its replenishment cycle time to stock fewer products and decrease inventory costs. This confirms Property 1(b). In addition, this paper observed that the difference between Π_{RFID} and Π_N (increasable profit) increases as the inventory holding cost increases. This indicates that the system yields increased benefits from RFID

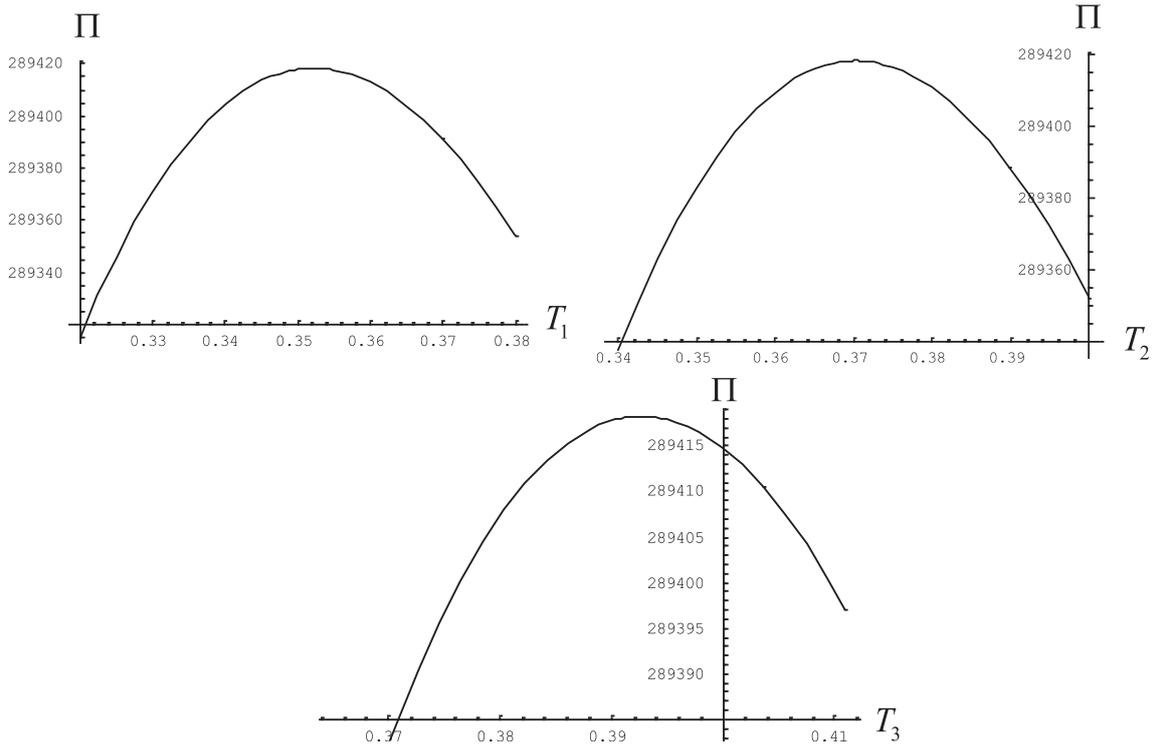


FIGURE 4. Graphic illustration of Π versus T_i .

adoption when inventory holding costs are high. In this case, the profit with RFID adoption is higher than that without RFID adoption.

- (4) In Table 7, when the ordering cost R_i increases, both the replenishment cycle time and the optimal DC influence area increase. When the ordering cost increases, each DC must increase the replenishment cycle time to reduce replenishment frequency. This confirms Property 4.1(a). In this case, the profit with RFID adoption is higher than that without RFID adoption.
- (5) In Tables 8 and 9, the reverse logistics process cost r and the fixed fraction of items that must go into reverse logistics process χ do not affect the influence area and replenishment cycle time decisions, but affect the total profit. The value of χ represents the product quality. Table 7 also shows that increasable profit increases as product quality decreases. Thus, the system yields increased benefits from RFID adoption when product quality is low. In this case, the profit with RFID adoption is higher than that without RFID adoption.
- (6) In Table 10, the RFID adoption cost τ does not affect the influence area and replenishment cycle time decisions, but affects the total profit. However, the system cannot benefit from RFID adoption when the RFID adoption cost excessive. In Table 8, when $\tau = 0.6$, the total profit is $\Pi_{\text{RFID}} = 956\,396$, which is less than the profit without RFID adoption ($\Pi_N = 968\,125$). This opens a new direction for our model to determine the boundary of τ . When the RFID adoption cost is larger than the boundary of τ , RFID adoption is not recommended. Based on $\Pi_{\text{RFID}}(A_i^\diamond, T_i^\diamond) > \Pi_N(A_i^\Delta, T_i^\Delta)$, it is easy to obtain the boundary of τ .
- (7) In Table 11, when the value of v_N (the factor by which order quantity must be increased relative to demand when RFID is not used) increases, it does not affect influence area and replenishment cycle time decisions, but affects total profit. The increase of the value of v_N means that the system must stock a larger quantity

TABLE 4. The decisions with different value of F for multi-item model.

F	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
2500	339.19	403.75	496.44	0.328	0.345	0.367	1210130		RFID adoption
5000	490.45	585.91	723.42	0.273	0.287	0.304	1061520	-	
7500	618.06	739.54	914.76	0.243	0.255	0.270	950868		
2500	362.39	431.43	530.59	0.334	0.352	0.374	-	1107100	without RFID adoption
5000	524.69	626.89	774.13	0.278	0.292	0.310	-	968125	
7500	661.61	791.72	979.50	0.247	0.260	0.275	-	864742	

TABLE 5. The decisions with different value of c_T for multi-item model.

c_T	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
2.5	811.12	967.39	1192.18	0.212	0.223	0.237	1418460		RFID adoption
5	490.45	585.91	723.42	0.273	0.287	0.304	1061520	-	
7.5	366.76	438.51	541.95	0.315	0.331	0.351	766268		
2.5	867.19	1034.41	1274.96	0.216	0.227	0.241	-	1300370	without RFID adoption
5	524.69	626.89	774.13	0.278	0.292	0.310	-	968125	
7.5	392.49	469.34	580.11	0.321	0.337	0.358	-	693241	

TABLE 6. The decisions with different value of h for multi-item model.

h_i	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
-50%	467.16	559.20	691.99	0.395	0.415	0.440	1 126 460		RFID adoption
0%	490.45	585.91	723.42	0.273	0.287	0.304	1 061 520	-	
+50%	508.76	606.91	748.13	0.219	0.230	0.244	1 006 580		
-50%	500.15	598.74	740.99	0.403	0.423	0.448	-	1 046 910	without RFID adoption
0%	524.69	626.89	774.13	0.278	0.292	0.310	-	968 125	
+50%	543.99	649.03	800.17	0.223	0.234	0.249	-	898 497	

of products than previously required. Therefore, the total profit decreases as the value of v_N increases. The system can yield increased benefits from RFID adoption when the factor by which order quantity must be increased relative to demand when RFID is not used is low.

- (8) In Table 12, the DC influence area increases as the expected lead time under RFID adoption μ_{RFID} increases. When parameters are fixed, the replenishment cycle time decreases as the DC influence area increases, based on equation (4.4). Therefore, the replenishment cycle time decreases as μ_{RFID} increases. However, the changes in the DC influence area in this case are minimal; therefore, we are unable to observe the changes in the replenishment cycle in Table 11.
- (9) In Table 13, the DC influence area increases as the standard error of lead time with RFID adoption σ_{RFID} decreases. In addition, based on the concept in the previous point, the replenishment cycle time increases as σ_{RFID} decreases. When the uncertainty of lead time increases, each DC must increase the replenishment time to pool the risk. This is one type of risk pooling strategy.
- (10) In Table 14, the average process time for reverse logistics with RFID adoption t_{RFID} does not affect the influence area and replenishment cycle time decisions. However, the total profit decreases as the average process time for reverse logistics increases. Thus, the system might not benefit from RFID adoption if the average process time for reverse logistics is excessive.

TABLE 7. The decisions with different value of S_i for multi-item model.

R_i	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
-50%	473.70	566.73	700.89	0.218	0.229	0.242	1 091 000		RFID adoption
0%	490.45	585.91	723.42	0.273	0.287	0.304	1 061 520	-	
+50%	504.36	601.84	742.13	0.316	0.333	0.353	1 037 710		
-50%	507.06	606.69	750.40	0.222	0.233	0.247	-	995 160	without RFID adoption
0%	524.69	626.89	774.13	0.278	0.292	0.310	-	968 125	
+50%	539.33	643.66	793.82	0.323	0.339	0.360	-	946 287	

TABLE 8. The decisions with different value of r for multi-item model.

r	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
1	490.45	585.91	723.42	0.273	0.287	0.304	1072030		RFID adoption
2	490.45	585.91	723.42	0.273	0.287	0.304	1061520	-	
3	490.45	585.91	723.42	0.273	0.287	0.304	1051000		
1	524.69	626.89	774.13	0.278	0.292	0.310	-	977586	without RFID adoption
2	524.69	626.89	774.13	0.278	0.292	0.310	-	968125	
3	524.69	626.89	774.13	0.278	0.292	0.310	-	958664	

TABLE 9. The decisions with different value of χ for multi-item model.

χ	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
0.01	490.45	585.91	723.42	0.273	0.287	0.304	10 76 760		RFID adoption
0.02	490.45	585.91	723.42	0.273	0.287	0.304	1 061 520	-	
0.03	490.45	585.91	723.42	0.273	0.287	0.304	1 046 270		
0.01	524.69	626.89	774.13	0.278	0.292	0.310	-	983 972	without RFID adoption
0.02	524.69	626.89	774.13	0.278	0.292	0.310	-	968 125	
0.03	524.69	626.89	774.13	0.278	0.292	0.310	-	952 278	

TABLE 10. The decisions with different value of τ for multi-item model.

τ	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
0.2	490.45	585.91	723.42	0.273	0.287	0.304	1 166 640		RFID adoption
0.4	490.45	585.91	723.42	0.273	0.287	0.304	1 061 520	-	
0.6	490.45	585.91	723.42	0.273	0.287	0.304	956 396		
-	524.69	626.89	774.13	0.278	0.292	0.310	-	968 125	without RFID adoption

TABLE 11. The decisions with different value of ν for multi-item model.

ν_N	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
-	490.45	585.91	723.42	0.273	0.287	0.304	1 061 520	-	RFID adoption
1.025	524.69	626.89	774.13	0.278	0.292	0.310	-	1 021 340	without RFID adoption
1.05	524.69	626.89	774.13	0.278	0.292	0.310	-	968 125	
1.075	524.69	626.89	774.13	0.278	0.292	0.310	-	914 908	

TABLE 12. The decisions with different value of μ_{RFID} for multi-item model.

μ_{RFID}	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
0.25	489.86	585.21	722.55	0.273	0.287	0.304	1 062 060	–	RFID adoption
0.5	490.45	585.91	723.42	0.273	0.287	0.304	1 061 520		
0.75	491.02	586.60	724.27	0.273	0.287	0.304	1 060 980		
–	524.69	626.89	774.13	0.278	0.292	0.310	–	968 125	without RFID adoption

TABLE 13. The decisions with different value of σ_{RFID} for multi-item model.

σ_{RFID}	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
0.025	491.48	587.13	724.91	0.272	0.286	0.304	1 079 960		RFID adoption
0.05	490.45	585.91	723.42	0.273	0.287	0.304	1 061 520	–	
0.075	490.06	585.45	722.86	0.273	0.287	0.304	1 042 420		
–	524.69	626.89	774.13	0.278	0.292	0.310	–	968 125	without RFID adoption

TABLE 14. The decisions with different value of t_{RFID} for multi-item model.

t_{RFID}	A_1	A_2	A_3	T_1	T_2	T_3	Π_{RFID}	Π_N	Case
0.5	490.45	585.91	723.42	0.273	0.287	0.304	1 066 250		RFID adoption
1	490.45	585.91	723.42	0.273	0.287	0.304	1 061 520	–	
1.5	490.45	585.91	723.42	0.273	0.287	0.304	1 056 790		
–	524.69	626.89	774.13	0.278	0.292	0.310	–	968 125	without RFID adoption

7. CONCLUSIONS

This study designs a supply network model that considered RFID adoption. The decisions are determining the influence areas of the DCs, establishing an inventory policy for the DCs, and the RFID adoption decision for maximizing total profits. Both single-item and multi-item cases are considered. This study formulates the supply network design problem as a two-branch nonlinear model and proposed an algorithm for solving the problem. Numerical studies are adopted for addressing the solution procedures and investigating the effects of facility costs, transportation costs, inventory holding costs, ordering costs, reverse logistics process costs, fixed fraction of items that must go into reverse logistics process, RFID adoption costs, factors by which order quantity must be increased relative to demand when RFID is not used, expected lead time, standard error of lead time, and reverse logistics process time on decisions and profits. This study obtains several new management implications from the numerical analysis. Specifically, a supply network can greatly benefit from RFID adoption when the inventory holding cost is high, when the product quality is low, when the factor by which order quantity must be increased relative to demand when RFID is not used is low, when the expected lead time under RFID adoption is low, and when the average process time for reverse logistics is low.

Several opportunities for further research exist; the findings can be extended to consider capacity limitations in DCs. This paper considers nondeteriorating items; however, formulating a model that considers deteriorating items [7–9, 27] is also valuable. This study does not consider stock-outs in our model; therefore, we suggest extending our model in consideration of shortages [10]. In addition, sustainability [28, 29], trade credit [37–39] and option contracts [42] are also interesting topics which could be incorporated into our model.

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