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The simulated impact of RFID-enabled supply chain on pull-based inventory replenishment in TFT-LCD industry

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Abstract

This research focuses on the analysis of simulated impact of the radio frequency identification (RFID) system on the inventory replenishment of the thin film transistor liquid crystal display (TFT-LCD) supply chain in Taiwan. A global operations and logistics case of a well-known LCD monitor manufacturer in Taiwan has been studied. The pull-based multi-agents supply chain was accordingly modeled and simulated with AnyLogic. An automatic inventory replenishment function adopting the (*s*, *S*) policy is enabled with RFID or not. The result of the experiment shows that the RFID-enabled pull-based supply chain can be effectively achieved with a 6.19% decrease in the total inventory cost, and a 7.60% increase in the inventory turnover rate.

Keywords: TFT-LCD; Simulation; Multi-agents; RFID; Inventory replenishment

1. Introduction

Due to globalization and work specialization, enterprise interactions are becoming more frequent and complicated. As a result, enterprise organizations are trying to enhance competence by seeking effective ways to integrate resources with the demand for information exchange. Lee et al. (1997) indicate that the bullwhip effect is caused by demand symbol process, batch ordering, price variation, demand-allocated unit, and several other factors. Kelle and Milne (1999) conclude that the bullwhip effect is mainly caused by lead time. So, for suppliers inventory management can be made more effective by means of batch ordering adopting the (*s*, *S*) policy. Chen et al. (2000) demonstrate that the bullwhip effect is due to the effects of demand forecasting and can be reduced by centralizing demand information. Christopher (2000) defines market sensitivity as the ability of supply chains to make immediate response to customer needs. Therefore, Kaihara (2001) considers the problem of resource allocation in supply chains to be a problem of distributed practical decision.

The AMR Research (2004) defines the demand-driven supply network (DDSN) as a structure consisting of clients, suppliers, and employees. It can sense and respond immediately, as well as integrate operation processes. In the age of consumer economy, the rebuilding of the traditional push-based supply chain is of critical importance to business development. Roddy (2003) of AMR

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summarizes that in order to gain more profit and increase customer delivery of goods rate, the DDSN should be implemented by integrating supply chain operation, production, marketing, and information technology. Greg (2005) of AMR in extension analyzes the fact that most business organizations know that they have to implement the DDSN to manage their global supply chains better. However, as related technology is separately found in different fields, business organizations should figure out solutions to integration.

The 96-bits radio frequency identification (RFID) electronic product code (EPC) was successfully developed by the MIT Auto-ID Center, in association with several large companies of manufacture, logistics, and information, in 2002. In November 2003, EPCglobal was established to promote the EPC standard. Moreover, in January 2005, a successful trial of the RFID/EPC system on pallets and cases was done by Wal-Mart and its top 100 suppliers. The University of Arkansas analyzes Wal-Mart's success and finds that after adopting the RFID/EPC system, there is a 16% decrease in the out-of-stock rate (Wal-Mart, 2005). Besides, the replenishment implementing RFID/EPC is three times faster than that using the traditional bar code. Therefore, the integration of the RFID/EPC system into supply chains becomes a new solution to the reduction of bullwhip effect and the enhancement of inventory replenishment management performance.

Kleijnen (2005) surveys four types of supply chain simulation: spreadsheet, system dynamics (SD), discrete-event dynamic system (DEDS), and business games. The survey concludes that the DEDS simulation is an important method in SCM. Borshchev and Filippov (2004) suggest that the system being modeled contains active objects (people, products, stocks, business units, etc.) with timing and event ordering suitable to add the agent-based model to the DEDS simulation background.

Gunasekaran et al. (2004) conduct a literature review and empirical study of selected British companies to develop six categories for supply chain management (SCM) performance measurement and metrics (order planning, evaluation of supply link, production level, evaluation of delivery link, customer service and satisfaction, supply chain, and logistics cost). The inventory and information processing costs are considered as the major elements within the category of supply chain and logistics cost. It is a valuable reference for measuring the performance indicators in RFID-enabled supply chains.

Lee et al. (2004) of IBM analyze experimental data to simulate the potential benefits of RFID in reducing stock and enhancing service standard. However, the research only focuses on three-tier supply chains. Thus, although it finds the potential benefits in using RFID, it is unable to completely simulate the complexity of global operations and logistics that implements DDSN.

The remainder of this paper is organized as follows: the current situation and future scope of the thin film transistor liquid crystal display (TFT-LCD) industry supply chain is presented in Section 2. The infrastructure of multi-agents-based supply chain simulation enabled by RFID is depicted in Section 3. In Section 4, the simulation conceptual model and formulation based on the company case are explained in details. The design of experiments for simulation model is analyzed in Section 5. Section 6 gives the results of simulation experiments. We conclude the paper in Section 7.

2. TFT-LCD industry supply chain

Before 1995, Japan was in a leading position in the global TFT-LCD industry. In related industries like liquid crystal display, key components, or equipments, Japan was next to none. However, the competition was becoming fierce as manufacturers in Taiwan and Korea joined in. To reduce the cost and expand the market to large-sized LCD TV, the size of the next generation's TFT-LCD is enlarging, and the amount of investment is becoming much higher.

TFT-LCD is a high-value industry in Taiwan, a major universal TFT-LCD supplier. Integration of supply chains is an inevitable trend, in order to enhance total operation efficiency. The TFT-LCD industry is sensitive to capacity planning, so the key point to a successful supply chain operation will be how to share information instantly, completely, and correctly in order to lower the risk of over-production, as well as to pursue the most profit.

Threatened by the rise of Taiwanese and Korean key components' industry, Japanese manufacturers begin to maintain their operational position by setting up a global market through technological authorization and establishment of operational locations abroad. Consequently, Japanese manufacturers gradually withdrew from the market of large-sized TFT-LCD monitors to TFT-LCD TVs and small-sized LCD panels. With government support and technological cooperation with Japan and Korea, China hopes to attract system producers and trigger the magnet effect to help the country enter the TFT-LCD monitor battlefield fast.

The Photonics Industry & Technology Association Development Association (PIDA) (2006) reported that the shipments of large-sized TFT-LCD panels in 2005 from Taiwan took 43.6% of the market, surpassing South Korea and becoming the largest producer of LCD panels. A forecast of the global demand and supply of TFT-LCD panels from 2005 to 2008 was made by PIDA, as shown in Table 1. They are categorized as note book, LCD monitor, and LCD TV. We can find that the annual supply units exceed the demand units from 2006. Most of all, the demand units of LCD TVs will grow by 100% in 2008. In the same year, the forecasted amount of the 17-in LCD panels will be 130 million, and that of the 19-in/20-in LCD panels will be 143 million. This implies that the 19-in/20-in LCD panels will replace the 17-in ones as the market mainstream.

Table 1
Demand and supply forecast of TFT-LCD panels (million sets)

Year	2005	2006	2007	2008
Note book (1)	64	74	87	98
LCD monitor (2)	108	133	158	173
LCD TV (3)	27	46	69	86
Demand = (1)+(2)+(3)	198	253	304	357
Supply	190	274	346	409

The quarterly average quotation of 17-in LCD panels from 2002 to 2005 has been depicted as shown in Fig. 1, with the average market price of LCD monitor shown in Fig. 2. Though the market price is dropping, the long-term demand of the global market is destined to grow.

The TFT-LCD monitor supply chain constructs three layers. The upstream layer contains key components like crystal, color filter, drive IC, transparent electrode, glass substrate, polarizer, and back light. The midstream layer consists of components like high-voltage plate, circuit plate, case, and LCD panel. The conceptual structure of

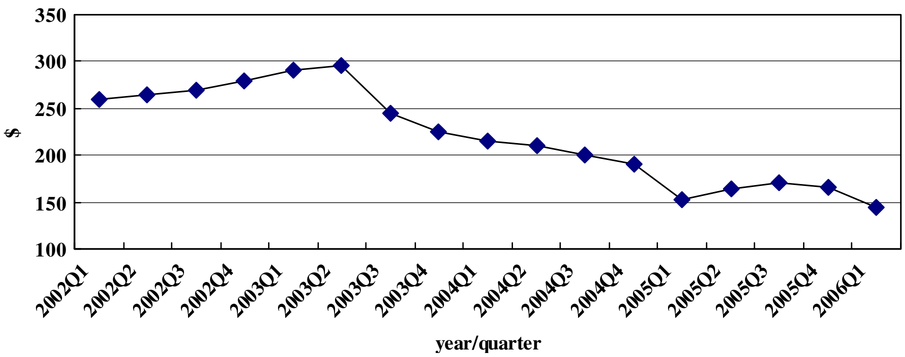

Fig. 1. Quarterly average prices of 17-in TFT-LCD panel.

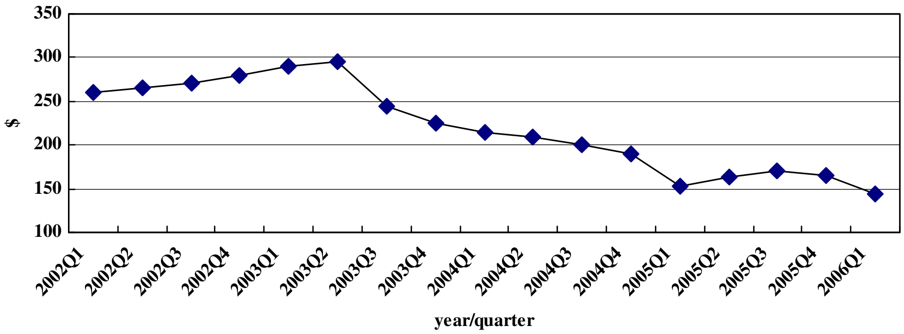

Fig. 2. Monthly average prices for 17-in TFT-LCD monitor.

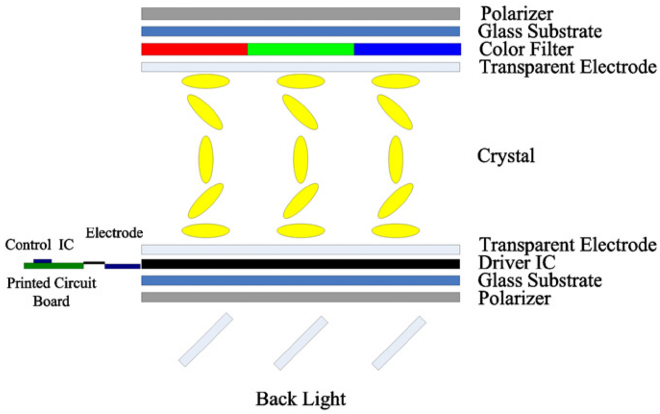

Fig. 3. Conceptual structure of TFT-LCD panel.

TFT-LCD panel is drawn as shown in Fig. 3. In the downstream layer, TFT-LCD manufacturers produce and sell LCD monitors to the customers through distribution channels.

3. Multi-agents-based supply chain simulation model

The multi-agents-based supply chain model is a combination of different agents designed for the operational process and functional requirements of every tier. The model is composed of the management processes of source, make, deliver, and plan, which are defined on the supply chain operation reference (SCOR) model (Supply Chain Council, 2005). Based on the structure of RFID/EPC system and current supply chain process, the conceptual flowchart of RFID/EPC supply chain application is shown in Fig. 4. When products are loaded into trucks and transported to downstream warehouses, the antenna of the RFID system will read the EPC tag on cases, retrieve the embedded information, and transform the data format. Through the Internet connection, transactions of stocks can be monitored at any time.

The structure of multi-agents embedded with the RFID/EPC system has been designed as shown in Fig. 5. In the figure, the structure of the supply chain decision making is divided into three levels from top to bottom. The top level is the supply chain planning agent, which decides the supply chain structure and the operational model. It also evaluates the policy of replenishment adopted by the supply chain. The middle level is the units control agent, which mainly deals with information related to demanding units. Such agents also play the role of information communication and logical conditions judgment. The bottom level is the executive operation agent, which is the actual task performer.

The agents simulate the behaviors of the supply chain members in real world. First, the individual executive operation agent is activated through the information transmitted by the stock units control agents. Then, the other agents are activated according to the results. By repeating the procedure under the given conditions, the operation of the supply chain can be simulated properly. The member structure of the supply chain consists of seven levels. They are components suppliers, LCD panel manufacturers, LCD monitor manufacturers, regional distribution centers, branch warehouses, retailers, and customers. The number of members in each level depends on the actual number of supply chain members and is not limited.

This research establishes a simulated function of automatic replenishment on the supply chain enabled with the RFID/EPC system with AnyLogic, a system simulation tool. The RFID-enabled pull-based supply chain (RPSC) simulation model with multi-agents functions designed with AnyLogic, and the non-RFID-enabled pull-based supply chain (NRPSC) simulation model also designed with AnyLogic software, is also shown in Fig. 6.

4. The company conceptual model and formulation

The research is based on the global operations and logistics case of a 17-in TFT-LCD monitor

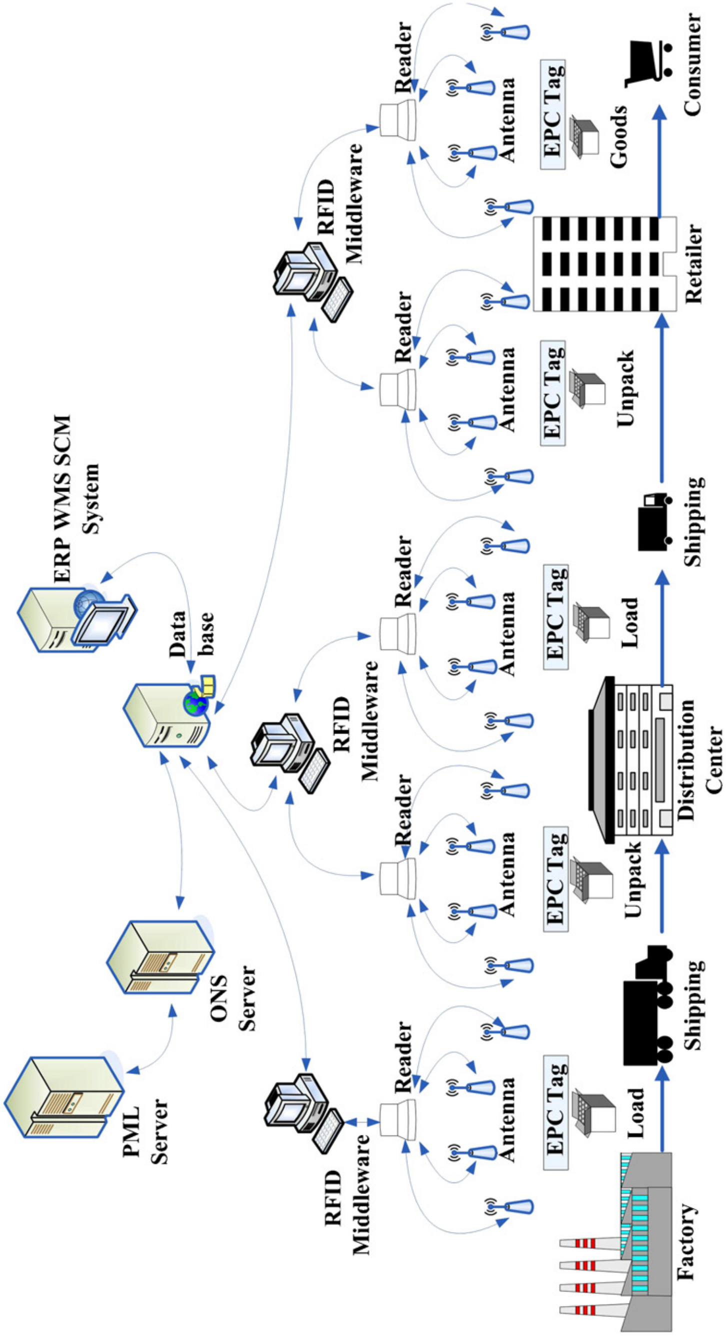

Fig. 4. Conceptual flowchart of RFID/EPC in supply chain application.

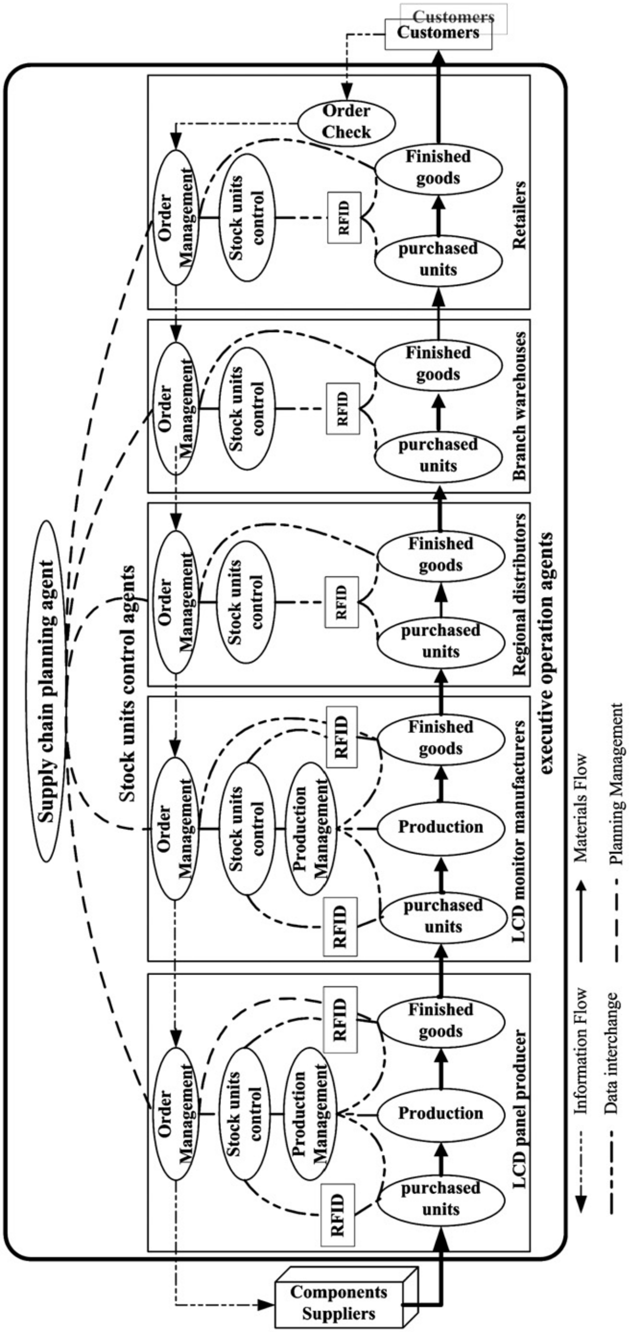

Fig. 5. Multi-agents structure of RFID-enabled pull-based supply chain.

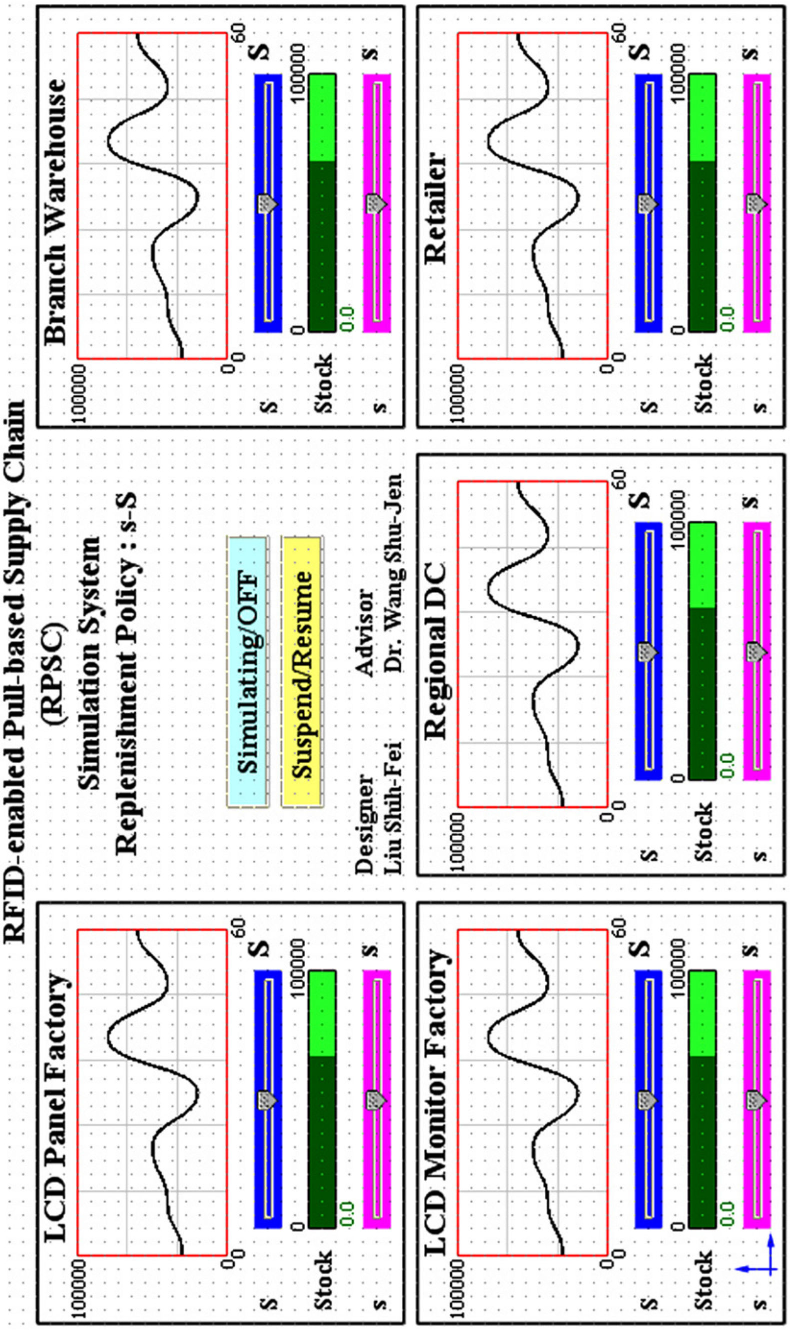

Fig. 6. The AnyLogic snapshot of RFID-enabled supply chain simulation.

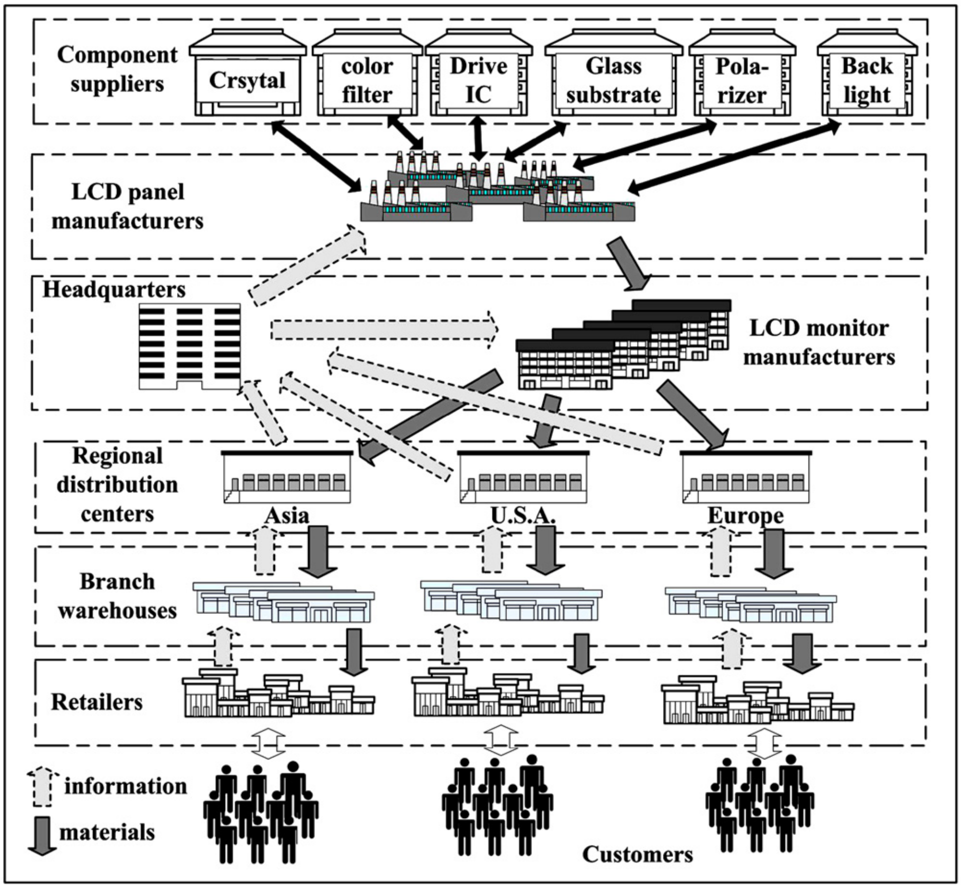

Fig. 7. Structure of global operations and logistics of the company.

produced by the company, a well-known TFT-LCD monitor manufacturer in Taiwan. It includes four LCD monitor factories, three regional distribution centers, more than 10 branch warehouses, and many upstream component suppliers located in all continents. The structure of global operations and logistics for the 17-in LCD monitor of the company is shown in Fig. 7.

The model is a multi-tier supply chain model. There are N supply chain tiers in T simulation periods, and each tier includes several supply chain members. The company collects the stock units and orders information of each tier in its information management center, in order to integrate the information and centralize the distributions. Therefore, the replenishment demand is set depending on the allocated proportion. Under limitations of capacity, stock level, distribution capability, and storage space, it seeks the optimal level of the throughput in each period, the distribution units, raw materials on-hand units, and times of purchasing. The prerequisites of the model are as follows:

- In T simulation periods, the unit costs of raw materials and operations, product price, related parameters, and coefficients are known and constant.
- The upstream raw materials are provided instantly and unlimitedly.
- The (s, S) replenishment policy is being adopted by each tier of the supply chain.
- The finished goods of the upstream are the incoming raw materials of the downstream, whether there are manufacturing factories or not in each tier of the supply chain.
- If there is no stock, backorder is permitted, and out-of-stock units should be issued in the next period.
- The simulation is based on the 17-in TFT-LCD monitor of the company.

- The reference data of customer demand units are based on the average of annual ordering units (forecasted units included) divided by 52 weeks, and then the statistics distribution model of customer demand units is analyzed with StatFit, a probability model analyzing tool. The probability model is the basis of the customer demand rate in the system simulation experiment. Then, the actual number of demand units of the company is imported to StatFit, and the result shows that the statistics distribution model of the company's customer demand is close to lognormal (minimum = 55,841 units/week, $\mu = 6.77923$, $\sigma = 0.342473$). Thus, the demand generation function of the supply chain simulation is set to lognormal.
- The key performance indicators (KPIs) are used for evaluating performances and analyzing deviations before and after business process reengineering or new methods' implementation. In this research, we hope to lower the total inventory cost of the supply chain operation. As a result, the accumulated inventory cost of all tiers and the inventory turnover rate are used as the KPIs in the simulation model.

4.1. Notations

The following notations are used in the RPSC and NRPSC simulation model:

N the set of members in each tier of the supply chain
D_{nt} the demand units received by the orders management agent of manufacturer n in period t
p_n the unit price of finished goods produced by manufacturer n
Q_{nt} the assigned production units of the production management agent of manufacturer n in period t
v_n the issuing operation unit cost of manufacturer n
V_{nt} the issued units by the finished goods agent of manufacturer n in period t
f_n the finished goods unit cost of manufacturer n
F_{nt} the amount of finished goods on-hand units monitored by the finished goods agent of manufacturer n in period t
w_n the work-in-process cost per unit of manufacturer n
W_{nt} the work-in-process units of the production management agent of manufacturer n in period t
o_n the raw materials purchasing unit cost of manufacturer n
S_{nt} the scheduled receipt units monitored by the stock units control agent of manufacturer n in period t
O_{nt} the raw materials purchased units issued by the orders management agent of manufacturer n in period t
d_n the raw materials carrying cost per unit of manufacturer n
h_n the raw materials unit cost of manufacturer n
I_{nt} the raw materials on-hand units monitored by the purchased units agent of manufacturer n in period t
u_n the raw materials dwelled volume per unit of manufacturer n
B_{nt} the backorder units recorded by the finished goods agent of manufacturer n in period t
b_n the backorder unit cost of the finished goods of manufacturer n
R_n the purchasing units percentage allocated by the supply chain planning agent for manufacturer n
$Q_{nt\ \max}$ the maximum production capacity executed by the production management agent of manufacturer n in period t
$L_{nt\ \max}$ the maximum raw materials on-hand units monitored by the purchased units agent of manufacturer n in period t
$H_{nt\ \max}$ the maximum raw materials dwelled volume of manufacturer n in period t
$V_{nt\ \max}$ the maximum issuing capability executed by the finished goods agent of manufacturer n in period t
$B_{nt\ \max}$ the maximum out-of-stock units assigned by the finished goods agent of manufacturer n in period t
$I_{nt\ \min}$ the minimum raw materials on-hand units set by the supply chain planning agent for manufacturer n in period t

4.2. Total inventory cost

The total inventory cost of the supply chain is the sum of the total production cost and the total replenishment cost for all of the tier's members:

$$
\begin{aligned}
\text{total inventory cost} = {} & \text{total production cost}\{(\$\ \text{finishedgoods/unit}) \times ((\text{on-hand} + \text{shipped})\text{units}) \\
& + (\text{on-hand raw materials units}) \\
& \times (\$(\text{carrying} + \text{purchased})/\text{unit}) \\
& + (\$\ \text{work-in-process/unit}) \times (\text{work-in-process units})\} \\
& + \text{total replenishment cost}\{(\$\ \text{purchasing operation/unit}) \\
& \times (\text{issued units/purchasing order}) \\
& + (\$\ \text{purchasing raw materials/unit}) \\
& \times (\text{raw materials purchasing units}) \\
& + (\$\ \text{backorder cost/unit}) \times (\text{backorder units})\} \\
= {} & \sum_{n=1}^{N}\sum_{t=1}^{T}\{p_n(Q_{nt} + V_{nt}) + I_{nt}(d_n + h_n) + w_n W_{nt})\} \\
& + \sum_{n=1}^{N}\sum_{t=1}^{T}(v_n V_{nt} + o_n O_{nt} + b_n B_{nt}). \qquad (1)
\end{aligned}
$$

The total production cost is the product of the sum of the current period on-hand units of finished goods and shipped units by the finished goods unit cost, which is then added to the product of the sum of the raw materials carrying cost per unit and the raw materials unit cost by the on-hand units of raw materials during the current period. After that, the previous period's product will add to the product of the work-in-process cost per unit by the work-in-process units during the current period. The total replenishment cost is the sum of the product of the unit cost of purchasing operation by the issued units of purchasing order, the product of the raw materials purchasing unit cost by the raw materials purchasing units, and the product of the current period backorder units by the backorder unit cost.

4.3. Inventory turnover rate

The inventory turnover rate is the ratio of the sales amount to the inventory cost. The sales amount is the product of the unit price of finished goods by the current period delivered units. The inventory cost is the sum of the cost of raw materials on-hand, the cost of work-in-process on-hand, and the cost of finished goods on-hand during the current period:

$$
\begin{aligned}
& \text{inventory turnover rate} = \text{sales amount} \div \text{inventory cost} \\
& = \sum_{n=1}^{N}\sum_{t=1}^{T} p_n D_{nt} \div \sum_{n=1}^{N}\sum_{t=1}^{T}(h_n I_{nt} + w_n W_{nt} + f_n F_{nt}). \qquad (2)
\end{aligned}
$$

4.4. Model constraints

- *Inventory level*: The actual amount of finished goods units is the deduction of the current period's finished goods on-hand units and the backorder units. To be precise, it is the sum of the last period's actual finished goods units, the current period's raw materials purchased units, the scheduled receipt units, the raw materials on-hand units, the work-in-process on-hand units, and the finished goods on-hand units, minus the current period's delivery units:

$$
\begin{aligned}
F_{nt} - B_{nt} = {} & F_{nt-1} - B_{nt-1} + Q_{nt} + S_{nt} + I_{nt} + W_{nt} \\
& + F_{nt} - D_{nt} \quad \forall n, \forall t. \qquad (3)
\end{aligned}
$$

The sum of the raw materials on-hand units and the scheduled receipt units has to be smaller than the maximum raw materials on-hand units:

$$\sum_{n=1}^{N} I_{nt} + S_{nt} \leqslant L_{nt\ \max} \quad \forall n, \forall t. \qquad (4)$$

The raw materials on-hand units need to be larger than the minimum raw materials on-hand units:

$$I_{nt} \geqslant I_{nt\ \min} \quad \forall n, \forall t. \qquad (5)$$

The backorder units need to be smaller than the maximum backorder units:

$$B_{nt} \leqslant B_{nt\ \max} \quad \forall n, \forall t. \qquad (6)$$

- *Delivery capacity*: The sales cost is the product of the sum of the issuing operation unit cost and the finished goods unit cost by the issued units:

$$\sum_{n=1}^{N} p_n D_{nt} = \sum_{n=1}^{N} (v_n + f_n) V_{nt} \quad \forall t. \tag{7}$$

Meanwhile, the issued units need to be smaller than the maximum issuing capability:

$$V_{nt} \leqslant V_{nt\ \max} \quad \forall n, \forall t. \tag{8}$$

- *Raw materials dwelled volume*: The product of the raw materials dwelled volume per unit by its on-hand units has to be smaller than the maximum dwelled volume:

$$\sum_{n=1}^{N} u_n I_{nt} \leqslant H_{nt\ \max} \quad \forall t. \tag{9}$$

- *Production capacity*: The throughput units equal the sum of all raw materials purchased units:

$$\sum_{n=1}^{N} R_n O_{nt} = Q_{nt} \quad \forall t. \tag{10}$$

- The throughput units need to be smaller than the maximum production capacity:

$$Q_{nt} \leqslant Q_{nt\ \max} \quad \forall n, \forall t. \tag{11}$$

The sum of allocated purchasing units percentage should be equal to 100%:

$$\sum_{n=1}^{N} R_n = 100\% \quad \forall t. \tag{12}$$

- *Decision variable non-zero constraint*: All variables should not be smaller than zero:

$$D_{nt}, Q_{nt}, V_{nt}, F_{nt}, W_{nt}, S_{nt}, B_{nt}, O_{nt}, R_n \geqslant 0 \quad \forall n, \forall t. \tag{13}$$

4.5. Model running procedure

The major procedure for running the RPSC simulation model is starting with customer demand generated by the system based on lognormal distribution. Then, the order check agent notifies the customer order management agent after the demand is confirmed and the finished goods agent was asked to ship the required TFT-LCD units to the customer. A real-time monitoring is performed through the RFID agent simultaneously. The finished goods stock units control agent obtains real-time transactions information of the on-hand finished units. If the on-hand finished units are in short supply, the existing finished units will be issued at once. The out-of-stock units will be recorded as a backorder by the order management agent and be released first after several days when newly finished units are received.

The finished goods stock units control agent monitors the transactions of on-hand units continuously. If the on-hand units are found to be smaller than the re-ordering point s, the requirements of replenishment are sent to the raw materials purchasing order management agent and are recorded as scheduled receipt units. The amount of the raw materials purchasing units is the deduction of the amount of the value of the on-hand goal S and the present on-hand units. When the purchased raw materials for replenishment arrive, the raw materials stock units control agent of each tier will receive the information of the gaining of on-hand units sent by the RFID agent. Then, the total of the present on-hand units and the scheduled receipt units will be checked to see if it exceeds the amount of the maximum raw materials on-hand units.

The production management agent of the manufacturing plant tier receives the information of an out of stock in the finished goods records; it will ask the production agent to begin fabrication for several days. The unit of work-in-process increased and the unit of raw materials units decreased simultaneously. The transactions of the raw materials on-hand units in the manufacturing plant are monitored by the RFID agent. The purchasing units agent is responsible for the release and carrying operation of the raw materials in stock.

In the NRPSC model, the RFID agents in the procedure above will be replaced with certain delayed time consumed by manual operations. The detailed RPSC simulation flow chart is depicted in Fig. 8.

4.6. Model verification and validation

The effectiveness of the supply chain automatic replenishment simulation model must be proved through the model effectiveness test. The test can be divided into three parts. In the first and second parts, the model will be tested of its ability to respond normally to changes in testing conditions. Therefore, the numerical data for the test are not limited to those of real-world cases, which will be used in the third part for experimental reference.

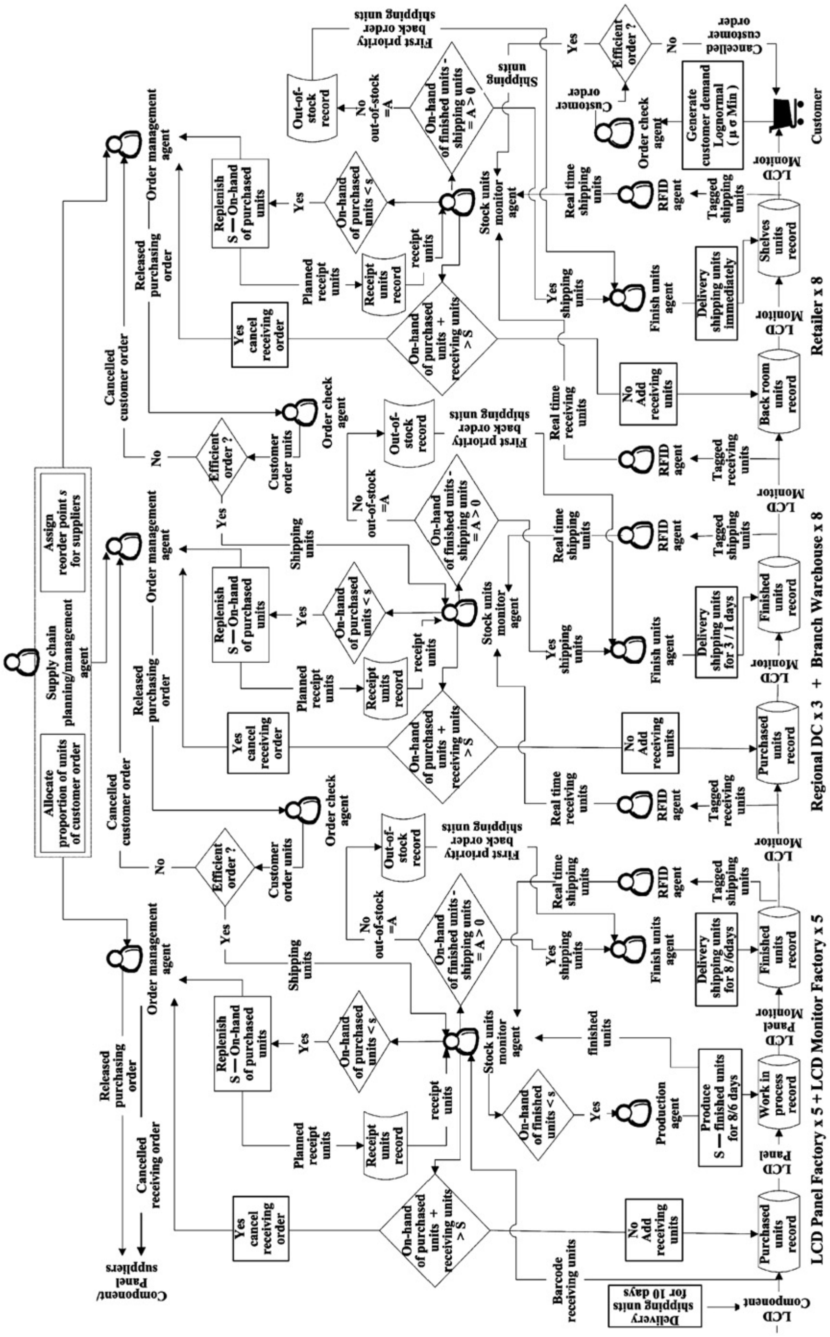

Fig. 8. Detailed flow chart for simulation running procedure of RPSC.

- *Stability test*: This test focuses on the impact of external variables on internal system variables in the simulation process. Through externally emerging factors, the response of the system will be checked to see if it is proper. And, if the system status turns stable after external factors are eradicated, then the degree of effect of the system is acceptable. At the beginning of the experiment, the fixed demand rate is adopted, and the simulation result shows that the system status can effectively turn equilibrated in the end. To prove the stability of the system for a second time, the production function will be activated in week 5, and this time without any external factors.
- *Time phase relationship test*: This test will check if there are cycle oscillation and interior degree of effect in the system model. First, the amount of demand per week is set to 2660, with that of the replenishment units every 6 weeks set to 15,000. The first replenishment signal will appear in week 5. The demand model of such cycles successfully proved the response pattern of the system to the oscillation of cyclic demand.
- *Integration test*: This part will test the pattern of oscillation and the cycle time of the model. At the beginning, the number of the actual demand units of the company's 17-in LCD monitor will be imported to the system, and the output of the simulation will be compared with the number of the actual demand units in order to check if it differs from actual data pattern and to prove the degree of effect of the simulation forecasting. The integrated experiment sets the average production from weeks 1 to 3 as the number of initial demand units. The t-value two-tailed test of the mean of population of the 52-week simulation is 0.015871241, which is less than the critical value of the 0.025 level of significance, 2.007583728. The p-value is 0.987399041. Therefore, this fact shows that there is no significant difference between the actual and simulated demand units.

5. Model design and analysis of experiment

In order to seek the best KPI output values (total inventory cost and inventory turnover rate) for the RPSC and NRPSC models of this research, five model entities (variables) are chosen. They are LCD panel factory, LCD monitor factory, regional distribution center (DC), branch warehouse, and retailer. The replenishment decision variables needed to do the simulation experiment factorial design and to perform the experiment task are the levels of the re-ordering point s and the purchase goal S, as shown in Table 2. Each tier of the supply chain adopts a combination of high and low values for its purchase goal, and the re-ordering point of each tier is a fixed value.

The design of this simulation experiment has 32 combinations of experiment factors, as shown in Table 3. Each factor will do a 52-week simulation experiment individually on the RPSC and NRPSC models. There will be 1920 runs of simulation and 30 replications for each run of the experiment, and the average output value will be used in the end. The KPI counting unit of the total inventory cost is US

Table 3
Partial design matrix for the company supply chain simulation experiments

No.	Design matrix variables—purchasing level					Treatment group
	LCD panel factory A	LCD monitor factory B	Regional DC C	Branch warehouse D	Retailer E	
1	–	–	–	–	–	(1)
2	+	–	–	–	–	a
3	–	+	–	–	–	b
4	+	+	–	–	–	ab
5	–	–	+	–	–	c
6	+	–	+	–	–	ac
9	–	–	–	+	–	d
17	–	–	–	–	+	e

Table 2
Seventeen-inch monitor inventory replenishment level (sets/week) for simulation experiments

Variable	LCD panel factory	LCD monitor factory	Regional DC	Branch warehouse	Retailer
Re-ordering point (s)	50,000	49,000	48,000	40,000	31,000
Purchasing level (S) high	84,000	76,000	68,000	63,000	58,000
Purchasing level (S) low	83,000	72,000	65,000	59,000	55,000

dollars, and that of the inventory turnover rate is times.

To compare the operational models of the RPSC and NRPSC, the KPI values of the results of the simulation experiment will be permutated from the largest to the smallest, and the best combination of supply chain purchase goal setting will become a reference for the supply chain planning management. We use P to represent the NRPSC model and R to represent the RPSC model.

The result, as shown in Table 4, shows that P1, which performs best in the NPRSC model, ranks only fourth. On the other hand, the PRSC, which has the same result as P1, is among the top eight. Therefore, the performance of the PRSC is better than that of the NPRSC.

The variations of means of the inventory turnover rate for experiments R1, R3, and P1 are shown in Fig. 9. The Bonferroni approach with paired-t confidence intervals is used to evaluate our hypotheses for the three alternative designs for the RPSC and NRPSC models. We wish to evaluate the hypotheses by letting $\alpha_1 = \alpha_2 = \alpha_3 = \alpha/3 = 0.06/3 = 0.02$ significance level with sample size $n_1 = n_2 = n_3 = 30$.

$$H_0 : \mu_{\mathrm{R1}} = \mu_{\mathrm{R3}} = \mu_{\mathrm{P1}} \text{ or } \mu_{\mathrm{R1}} - \mu_{\mathrm{R3}} = \mu_{\mathrm{R1}} - \mu_{\mathrm{P1}} = \mu_{\mathrm{R3}} - \mu_{\mathrm{P1}} = 0,$$

$$H_1 : \mu_{\mathrm{R1}} \neq \mu_{\mathrm{R3}} \text{ or } \mu_{\mathrm{R1}} \neq \mu_{\mathrm{P1}} \text{ or } \mu_{\mathrm{R3}} \neq \mu_{\mathrm{P1}}$$

$$\because\ \bar{x}_{(\mathrm{R1-R3})} = 0.0935 \quad \bar{x}_{(\mathrm{R1-P1})} = 0.1111 \quad \bar{x}_{(\mathrm{R3-P1})} = 0.0176$$

$$\because\ s_{(\mathrm{R1-R3})} = 0.0337 \quad s_{(\mathrm{R1-P1})} = 0.0968 \quad s_{(\mathrm{R3-P1})} = 0.0969,$$

$$P[\bar{x}_{(\mathrm{R1-R3})} - hw \leqslant \mu_{(\mathrm{R1-R3})} \leqslant \bar{x}_{(\mathrm{R1-R3})} + hw] = 1 - \alpha_1 = 1 - 0.02 = 0.98,$$

$$hw = \frac{(t_{n-1,\alpha/2})s_{(\mathrm{R1-R3})}}{\sqrt{n}} = \frac{(t_{29,0.01})0.0337}{\sqrt{30}} = \frac{(2.462)0.0337}{\sqrt{30}} = 0.0151.$$

Table 4
Mixed ranking of NRPSC and RPSC simulation experiments

Rank	Ascending by total inventory cost			Descending by inventory turnover rate		
	No.	Total inventory cost/week	Inventory turnover rate	No.	Total inventory cost/week	Inventory turnover rate
1	R1	21,091,613	1.4625	R1	21,091,613	1.4625
2	R3	21,795,432	1.3689	R3	21,795,432	1.3689
3	R2	21,908,863	1.3460	R6	22,392,355	1.3517
4	P1	21,912,988	1.3513	P1	21,912,988	1.3513
5	R9	22,159,067	1.3268	R2	21,908,863	1.3460
6	R5	22,165,507	1.3304	R5	22,165,507	1.3304
7	R4	22,185,655	1.3178	R9	22,159,067	1.3268
8	R17	22,244,727	1.3032	R4	22,185,655	1.3178

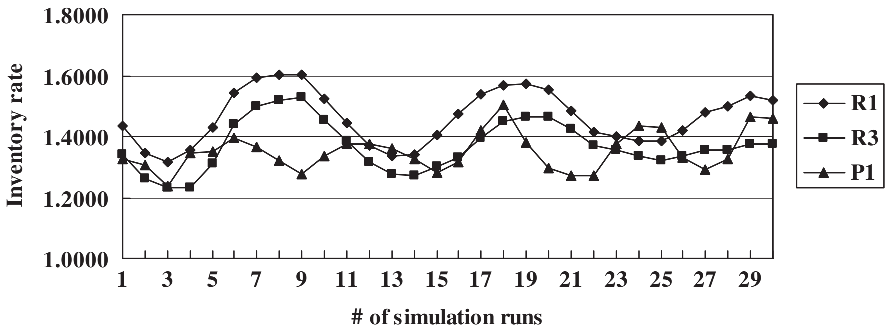

Fig. 9. Comparing inventory turnover rate by experiments R1, R3, and P1.

The approximate 98% confidence interval is

$$0.0935\square 0.0151\leqslant\mu_{(R1-R3)}\leqslant 0.0935+0.0151$$
$$0.0784\leqslant\mu_{(R1-R3)}\leqslant 0.1086.$$

Additionally, we have $0.0676\leqslant\mu_{(R1-P1)}\leqslant 0.1546$ and $-0.026\leqslant\mu_{(R3-P1)}\leqslant 0.0612$.

From the result of the Bonferroni experiment, we can see that there are significant differences between experiments R1 and R3, for 0 is not included in the 98% confidence interval of $\mu_{(R1-R3)}$. Also, there are differences between R1 and P1, for 0 is not included in the 98% confidence interval of $\mu_{(R1-P1)}$. However, there are no significant differences between R3 and P1, for 0 may be included in the 98% confidence interval of $\mu_{(R3-P1)}$. These facts prove that the performance of the RPSC is better than that of the NPRSC. With the same conditions as the pull-based supply chain, the RFID-enabled supply chain will have lower total inventory cost and higher inventory turnover rate.

6. Analysis of KPI outputs

6.1. RFID system cost

In the RPSC simulation model, one RFID system is composed of two antennas and one reader. The cost of an antenna is \$290. The cost of a reader is \$995. The total cost of one RFID system is \$1575. The simulation running length is set to be 1 year. We assume that the RFID system has a 5-year useful life. Based on the accelerated depreciation method, the salvage value of one RFID system at the end of the fifth year will be \$1575/10 = \$157.5. The depreciation expense of one RFID system at the end of the first year equals (\$1575−\$157.5) × [(5−1+1)/(1+2+3+4+5)] = \$472.5. The annual maintenance cost of one RFID system is multiplied by 12% of the cost of one RFID system \$1575 × 12% = \$189. The annual operating cost of one RFID system is forecasted to be \$1575 × 15% = \$236.25. The total cost of one RFID system at the end of first year equals \$472.5 + \$189 + \$236.25 = \$897.75.

The four-tier members (five TFT-LCD monitor factories, three regional distribution centers, eight regional branch warehouses, and eight retailers) in the TFT-LCD supply chain simulation model, two RFID systems are virtually installed at the entrance of purchased units receiving area and the platform of finished units shipping area separately. For the five TFT-LCD panel factories, only one RFID system is virtually installed at the platform of finished units shipping area.

Moreover, the cost of one piece of RFID tag is \$1. Based on the simulation results, the five TFT-LCD panel factories have produced 3,626,381 units, so the cost of RFID tags is \$3,626,381. On the other hand, the five TFT-LCD monitor factories have produced 3,544,387 units, so the cost of RFID tags is \$3,544,387.

Therefore, the cost of RFID systems 1 year later at the five-tier member of the TFT-LCD supply chain is calculated as follows:

Five TFT-LCD panel factories :
$$\$897.75\times 1\times 5 \risingdotseq \$4489+\$3,626,381$$
$$=\$3,630,870.$$

Five TFT-LCD monitor factories :
$$\$897.75\times 2\times 5 \risingdotseq \$8978+\$3,544,387$$
$$=\$3,553,365.$$

Three regional distribution centers :
$$\$897.75\times 2\times 3 \risingdotseq 5387.$$

Eight regional branch warehouses :
$$\$897.75\times 2\times 8 \risingdotseq \$14,364.$$

Eight retailers : $\$897.75\times 2\times 8 \risingdotseq \$14,364.$

6.2. Experiment results

The experiment result shows that the KPI of the combination of experimental variables in R1 of RPSC is the highest, as shown in Table 5.

The comparison of the KPIs of R1 in RPSC to P1 in NPRSC based on $s\ \pm 5\%$ and the improvement on the inventory cost included in the RFID system cost of each tier are shown in Table 6. The average total inventory cost of RPSC based on $s+5\%$, s, and $s-5\%$ saves \$85,302,240, \$41,263,821, and \$28,039,456, respectively, representing reductions of 6.59%, 3.38%, and 2.74%, respectively. Among the inventory costs based on s of all tiers, the regional DCs save \$82,734,491 every year, which means it has a 6.42% decrease and the best performance.

At the same time, we compare the inventory turnover rates of the RPSC and NPRSC models based on $s+5\%$, s, and $s-5\%$, as shown in Table 7, and we find that the RPSC has an increase of 6.89%, 7.6%, and 10.78%, respectively. Among the inventory turnover rates of all tiers, the branch warehouse has a 14.04% increase in its inventory turnover rate, which means it has the best performance.

Table 5
Optimal value (sets/week) of (s) and (S) for experiment R1

Variable	LCD panel factory	LCD monitor factory	Regional DC	Branch warehouse	Retailer
(*s*)	50,000	49,000	48,000	40,000	31,000
(*S*)	83,000	72,000	65,000	59,000	55,000

We find that the degree of improvement in the retailer tier is the lowest. This is because the retailer tier is at the downstream position of the supply chain, where the impact of the bullwhip effect is not apparent and the room for improvement is relatively small. In contrast, the LCD panel and LCD monitor manufacturers are at the midstream and upstream positions, so there should be more room for improvement according to the bullwhip effect theory. However, the result shows that the degree of improvement of the two tiers in total inventory cost or inventory turnover rate is lower than that of the regional distribution center. For example, there is a 2.79% decrease in the total inventory cost of the LCD monitor manufacturer. This is because the LCD panel and LCD monitor manufacturers are

Table 6
Comparing the inventory cost (US/year) by five experimental variables based on $\pm5\%$ *s*

Variable	LCD panel factory	LCD monitor factory	Regional DC	Branch warehouse	Retailer	Average
NRPSC						
s+(1)	830,014,115	1,237,197,343	1,397,358,879	1,407,588,615	1,300,861,097	1,234,604,010
s (2)	802,791,046	1,107,808,442	1,287,838,537	1,285,672,667	1,213,266,180	1,139,475,374
s−(3)	790,546,643	1,031,241,511	1,078,517,946	1,046,107,579	1,007,819,005	990,846,537
RPSC						
s+(4)	810,324,438	1,102,462,074	1,300,422,042	1,311,818,657	1,214,243,244	1,147,854,091
s (5)	788,698,451	996,585,993	1,205,095,494	1,204,391,607	1,142,114,112	1,067,377,131
s−(6)	779,625,464	983,713,917	1,061,613,337	986,106,975	995,737,315	961,359,402
RFID COST (7)	3,630,870	3,553,365	8,552	22,804	22,804	None
(8) = (1)−(4)−(7)	16,058,807	131,181,904	96,928,285	95,747,154	86,595,049	85,302,240
(9) = (2)−(5)−(7)	10,461,725	30,893,056	82,734,491	81,258,256	971,577	41,263,821
(10) = (3)−(6)−(7)	7,290,309	43,974,229	16,896,057	59,977,800	12,058,886	28,039,456
(8)/(1) (%)	1.93	10.60	6.94	6.80	6.66	6.59
(9)/(2) (%)	1.30	2.79	6.42	6.32	0.08	3.38
(10)/(3) (%)	0.92	4.26	1.57	5.73	1.20	2.74

Table 7
Comparing the inventory turnover rate (%) by five experimental variables based on $\pm5\%$ *s*

Variable	LCD panel factory	LCD monitor factory	Regional DC	Branch warehouse	Retailer	Average
NRPSC						
s+(1)	1.3885	1.4639	1.1896	1.3672	1.8855	1.4643
s (2)	1.3430	1.3108	1.0964	1.2488	1.7573	1.3513
s−(3)	1.3225	1.2202	0.9182	1.0161	1.4608	1.1752
RPSC						
s+(4)	1.4463	1.5644	1.3639	1.5824	1.8857	1.5728
s (5)	1.4077	1.4142	1.2639	1.4528	1.7737	1.4625
s−(6)	1.3915	1.3959	1.1134	1.1895	1.5464	1.3172
[(4)−(1)]/(1) (%)	3.99	6.43	12.78	13.60	0.01	6.89
[(5)−(2)]/(2) (%)	4.60	7.31	13.25	14.04	0.92	7.60
[(6)−(3)]/(3) (%)	4.96	12.59	17.53	14.58	1.54	10.78

tiers that have production plants. If there are production plants, there will inevitably be work-in-process on-hand units, and they limit the degree of improvement on the KPI. Therefore, the agent-based simulation system established in this research is relatively close to the real-world supply chain operation compared with other systems established according to the bullwhip effect theory.

7. Conclusion

This research is based on the case of a real-world company and the pull-based DDSN environment, establishing a RFID-enabled and a non-RFID-enabled TFT-LCD supply chain embedded with automatic replenishment simulation systems to analyze and compare the degree of improvement in the KPIs of total inventory cost and inventory turnover rate. The simulation system proves its effectiveness through stability test, time phase relationship test, and integration test. After nearly 2500 runs of experiment, we find that there is more decrease in total inventory cost and more increase in inventory turnover rate of the RPSC than the NRPSC. It also finds that due to the existence of work-in-process on-hand units, the degree of improvement in the bullwhip effect on tiers with production plants is limited. As a result, we should focus on improving the manufacturing process and the materials process in factories so that a total improvement in the supply chain can be expected.

References

AMR Research, 2004. Welcome to the DDSN Diagnostic Tool. 〈http://www.amr-research.com/tools/ddsn/welcome.asp〉.

Borshchev, A., Filippov, A., 2004. From system dynamics and discrete event to practical agent based modeling: Reasons, techniques, tools. In: Proceedings of the 22nd International Conference of the System Dynamics Society, July 25–29, 2004, p. 45.

Chen, F.Z., et al., 2000. Quantifying the bullwhip effect in a simple supply chain: The impact of forecasting, lead time, and information. Management Science 46 (3), 436–443.

Christopher, M., 2000. The agile supply chain competing in volatile markets. Industrial Marketing Management 29, 37–44.

Greg, A., 2005. DDSN visibility for global supply lines: Technology options abound. AMR Research Outlook, February 3. 〈http://www.amrresearch.com/Content/View.asp?pmillid=17984〉.

Gunasekaran, A., Patel, C., McGaughey, R.E., 2004. A framework for supply chain performance measurement. International Journal of Production Economics 87 (3), 333–347.

Kaihara, T., 2001. Supply chain management with market economics. International Journal of Production Economics 73, 5–14.

Kelle, P., Milne, A., 1999. The effect of (*s*, *S*) ordering policy on the supply chain. International Journal of Production Economics 59, 113–122.

Kleijnen, J.P.C., 2005. Supply chain simulation tools and techniques: A survey. International Journal of Simulation and Process Modelling 1 (1/2), 82–89.

Lee, H.L., Padamanabhan, V., Whang, S., 1997. Information distortion in a supply chain: The bullwhip effect. Management Science 43 (4), 546–558.

Lee, Y.M., Chen, F., Leung, Y.T., 2004. Exploring the impact of RFID on supply chain dynamics. In: Proceedings of the 2004 Winter Simulation Conference, pp. 1145–1152.

Pacific News, 2006. PIDA reported that Taiwan's large-sized LCD panel shipments took 43.6% global market in 2005, surpassing South Korea as the #1 producer, January 20. 〈http://www.pacificnews.com.tw/shownews.php?postnewsid=2&titleid=32493〉.

Roddy, M., 2003. DDSN requires optimization across products, customers, and operations. AMR Research Outlook, September 23. 〈http://www.amrresearch.com/Content/View.asp?pmillid=16628〉.

Supply-Chain Council, 2005. SCOR 7.0 Model. 〈http://www.supply-hain.org/page.ww?section=SCOR+Model&name=SCOR+Model〉.

Wal-Mart Facts, 2005. Wal-Mart corporate communications: Wal-Mart improves on-shelf availability through the use of electronic product codes, October 14. 〈http://www.walmartfacts.com/newsdesk/article.aspx?id=1401〉.