Investigating the Impacts of RFID Application on Supply Chain Dynamics with Chaos Theory

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Abstract: - Radio Frequency Identification is regarded as the most cutting edge technology for the optimization of supply chain processes in recent years. Researchers of supply chain management have often suggested that the measurement of RFID benefits is very important. This research investigated how the different levels of a multi-level supply chain dynamically behave under the impacts of RFID application and offer insights into how to manage relevant supply chain factors to eliminate supply chain uncertainty. The study involved the simulation model to characterize the supply chain with the conventional beer distribution model and some modifications. We observed the supply chain dynamics under the influence of various factors: demand pattern, demand information sharing, lead time, and the degree of RFID application through the Lyapunov exponent calculating. Results of this study showed that the adjustment parameters for both inventory and supply line discrepancies, RFID application, and lead time are critical factors to influence the supply chain dynamics. To conclude, this research may be of importance in explaining the effects of RFID application and dynamic relationship between supply chain factors and the effective inventory, as well as in providing supply chain managers with an effective supply chain management and strategy of the investment of RFID technology.

Key-Words: - Supply chain management; RFID; Chaos theory; Lyapunov exponent; Beer distribution model

1 Introduction

Recently globalization and work specialization, enterprises interactions are becoming more prevalent and intricate. As a result, enterprises are devoted to enhance efficacy of supply chain through seeking effective methods to integrate distributed resources. However, a supply chain is a complex system which involves a connected series of multiple entities (e.g., suppliers, original equipment manufacturer, distributors, transporters, etc.) encircling activities of goods shipping and value adding from the procurement of the raw material through manufacturing to distribution of end-products to customers, and this exist several types of uncertainties (e.g., demand uncertainty, production uncertainty, and delivery uncertainty, etc.) in this chain [15]. In order to diminish uncertainties and promote efficacy in a complex supply chain system, managers are seeking evidence that these efforts produce better supply chain performance. Therefore, recent years have seen increased attention being given to supply chains management (SCM), analysis, and control in the practice and academia [2].

With the increasing usage of information technology (IT) in business, IT has become a critical and integral constituent in SCM. Due to operating cost reduction, efficiency, effective fulfillment of market demand and competitive advantage promotion, business-to-business transactions are increasing on the IT, it is becoming critical for enterprises to rely on e-supply chains in order to response real-time market conditions [5,13]. Recently, the Radio Frequency Identification (RFID) technology is receiving great attention in the e-supply chains field. RFID is an automatic identification technology which is composed of three components: tags, reader and RFID information system (middleware). The tag is formed by a chip connected with an antenna. The reader emits radio signals and receives return message from tags. And finally, RFID information system establishes a bridge between reader and enterprise application systems (e.g., ERP). RFID provide a real-time communication with considerable objects simultaneously and without direct contact, so it can meliorate the goods traceability, promote supply chain visibility, increase efficiency and accuracy of operation, and reduce reserves and delivery cost [10]. As far as these advantages are concerned, RFID for materiel and products identification and information management is practicing an increasing diffusion in supply chain nowadays [12]. Therefore, the contribution of RFID to supply chains is not only in improving the efficiency of supply chain operations but also in asset tracking and inventory control.

RFID have paid significant attention from supply chain industries and academics in recent years. Nevertheless, the literature on RFID in supply chains is limited, most of the existing researches were revealed in the recent years. Current researches of RFID in supply chains mainly concentrates on logistics, inventory management, environment sensors, manufacturing, object tracking, etc. [4]. In these academic papers, researches mainly adopt simulations [1,3,8,9,20], analytical models [6,18,24], experiments [21] and case studies [19] to investigate the impact and potential benefit of RFID on SCM.

In these simulation researches, Lee et al.(2004) [8] explored the potential benefits of RFID in inventory reduction and service-level improvement by a quantitative analysis. They demonstrated that RFID can diminish the inventory level by 23% and completely exterminate backorders at the distribution center. However, this study considers that RFID provide 100% accuracy. Basinger(2006) [1] established a simulation model of a single item and three-level supply chain to discuss the impact of inventory inaccuracy on supply chain performance. The results indicated that RFID can improve the accuracy of supply chain inventory. Nevertheless, Single-setting for the expected demand conditions is the limitations of this research. Leung et al.(2007) [9] built a simulation model to explore the impact of RFID on shrinkage errors in supply chain. The results showed that RFID can decrease inventory levels. The originality of this research is that they elaborate the cost of RFID investment and its benefits about inventory shrinkage. However, the main limitation in this study is that they assume RFID as a perfect technology to completely exterminate the inaccuracy. Ustundag and Tanyas(2009) [20] developed a simulation research to explore the benefits of RFID system integration on a three-level supply chain and highlighted on the demand uncertainty and lead time as the cost factors to demonstrate that RFID systems can improve the efficiency, accuracy, visibility, and security. This result presented that the increase of demand uncertainty reduces the cost saving and the retailer gain the highest cost savings from RFID integration. Besides, the increase of lead time decreases the cost saving of the retailer. Finally, the increase of the product value and the decrease of demand uncertainty magnify almost equally the cost savings for the distributor and manufacturer. The limitation of this research is that the assumption is set that RFID can quite obliterate thefts, misplacements and shipment errors.

The above-mentioned these simulation researches consider that RFID can perfectly dispose of all inaccuracy and inefficiency problems in supply chains. However, read rate of current RFID and RFID system integration are not unexceptionable in the real applications. Concerning read rate of RFID, due to message transmission of RFID rely on radio waves, radio waves is interfered easily by metal, liquid, and other electromagnetic wave around working space. The RFID reader is unable to receive return message from tags when radio waves is interfered. At this time, reading performances of RFID is disturbed and it leads to bad effect on the efficiency of supply chain operations. Additionally, the RFID system integration and the degree of fit for business process and management are crucial for RFID application.

In this respect, this paper intends to investigate how various factors contribute to the complex dynamics and chaotic behaviors of supply chain. This research is interested in a multi-level supply chains that can be represented by the famous beer distribution model [7]. Various factors are considered, such as demand pattern, lead time, degree of RFID application, and demand-information sharing with different weight factors determined through regressive expectation for stock and supply line and different levels. The simulation model is developed to observe dynamics, particularly the inventory across all supply chain levels and the inventory cost on whole supply chain. The above-mentioned dynamics and complex behaviors in a supply chain, this paper intends to adopt the Lyapunov Exponent that is the celebrated chaos theory and system dynamics approach to quantify the degree of chaos in terms of inventory for all supply chain levels.

The objective of this paper understands how the different levels of a multi-level supply chain behave under the impacts of degree of RFID application.

The remainder of this paper is organized as follows. We present a general overview of our simulation model and the Lyapunov Exponent in Section 2. In Section 3, we describe the major influence factors such as demand pattern, lead time, degree of RFID application, and demand information sharing. The design of experiments for simulation model is analyzed in Section 4. Section 5 gives the results of simulation experiments. In the last section, we conclude the paper.

2 The Simulation Model

In this section, we present the famous simulation model of the supply chain which is named as the beer distribution model, and explain the dynamics in the supply chain for beer distribution model to assist us in model building. Lastly, we describe the quantitative approach in the chaos theory and system dynamics.

2.1 The beer distribution model

The beer distribution model is a practical simplification and simulation of the supply chain for beer manufacture. It is initiated by MIT Sloan School of Management in early 1960s [7]. This model represents a multi-level supply chain and it includes four levels: Retailer (R), Wholesaler (W), Distributor (D), and Factory (F), as shown in Fig.1.

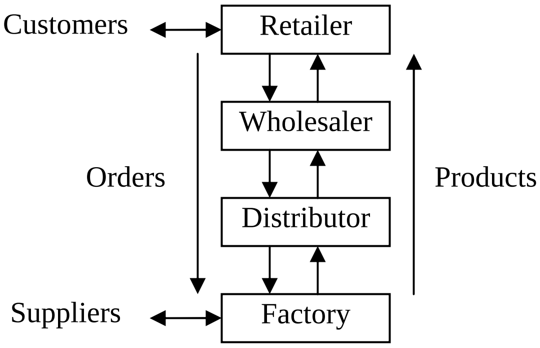

Fig.1. The beer distribution model

In this model, customers submit their demand to the retailer and orders propagate from retailer to the factory in turn. The retailer fulfils customers' demand from his inventory and estimates customers' demand in the future to place an order to the wholesaler. The wholesaler provides it out of current inventory and determines how many units to order with the distributor. The distributor places an order with the factory and the production decision of the factory is based on the distributor's order and other related information. On the other hand, products flow from the factory to the retailer. The factory ships products to the distributor. In the distributor, if its inventory is sufficient, it receives the products and ships them to the wholesaler. Next the wholesaler acquires the products and distributes them to the retailer. Lastly, customers shop the products from the retailer.

There are important points to deserve to be mentioned that inventory is held at each supply chain level, no sharing of the demand information in the system and each sector does not know the state of other sectors, and time delays exist in the transmission of orders, the manufacture and shipment of products. In respect of time delays, the default values of orders and shipment transmission time and production time are one time period and three time periods. Moreover, the customers' demand is generated with step function. The demand pattern is shown that four units per time period in the first four time periods and is increased to eight units per time period from the fifth period till the end of the simulation. Finally, this model is regulated according to the following rules: (1) shipments made cannot be returned and placed orders cannot be cancelled; (2) orders must be filled if inventory is sufficient; and (3) unfilled orders are held in backlog and shall be filled when the inventory is sufficient.

The number of units to be ordered in each period is main decision variable for all supply chain levels. This order decision is based on information (e.g., expected orders, the desired and actual inventory levels, incoming shipments, and backlog) to make. Additionally, each supply chain level managers must control the inventory to minimize holding costs and avoid out of stock situations. Therefore, the objective is to minimize supply chain costs for each all supply chain levels in this model. This supply chain cost is composed by the inventory holding cost and the stock-out cost.

This paper built this beer distribution model and intermingled with extra supply chain factors.

2.2 A system dynamics model for the beer distribution

The order decision making is a crucial action for managers each supply chain levels in the beer distribution model. The ordering heuristic plays the critical role of an anchoring and adjustment heuristic for stock management which applies a feedback mechanism in the order decision making [17]. Next, the following notations and equations are introduced to facilitate the model description:

O_t	the order quantity at time t,
IO_t	the indicated order rate at time t,
L_t	the actual demand at time t,
AS_t	the dissimilarity between desired and actual stock at time t,
ASL_t	the dissimilarity between desired and actual supply line at time t,
L^e_t	the expected demand at time t,
S_t	the actual stock level at time t,
S^*	the desired stock level,
SL_t	the actual supply line at time t,
SL^*	the desired supply line,
ω	the weight factor determines how fast expectations are updated for expected losses from the stock, $0 \le \omega \le 1$,
A	the weight factor at which the discrepancy between actual and desired stock levels is eliminated, $0 \le A \le 1$,
B	the weight factor at which the discrepancy between actual and desired supply line is eliminated, $0 \le B \le 1$, usually $B \le A$.

The general decision rule of the order quantity at time t for each supply chain level is defined as [17]:

$$O_t = Max(0, IO_t) \\ = Max(0, L_t + AS_t + ASL_t) \tag{1}$$

There is the assumption that the decision makers have adaptive expectations, the expected demand at time t can be defined as [17]:

$$L^e_t = \omega L_{t-1} + (1-\omega) L^e_{t-1} \tag{2}$$

The dissimilarity between desired and actual stock at time t for each supply chain level is defined as [17]:

$$AS_t = A(S^* - S_t) \tag{3}$$

Likewise, the dissimilarity between desired and actual supply line(1) at time t for each supply chain level is defined as [17]:

$$ASL_t = B(SL^* - SL_t) \tag{4}$$

This paper adopted the changes of the two weight factors, A and B, the heuristic can express many variety of ordering decisions, and we can observe and analyze the dynamic behavior in the supply chain for each ordering decisions.

2.3 The Lyapunov Exponent

A supply chain is a complex system which involves multiple entities, various types of uncertainties, feedback processes triggering interaction between entities, and time delay therefore supply chain may result in a dynamic system that teem with instable, variable, and non-linear behaviors. Chaos is irregularity looking long-term evolution existing in a deterministic nonlinear system; hence chaos theory is concerned with chaotic behavior in nonlinear dynamical system with the principles, mathematical operations, and methodology to identify chaos [22]. In the chaos analysis, there are graphical and quantitative methods to identify chaos or characterize whether a system is stable or chaotic. The advantage of graphical methods is visually efficient in trends and patterns exposition; however, graphical methods are limited in their precision. According to this limit of graphical methods, quantitative methods provide a more accurate alternative. Widely adopted quantitative methods include the Lyapunov exponent, fractal dimension, capacity dimension, correlation dimension and entropy [16]. Especially, Lyapunov exponent is a proven and universal measure for determining nonlinear behavior [23].

The Lyapunov exponent analysis measures the rate at which neighboring trajectories in phase space disperse and the sensitivity to initial conditions. There is an assumption that a successive dynamical system exists in an infinitesimal n-dimensional phase space. These initial conditions in this n-dimensional phase space will become an n-ellipsoid in the long term, as shown in Fig.2. Consider two near points at step n, X_n and $X_n + \Delta X_n$. After a long term, these points will have diverged at the next time step, that is X_{n+1} and $X_{n+1} + \Delta X_{n+1}$. Therefore, the LE is an average rate of divergence or convergence. The LE formula is presented as:

$$\lambda = \lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} \ln \frac{|\Delta X_{n+1}|}{|\Delta X_n|} \tag{5}$$

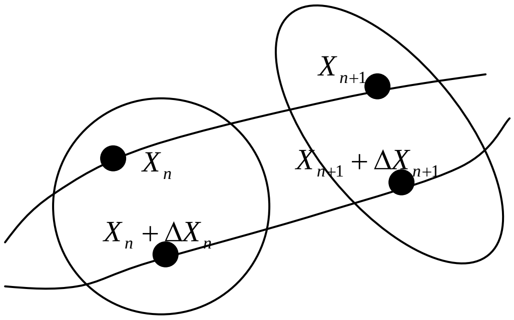

Fig.2. The diagram of the Lyapunov Exponent

If the average Lyapunov exponent or the largest Lyapunov exponent is positive, these near points become diverge. It implies that the system is chaotic and unstable. On the other side, the average Lyapunov exponent or the largest Lyapunov

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(1) A supply line is a proper noun on the domain about supply chain management or business administration. This term indicates that the supportable quantity of material or merchandise to support the next supply chain level.

exponent is less than zero then the system pulls to a fixed point or stable periodic orbit. This paper adopted the widely used algorithm [17] to calculate the largest Lyapunov exponent.

3 Supply Chain Factors

In this section, we present four major supply chain factors that include demand pattern, lead time, demand information sharing, and degree of RFID application. These factors have impact on the supply chain dynamics and are considered in the simulation model.

3.1 Demand pattern

The demand pattern is a crucial factor that drives the order information flow in the supply chain model. It presents market state that come from the customers' order to the retailer. There are varied types of demand patterns, mainly include the step demand function and broad pulse function. The step demand function generally occurs in price reductions or sales promotions. When the price is reduced or sales are promoted in an extensive period of time, the demand may leap to a higher level for an extensive term. On the contrary, when the demand incentive is temporary, the demand may increase only for a short period of time. After the promotion ends, the demand may come back to the normal level. This demand pattern of above situation is like a broad pulse function.

In the step demand function, the demand remains at an original level and thereafter is augmented to a shifted level. On the other hand, the demand of broad pulse function stays at an original level for some time, then is leapt to a shifted level for a short term, and eventually returns to an original level. Two kinds of demand patterns are shown in Fig.3.

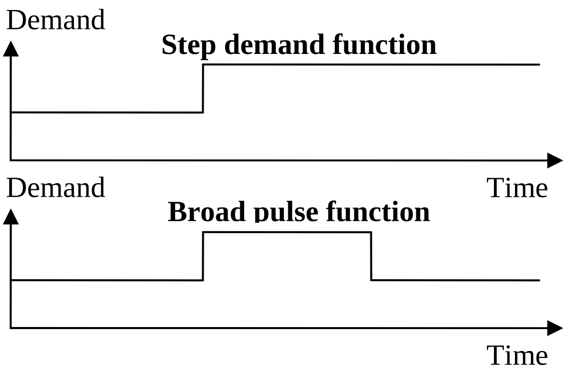


Fig.3. The diagram of two demand patterns

In this paper, we still adopted setting values of traditional beer distribution model that are four units in the original demand level, eight units in the shifted level, and the original demand level in the first four periods for both demand patterns. Furthermore, the demand is augmented to eight units from the fifth period till the end of the simulation for the step demand function. However, the broad pulse function in this research, the first shifted level begin from the fifth period and stays at eight per period for 495 periods and returns to four units per period for 500 periods, the second shifted level begin from the one thousandth period and stays at eight per period for 500 periods and returns to four units per period for 500 periods, as shown in Fig.4.

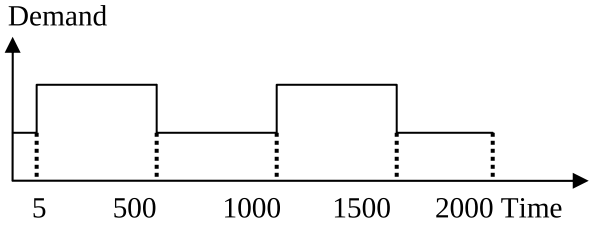


Fig.4. The diagram of the broad pulse function in this research

3.2 Lead time

The lead time between two seriate levels includes the shipment delay and orders transmission delay. This study considered two lead time options, namely, short lead time and long lead time. This short lead time is used in the traditional beer distribution model. The two lead time options differ in the length of shipment delay. The short lead time has one time period, and the long lead time has two time periods.

3.3 Demand information sharing

The original beer distribution model does not consider the customers' demand information sharing. With the increasing usage of IT in supply chain, sharing information becomes fewer costly and easier. In this paper, we considered two situations that include "with demand information sharing" and "without demand information sharing" in the model. For the "with demand information sharing", the retailer must share demand information to the other supply chain levels. When the other supply chain levels make order decision, the decision making will be based on the customers' demand information. Contrastingly in the "without demand information sharing", the retailer prohibits the demand information to be shared to the other supply chain levels. Hence, the other supply chain levels can not obtain the customers' demand information and consider this information in their order decision making.

3.4 Degree of RFID application

The degree of RFID applications in supply chains is influenced by the read rate and the RFID system integration that is the degree of fit for business process and management. The read rate mainly influences the degree of flowing business in all supply chain levels. In the beer distribution model, the degree of flowing business principally reflects the length of lead time. As for the RFID system integration, it mainly influences the degree of accuracy on business process in all supply chain levels especially for storehouse or inventory. These research [14,20] surveyed literatures that are about the inventory management to conclude causes of the inventory inaccuracy. These causes of the inaccuracy include theft, misplacement, and incomplete shipment. The setting values of error rates in this research [20] are shown in Table 1.

Most researches about exploring the RFID benefit on the supply chain were only comparing "with RFID" with "without RFID". In addition, "with RFID" is dropped on the assumption of the perfect RFID. In this paper, we considered six situations that include "without RFID", "with perfect RFID", "with better read rate and better RFID system integration", "with better read rate and worse RFID system integration", "with worse read rate and better RFID system integration", and "with worse read rate and worse RFID system integration". Table 2 presents parameters of six situations for the read rate and error rates on theft, misplacement, and incomplete shipment.

4 Simulation Design and Analysis

In order to facilitate easy illustration to various supply chain factors and scenarios, Table 3 summarizes the factors and scenario coding. There are the two demand patterns, the two lead time options, the two kinds of demand information sharing, the six situations of RFID application and four supply chain levels, thus there are 192 scenarios. This paper adopts the same initial conditions as the original beer distribution model. The initial values, the ranges of parameters, and simulation equations are presented in the appendix.

Table 1
Error rates of without-RFID and with-RFID integrated systems [20]

Error type / RFID utilization	Theft(%)	Misplacement(%)	Incomplete shipment(%)
With RFID	0	0	0
Without RFID	0.5	2	0.3

Table 2
Parameters of six situations for the read rate and error rates

Situations of the RFID	Read rate(%)	Theft(%)	Misplacement(%)	Incomplete shipment(%)
Without RFID	0	0.5	2	0.3
With perfect RFID	100	0	0	0
With better read rate and better RFID system integration	80	0.05	0.5	0.03
With better read rate and worse RFID system integration	80	0.2	1	0.1
With worse read rate and better RFID system integration	30	0.05	0.5	0.03
With worse read rate and worse RFID system integration	30	0.2	1	0.1

Table 3
The simulation scenario coding

Demand pattern		The step demand function												The broad pulse function											
Demand information sharing		With						Without						With						Without					
The degree of RFID applications		S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6	S1	S2	S3	S4	S5	S6
Short lead time																									
Supply chain level	R	1	5	9	13	17	21	49	53	57	61	65	69	97	101	105	109	113	117	145	149	153	157	161	165
	W	2	6	10	14	18	22	50	54	58	62	66	70	98	102	106	110	114	118	146	150	154	158	162	166
	D	3	7	11	15	19	23	51	55	59	63	67	71	99	103	107	111	115	119	147	151	155	159	163	167
	F	4	8	12	16	20	24	52	56	60	64	68	72	100	104	108	112	116	120	148	152	156	160	164	168
Long lead time																									
Supply chain level	R	25	29	33	37	41	45	73	77	81	85	89	93	121	125	129	133	137	141	169	173	177	181	185	189
	W	26	30	34	38	42	46	74	78	82	86	90	94	122	126	130	134	138	142	170	174	178	182	186	190
	D	27	31	35	39	43	47	75	79	83	87	91	95	123	127	131	135	139	143	171	175	179	183	187	191
	F	28	32	36	40	44	48	76	80	84	88	92	96	124	128	132	136	140	144	172	176	180	184	188	192

Notation: S1: Without RFID, S2: With perfect RFID, S3: With better read rate and better RFID system integration, S4: With better read rate and worse RFID system integration, S5: With worse read rate and better RFID system integration, S6: With worse read rate and worse RFID system integration, R: Retailer, W: Wholesaler, D: Distributor, F: Factory

The simulation model in this research was built with the well-known system dynamics simulation software, Vensim. In the simulation, the two decision weight factors, A and B, are studied on many variety of ordering decisions to observe and analyze the supply chain dynamic behavior. For each decision weight factor, 11 dissimilar values with an increment of 0.1 from 0 to 1 are adopted. There are 65 ordering decisions in total for each scenario since $B \le A$. The length of time for each simulation scenario is 2000 time periods.

This paper focused on the system dynamics behavior presented in the effective inventory at different levels. The effective inventory is defined as the inventory level after fulfilling the backlog. In each scenario, we assembled the effective inventory data for each decision weight factors set and calculated the largest Lyapunov exponent from the 2000 time periods of effective inventory data, therefore we can obtain 65 largest Lyapunov exponents. Strictly speaking, we must analyze the largest Lyapunov exponents calculated from the effective inventories for 65 decision weight factors sets in 192 scenarios. Nevertheless, if we analyze the largest Lyapunov exponents for all decision weight factors sets in each scenario, the analysis becomes multifarious to lead the analytic result is presented arduously. In order to efficient analysis in this research, we should cluster the decision weight factors sets into different areas. These criteria of clustering are based on: (1) the number of areas should be reasonably manageable; (2), the system behaviors or the largest Lyapunov exponents of sets are similar in the same group.

According to the above criteria, this paper adopted K-means methods to cluster the decision weight factors sets and used the coefficient of variation, which is defined as standard deviation divided by mean, to assure the homogeneity of the largest Lyapunov exponents in each area. The number of the decision weight factors sets in each area is arranged in Table 4 via clustering.

Table 4
The number of the decision weight factors sets in each area

Areas	Number of data
1	3
2	5
3	2
4	4
5	3
6	4
7	7
8	13
9	5
10	6
11	13

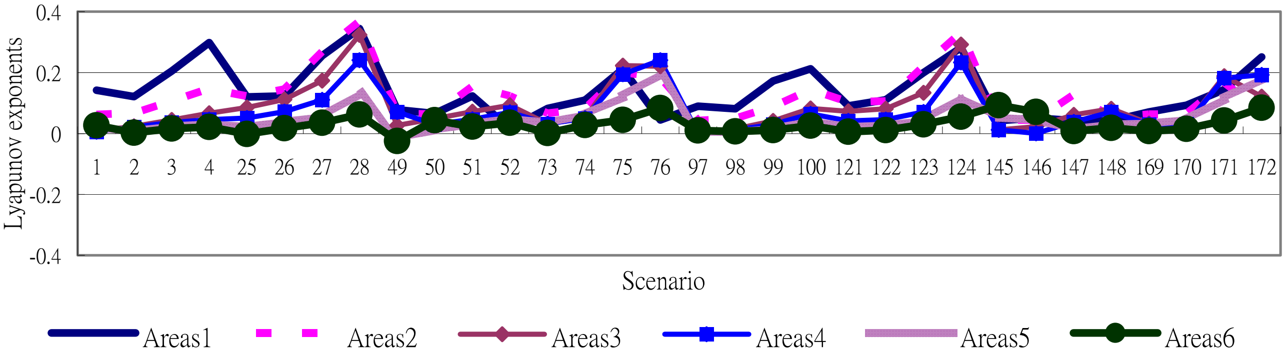
5 Evaluation of the Simulation Results

Of the four major supply chain factors, demand pattern, lead time, and demand information sharing each has two levels, whereas the degree of RFID application has six situations. The response variable is the average of the largest Lyapunov exponents in each area for 192 scenarios.

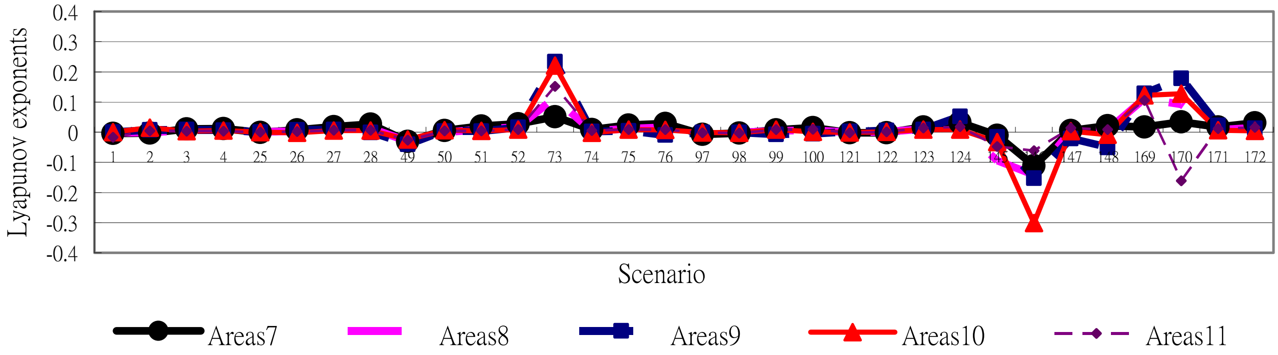
We primarily observe the effects of RFID application on the effective inventories. The average of the largest Lyapunov exponents in without RFID (S1) is shown in the Fig.5(a) and (b). In the without RFID supply chain, the most of the average of the largest Lyapunov exponents are positive in Areas 1-6 (Fig.5(a)), whereas most of them are negative in Areas 7-11(Fig.5(b)). The positive of average of the largest Lyapunov exponent implies that the system is chaotic and unstable. The results show that the supply chain system is more chaotic in lower areas. In the Areas 1-6, the decision weight factor A for inventory ranges from 0.4 to 1.0, whereas the decision weight factor B for supply line shifts from 0.0 to 0.5. The distance between A and B ranges from 0.4 to 1.0 in these areas, the disparity in magnitude between the two decision weight factors could engender the supply chain system to be chaotic or unstable. It is usually due to extremely large or small values of AS_t, ASL_t, and O_t existing in a repeating fashion. Therefore, decision makers should choose the decision weight factors in upper areas (Areas 1-6) where the adjustment for inventory discrepancies and supply line discrepancies are more comparable in their magnitude to avoid unstable and chaotic behavior.

To expose the effects of RFID application on the effective inventories, we illustrated the The average of the largest Lyapunov exponents in other degree of RFID applications, which include “with perfect RFID” (S2), “with better read rate and better RFID system integration” (S3), “with better read rate and worse RFID system integration” (S4), “with worse read rate and better RFID system integration” (S5), and “with worse read rate and worse RFID system integration” (S6), in Areas 1-6 (Fig.6) and compared with the situation of without RFID.

The results show that the most of the average of the largest Lyapunov exponents are negative in Areas 1-6 even though it is in the worst situation. In addition to the illustration observation, we adopted the objective statistical measure that is t-test to prove and display the effects of RFID application on the effective inventories. This paper examined the significant effect between S1 and S2, S1 and S3, S1 and S4, S1 and S5, and S1 and S6 through t-test. The result of t-test is shown in Table 5. A p-value $<\alpha$ means that the effects of RFID application are significant. The results of t-test showed that the significant effect of varied RFID applications on the effective inventories in all scenarios.

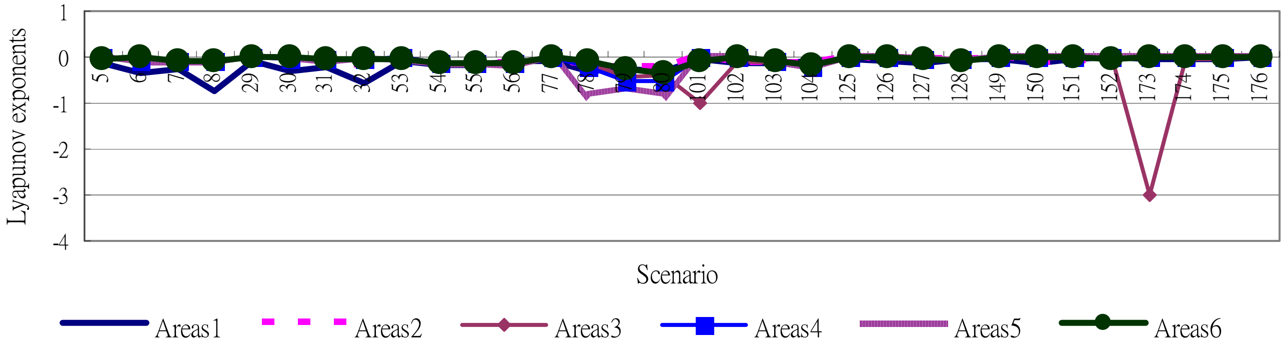


(a) Areas 1-6.

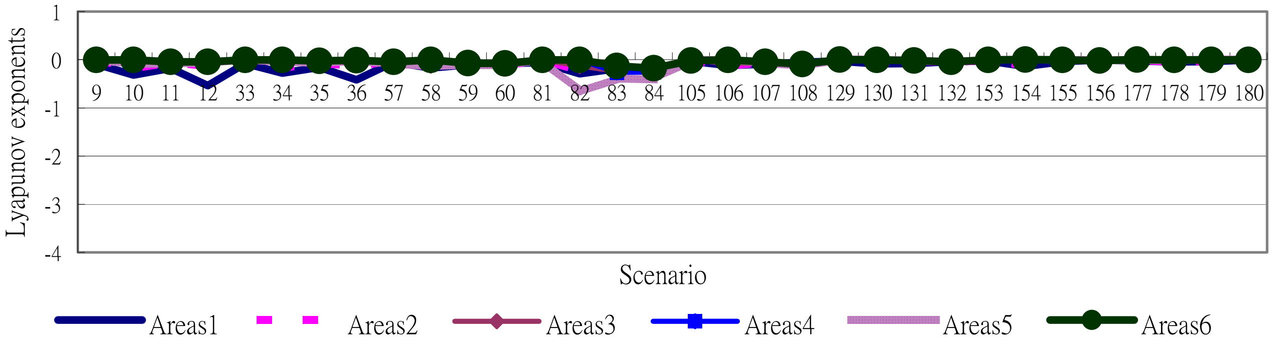


(b) Areas 7-11.

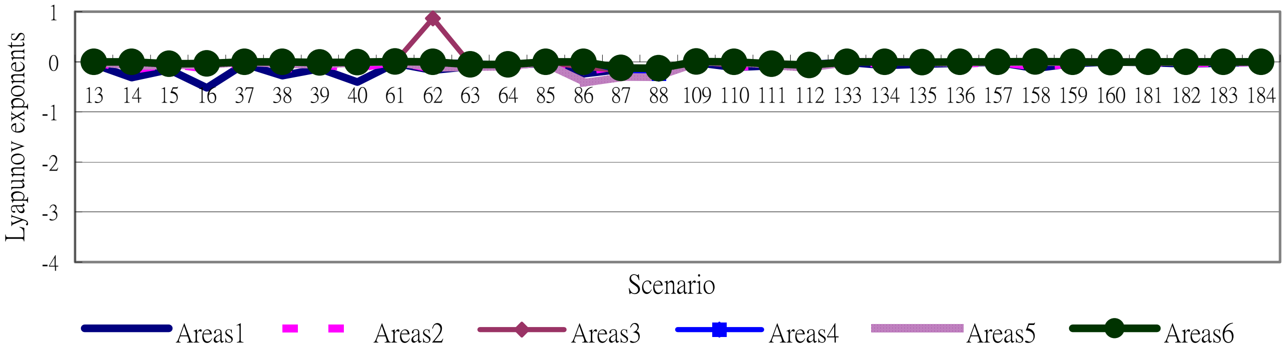
Fig. 5.The average of the largest Lyapunov exponents for the without RFID scenarios and areas



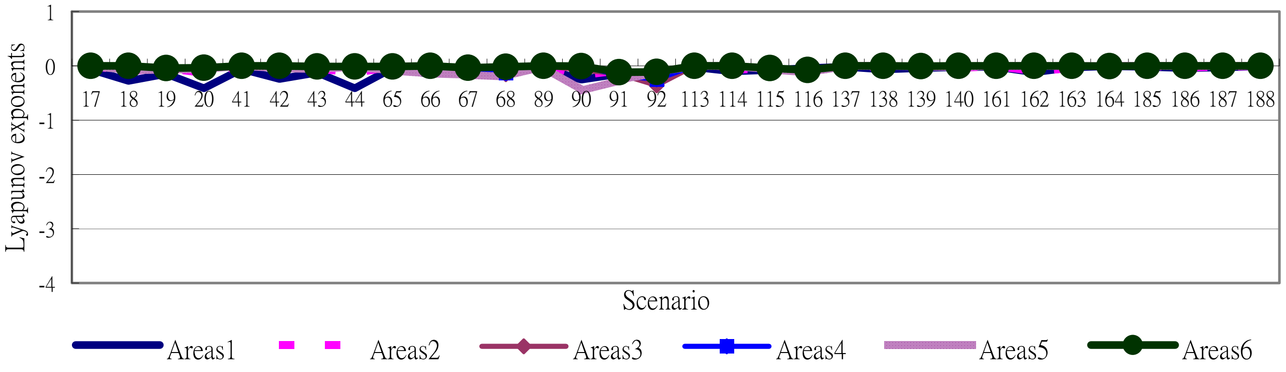
(a) S2: With perfect RFID



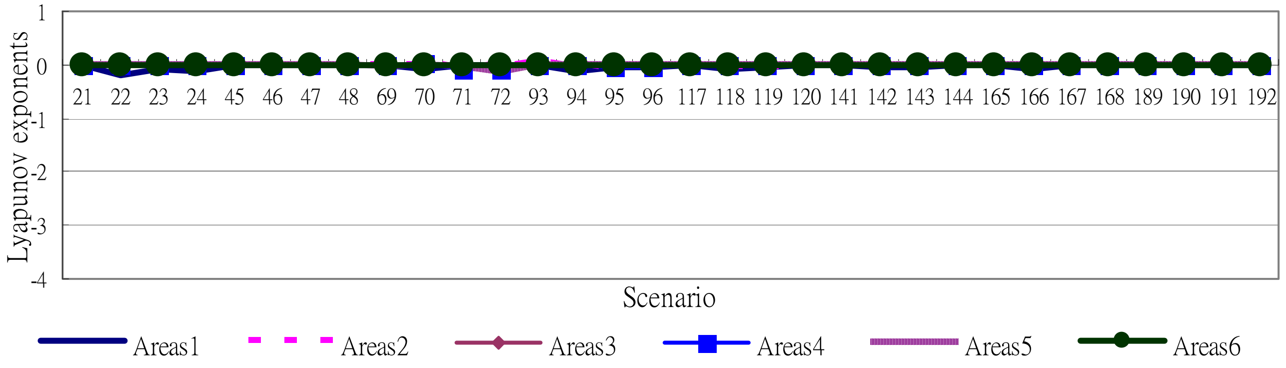
(b) S3: With better read rate and better RFID system integration



(c) S4: With better read rate and worse RFID system integration



(d) S5: With worse read rate and better RFID system integration



(e) S6: With worse read rate and worse RFID system integration

Fig. 6.The average of the largest Lyapunov exponents for with RFID scenarios in areas 1-6

Table 5
The effect of the degree of RFID applications for each scenario

Scenario	Supply chain levels	p-Value				
		The degree of RFID applications				
		S2	S3	S4	S5	S6
Demand pattern: The step demand; Demand information sharing: With; Lead time: Short[Scenario 1-24]	R	0.0382*	0.0471*	0.0411*	0.0478*	0.0462*
	W	0.0019**	0.0045**	0.0057**	0.0061**	0.0560
	D	0.0007***	0.0018**	0.0033**	0.0030**	0.0237*
	F	0.0164*	0.0285*	0.0304*	0.0244*	0.0357*
Demand pattern: The step demand; Demand information sharing: With; Lead time: Long[Scenario 25-48]	R	0.0013**	0.0165*	0.0209*	0.0229*	0.0187*
	W	0.0012**	0.0030**	0.0044**	0.0031**	0.0058**
	D	0.0013**	0.0028**	0.0038**	0.0036**	0.0080**
	F	0.0073**	0.0090**	0.0097**	0.0104*	0.0060**
Demand pattern: The step demand; Demand information sharing: Without; Lead time: Short[Scenario 49-72]	R	0.0001***	0.0002***	0.2659	0.1710	0.3170
	W	0.0000***	0.0000***	0.3678	0.0002***	0.0016**
	D	0.0000***	0.0000***	0.0093**	0.0005***	0.0008***
	F	0.0000***	0.0000***	0.0000***	0.0002***	0.0016**
Demand pattern: The step demand; Demand information sharing: Without; Lead time: Long[Scenario 73-96]	R	0.1689	0.0033**	0.0027**	0.0022**	0.0020**
	W	0.0026**	0.0096**	0.0047**	0.0071**	0.0229*
	D	0.0000***	0.0001***	0.0001***	0.0001***	0.0041**
	F	0.0006***	0.0007***	0.0009***	0.0014**	0.0043**
Demand pattern: The broad pulse; Demand information sharing: With; Lead time: Short[Scenario 97-120]	R	0.0785	0.0048**	0.0075**	0.0101*	0.0642
	W	0.0122*	0.0203*	0.0218*	0.0270*	0.0642
	D	0.0002***	0.0019**	0.0034**	0.0031**	0.0243*
	F	0.0000***	0.0004***	0.0005***	0.0005***	0.0100**
Demand pattern: The broad pulse; Demand information sharing: With; Lead time: Long[Scenario 121-144]	R	0.0001***	0.0001***	0.0001***	0.0002***	0.0084**
	W	0.0078**	0.0114*	0.0137*	0.0129*	0.0156*
	D	0.0018**	0.0020**	0.0053**	0.0053**	0.0082**
	F	0.0004***	0.0012**	0.0024**	0.0024**	0.0033**
Demand pattern: The broad pulse; Demand information sharing: Without; Lead time: Short[Scenario 145-168]	R	0.0016**	0.0013**	0.0048**	0.0101*	0.3096
	W	0.0010***	0.0008***	0.0067**	0.0054**	0.1751
	D	0.0111*	0.0053**	0.0083**	0.0097**	0.0184*
	F	0.0006***	0.0001***	0.0003***	0.0002***	0.0208*
Demand pattern: The broad pulse; Demand information sharing: Without; Lead time: Long[Scenario 169-192]	R	0.1009	0.0007***	0.0006***	0.0006***	0.0003***
	W	0.0009***	0.0009***	0.0036**	0.0037**	0.0261*
	D	0.0009***	0.0021**	0.0025**	0.0026**	0.0026**
	F	0.0012**	0.0028**	0.0030**	0.0030**	0.0032**

*p<0.05, **p<0.01, ***p<0.001

Next to deep analysis, we were concerned to understand the main effects of each supply chain factors on the effective inventories and the interaction effects about RFID applications. This analysis is beneficial for the practice of supply chain management and the strategy of RFID investment. According to the sparsity of effects principle, the three-factors and higher-order interactions are insignificant and thus can be combined as an estimate of error [11]. The analysis of variance (ANOVA) is a main statistical analysis instrument to understand the main effects and two-factor interactions effects. This paper adopted the ANOVA to examine the main effects and two-factor interactions effects in 11 areas. The ANOVA is calculated and summarized in Table 6 and the result discussion as follows.

5.1 Effect of Demand pattern

A supply chain system becomes more chaotic when the market demand follows the step demand function. This phenomenon is more manifest in the two lowest areas, which are the Area 1 and Area 2, where the effect of demand pattern is significant with p-Value < 0.001. In these two areas, A and B ranges from 0.65 to 1.0 and from 0.0 to 0.25. Future, the effects of demand pattern in areas 6-11 are significant for the broad pulse function demand pattern. In areas 3-5, the dissimilitude between the Lyapunov exponents for these demand patterns is not significant although the supply chain system is usually more chaotic when the market demand follows the step demand function.

The above result explanation indicates that the degree of supply chain system chaos increases when the impact of customer demand shift is sustained for a longer period. Decision makers should more carefully compress the lead time and manage other factors to avoid the chaotic behavior as presented in the inventories under the condition of longer sustained period demand shift.

5.2 Effect of Demand information sharing

With the advance of information technology, sharing information becomes easier and less costly in the present supply chain. In this study, the effect of sharing demand information is insignificant except for Areas 1, 2, and 5. It is interesting to note that sharing demand information seems to make the supply chain more chaotic in Areas 1 and 2, but less chaotic in Areas 5. It is beneficial to share demand information only when a fitting decision area, which is in Areas 5, is adopted. According to this finding, it is slightly divergent to the general opinion that information sharing is absolutely beneficial for supply chain.

5.3 Effect of Lead time

The effect of lead time is significant in most cases except for Areas 1, 9 and 10. The benefit of lead time decreasing is distinctly neutralized by the largeness discrepancy between A and B in Areas 1. As to Areas 9 and 10, the supply chain system is more stable, so the effect of lead time decreasing is more difficult to be manifested. In general, the lead time decreasing can diminishes the negative impact of inventory differences and supply line discrepancies to promote the degree of chaos of the supply chain system reduction.

5.4 Effect of Supply Chain Level

The effect of the supply chain level is significant in all areas. The degree of chaos augments as it goes upstream in the supply chain. This augmentation of chaos in inventory is observed in other research about the bullwhip effect.

5.5 Effect of RFID Application

The effect of RFID application is significant in all areas in the ANOVA. Through the ANOVA and the previous t-test analysis, it is demonstrated that RFID can effectively diminish lead time and the inventory inaccuracy in the supply chain process. Therefore, the RFID can promote the degree of stable of the supply chain system.

5.6 Interactions Effect of RFID Application

The interactions effect of RFID application with other factors is more significant in the interactions of RFID application with the lead time and RFID application with the supply chain level. The benefit of RFID application for all supply chain level is significantly obvious. The degree of RFID benefit augments as it goes upstream in the supply chain. Additionally, the benefit of RFID application is significant in the long lead time. A number of supply chain research have shown the higher the supply chain level and the longer the lead time, the more unstable the supply chain system is likely to be. As a result of interactions, the benefit of using RFID technology becomes more decided when the long lead time at upper supply chain levels.

Table 6
Main supply chain factors effects and two-factor interaction effects about RFID applications in 11 regions

Factors	p-Value										
	Areas1	Areas2	Areas3	Areas4	Areas5	Areas6	Areas7	Areas8	Areas9	Areas10	Areas11
Demand pattern	0.0000 ***	0.0000 ***	0.5411	0.5754	0.1083	0.0058 **	0.0029 **	0.0441 *	0.0010 ***	0.0000 ***	0.0130 *
Demand information sharing	0.0000 ***	0.0000 ***	0.4362	0.0501	0.0000 ***	0.7321	0.3426	0.1823	0.3745	0.3981	0.7147
Lead time	0.3245	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.6841	0.0018 **	0.0532
Supply chain level	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.0000 ***	0.0009 ***	0.0000 ***	0.0000 ***	0.0000 ***
The degree of RFID applications	0.0001 ***	0.0001 ***	0.0009 ***	0.0006 ***	0.0000 ***	0.0433 *	0.0012 **	0.0000 ***	0.0037 **	0.0015 **	0.0047 **
Demand pattern × The degree of RFID applications	0.0008 ***	0.0008 ***	0.6072	0.6098	0.1095	0.0505	0.0488 *	0.0493 *	0.0502	0.0614	0.0696
Demand information sharing × The degree of RFID applications	0.0033 **	0.0032 **	0.4423	0.0578	0.0003 ***	0.7326	0.3712	0.1839	0.3846	0.3983	0.7207
Lead time × The degree of RFID applications	0.1983	0.0002 ***	0.0002 ***	0.0003 ***	0.0005 ***	0.0015 **	0.0009 ***	0.0000 ***	0.3226	0.0031 **	0.0393
Supply chain level × The degree of RFID applications	0.0006 ***	0.0006 ***	0.0017 **	0.0013 **	0.0002 ***	0.0494 *	0.0201 *	0.0334 *	0.0237 *	0.0244 *	0.0138 *

*p<0.05, **p<0.01, ***p<0.001

6 Conclusion

The RFID is the most cutting edge technology for supply chain and it has paid significant attention from many commercial applications and industries in recent years. Thus, it is very important to accurately measure the benefits of RFID implementation.

This research investigated the effects of RFID application, demand pattern, lead time, and demand information sharing on the supply chain dynamics through chaos theory perspective. Especially in the exploring of RFID application, we joined some imperfect RFID that include “with better read rate and better RFID system integration”, “with better read rate and worse RFID system integration”, “with worse read rate and better RFID system integration”, and “with worse read rate and worse RFID system integration”. The imperfect RFID joining in our simulation model is main contribution in this research. The simulation model in this research is based on the widely known beer distribution model and intermingled with extra supply chain factors. Through this simulation model, we obtained various inventories data for each ordering decisions and analyzed these inventories data by the Lyapunov exponents calculating. The main of research finding are summarizing as follow:

The first finding is shown that the supply chain system become more chaotic when the weight factor for the inventory discrepancy between actual and desired stock levels and that for the supply line discrepancy between actual and desired supply line are increased. In order to diminish the degree of chaos in the supply chain system, the weight factor for the inventory discrepancies and supply line discrepancies should be more comparable in their magnitude.

The second finding is shown that the RFID application can effectively diminish the degree of chaos in the supply chain system and the benefit of using RFID technology becomes more obvious when the long lead time at upper supply chain levels. Therefore, the investment of RFID technology is more essential and meaningful.

The finally finding is shown that the chaotic supply chain system can be diminished when the impact of customer demand shift is sustained for a shorter period or the lead time decreasing. This result can provide suggestion to supply chain manager that keeping the market demand stability and reducing the lead time.

The supply chain manager must understand not only the effect of various supply chains factors on the supply chain system dynamics behavior, but also endogenous factors to diminish inventory variability and supply chain system chaos. The above findings can provide an effective supply chain management and strategy of the investment of RFID technology to managers.

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Appendix

The initial values, the ranges of parameters, and simulation equations

Variable(parameters) and defining equation	Comments
A	0.0-1.0, an increment of 0.1
B, $B \le A$.	0.0-1.0, an increment of 0.1
Backlog = INTEG(bFlow, 0)	Backlog at retailer
Backlog0 = INTEG(bFlow0, 0)	Backlog at wholesaler
Backlog1 = INTEG(bFlow1, 0)	Backlog at distributor
Backlog2 = INTEG(bFlow2, 0)	Backlog at factory
bFlow = ORDer - sold	Accumulation of backlog at retailer
bFlow0 = ordered – sold0	Accumulation of backlog at wholesaler
bFlow1 = ordered0 – sold1	Accumulation of backlog at distributor
bFlow2 = ordered1 – sold2	Accumulation of backlog at factory
coming = ordered 2	Materials in transit to factory
Cost = INTEG(cost increase, 0)	Total supply chain cost
cost increase = 1 × (Backlog + Backlog0 + Backlog1 + Backlog2) + 0.5 × (Inventory + Inventory0 + Inventory1 + Inventory2)	
Eff Env = Inventory – Backlog	Effective Inventory at retailer
Eff Inv0 = Inventory0 – Backlog 0	Effective Inventory at wholesaler
Eff Inv1 = Inventory1 – Backlog 1	Effective Inventory at distributor
Eff Inv2 = Inventory2 – Backlog2	Effective Inventory at factory
In = DELAY FIXED(sold0, 4 × (1 – RFID read rate), 4)	Incoming orders at retailer for the short lead time; RFID read rate(see Table 2)
In = DELAY FIXED(sold0, 8 × (1 – RFID read rate), 4)	Incoming orders at retailer for the long lead time; RFID read rate(see Table 2)
In0 = DELAY FIXED(sold1, 4 × (1 – RFID read rate), 4)	Incoming orders at wholesaler for the short lead time; RFID read rate(see Table 2)
In0 = DELAY FIXED(sold1, 8 × (1 – RFID read rate), 4)	Incoming orders at wholesaler for the long lead time; RFID read rate(see Table 2)
In1 = DELAY FIXED(sold2, 4 × (1 – RFID read rate), 4)	Incoming orders at distributor for the short lead time; RFID read rate(see Table 2)
In1= DELAY FIXED(sold2, 8 × (1 – RFID read rate), 4)	Incoming orders at distributor for the long lead time; RFID read rate(see Table 2)
In2 = DELAY FIXED(coming, 4 × (1 – RFID read rate), 4)	Incoming orders at factory for the short lead time; RFID read rate(see Table 2)
In2= DELAY FIXED(coming, 8 × (1 – RFID read rate), 4)	Incoming orders at factory for the long lead time; RFID read rate(see Table 2)
Inventory = INTEG(In – sold, 12)	Actual inventory at retailer
Inventory0 = INTEG(In0 – sold0, 12)	Actual inventory at wholesaler
Inventory1 = INTEG(In1 – sold1, 12)	Actual inventory at distributor
Inventory2 = INTEG(In2 – sold2, 12)	Actual inventory at factory
ORDer = 4 + STEP (4, 5)	The demand pattern for step demand function
ORDer = 4 + (4 × PULSE TRAIN(5, 500, 1000 , 1500))	The demand pattern for broad pulse function
ordered = DELAY FIXED(placed, 1, 4)	In transit orders by retailer
ordered0 = DELAY FIXED(placed0, 1, 4)	In transit orders by wholesaler
ordered1 = DELAY FIXED(placed1, 1, 4)	In transit orders by distributor
ordered2 = DELAY FIXED(placed2, 1, 4)	In transit orders by factory
placed = MAX(0, SMOOTH(ORDer, smoothtime) + A × (S – (Inventory – Backlog) – B × (SL – supplyL)))	Orders placed by retailer without demand information sharing

SMOOTHTIME = 1, S = 12, SL = 2 × supplyL	
placed0 = MAX(0, SMOOTH(ordered, smoothtime) + A × (S – (Inventory0 – Backlog0) – B × (SL0 – supplyL0))) SMOOTHTIME = 1, S = 12, SL0 = 2 × supplyL0	Orders placed by wholesaler without demand information sharing
placed1 = MAX(0, SMOOTH(ordered0, smoothtime) + A × (S – (Inventory1–Backlog1) – B × (SL1 – supplyL1))) SMOOTHTIME = 1, S = 12, SL1 = 2 × supplyL1	Orders placed by distributor without demand information sharing
placed2 = MAX(0, SMOOTH(ordered1, smoothtime) + A × (S – (Inventory2–Backlog2) – B × (SL2 – supplyL2))) SMOOTHTIME = 1, S = 12, SL2 = 2 × supplyL2	Orders placed by factory without demand information sharing
placed = MAX(0, FORECAST(ORDer, 1, 2) + A ×(S – (Inventory–Backlog) – B × (SL – supplyL))) S = 12, SL = 2 × supplyL	Orders placed by retailer with demand information sharing
placed0 = MAX(0, FORECAST(ORDer, 2, 4) + A ×(S – (Inventory0–Backlog0) – B × (SL0 – supplyL0))) S = 12, SL0 = 2 × supplyL0	Orders placed by wholesaler with demand information sharing
placed1 = MAX(0, FORECAST(ORDer, 3, 6) + A ×(S – (Inventory1–Backlog1) – B × (SL1 – supplyL1))) S = 12, SL1 = 2 × supplyL1	Orders placed by distributor with demand information sharing
placed2 = MAX(0, FORECAST(ORDer, 4, 8) + A ×(S – (Inventory2–Backlog2) – B × (SL2 – supplyL2))) S = 12, SL2 = 2 × supplyL2	Orders placed by factory with demand information sharing
sFlow = placed - In	Supply line accumulation for retailer
sFlow0 = placed0 – In0	Supply line accumulation for wholesaler
sFlow1 = placed1 – In1	Supply line accumulation for distributor
sFlow2 = placed2 – In2	Supply line accumulation for factory
sold = MIN(Inventory + In, ORDer + Backlog) ×((100 – (misplacement + theft + incomplete shipment)) / 100)	Crates sold by retailer; misplacement, theft, incomplete shipment(see Table 2)
sold0 = MIN(Inventory0 + In0, ordered + Backlog0) ×((100 – (misplacement + theft + incomplete shipment)) / 100)	Crates sold by wholesaler; misplacement, theft, incomplete shipment(see Table 2)
sold1 = MIN(Inventory1 + In1, ordered0 + Backlog1) ×((100 – (misplacement + theft + incomplete shipment)) / 100)	Crates sold by distributor; misplacement, theft, incomplete shipment(see Table 2)
sold2 = MIN(Inventory2 + In2, ordered1 + Backlog2) ×((100 – (misplacement + theft + incomplete shipment)) / 100)	Crates sold by factory; misplacement, theft, incomplete shipment(see Table 2)
SupplyL = INTEG(sFlow, 0)	Supply line for retailer
SupplyL0 = INTEG(sFlow0, 0)	Supply line for wholesaler
SupplyL1 = INTEG(sFlow1, 0)	Supply line for distributor
SupplyL2 = INTEG(sFlow2, 0)	Supply line for factory
INITIAL TIME = 0	The initial time for the simulation
FINAL TIME = 2000	The final time for the simulation
SAVEPER = TIME STEP	Frequency at which output is stored
TIME STEP = 1	The time step for the simulation